# Modelling the Impacts of Land Cover Change on Flood Hydrographs in Upland Peat Catchments

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Submitted in accordance with the requirements for the degree of Doctor of Philosophy

The University of Leeds
School of Geography

November 2013

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

To Mam

## Acknowledgements

I am very grateful to my supervisors, Professor Joseph Holden and Professor Mike Kirkby, for their encouragement, support, guidance and inspiration. I would also like to thank Dr. Richard Grayson and Dr. Duncan Quincey for their helpful suggestions on my research.

I am also grateful to the Environmental Change Network, the Centre for Ecology and Hydrology, and the North Pennines AONB Partnership who provided useful data for this thesis.

For my Ph.D funding, I would like to gratefully thank the China Scholarship Council and the School of Geography, University of Leeds.

I would like to thank all my friends in Leeds and the CSC Ph.D student group who have provided warm help.

Finally I would like to thank my parents and my wife who give unique, loving support.

## Abstract

There is global concern about headwater management and associated impacts on river flow. In many wet temperate zones peatlands can be found in headwater catchments. In the UK there is major concern about how environmental change, driven by human interventions, has altered the surface cover of headwater blanket peatlands. However, the impact of such cover changes on river flow is poorly understood. In particular, there is poor understanding of the impacts of different spatial configurations of bare peat or well-vegetated restored peat on river flow peaks in upland catchments. This thesis employs a numerical modelling approach to explore such impacts.

TOPMODEL, due to its process representation which is very suitable for blanket peat catchments, was utilized as a prototype acting as the basis for a new distributed catchment hydrological model. A new overland flow module with a set of detailed stochastic algorithms representing overland flow routing and re-infiltration mechanisms was created to simulate saturation-excess overland flow movement. The influence of land cover on surface roughness could be represented in the model. The new model was tested in three upland peat catchments in different parts of the UK: Trout Beck in the North Pennines, the Wye in mid-Wales and the East Dart in southwest England. The model was found to work well in all three cases.

Land cover scenarios were designed for the three catchments to investigate land cover impact on river flow through simulation runs of the new version of TOPMODEL. As a result of hypothesis testing three land cover principles emerged from the work as follows:

Principle (1): A wider bare peat strip nearer to the river channel gives a higher flow peak and reduces the delay to peak; conversely, a wider buffer strip with higher density vegetation (e.g. *Sphagnum*) leads to a lower peak and postpones the peak. In both cases, a narrower buffer strip 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 equal, the size of land cover change patches has no effect on river flow for patch sizes up to 10000m$^2$.

Principle (3): Bare peat on gentle slopes gives a faster flow response and higher peak value at the catchment outlet, while high density vegetation or

re-vegetation on a gentle slope area has larger positive impact on peak river flow delay when compared with the same practices on steeper slopes.

These simple principles should be useful to planners who wish to determine resource efficiency and optimisation for peatland protection and restoration works in headwater systems. If practitioners require further detail on impacts of specific spatial changes to land cover in a catchment then the new model can be readily applied to new catchments of concern. The model also has the potential to provide useful information on potential sediment or contaminant transfers because it has a fully distributed overland flow module.

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# Chapter 1
# Introduction

## 1.1 Background

The landscape has been heavily modified by human activities in many parts of the world. One of the key modifications is to vegetation cover. Deforestation, urbanisation, food production and climate change have played a large role in dramatically altering the terrestrial biosphere (Houghton, 1994). In turn, such changes to the surface condition of the landscape impact the hydrological cycle (Sitch and Drake, 2013). As a consequence river regimes may be altered due to changes in the overall water balance (inputs versus outputs) and also because of changes to the flowpaths for water to the river channel. Such changes may influence the shape of storm hydrographs and the magnitude of flow peaks (e.g. Peffy and Nawaz, 2008; Pikounis et al., 2003). One major concern is that of land management impacts on flood risk (Wheater and Evans, 2009). Understanding the impact of vegetation cover and management on flood risk is vital to provide land managers with information needed to inform planning decisions and resource allocations.

Peatland landscapes are a particularly sensitive to external drivers of change and slight shifts in local hydrology or chemistry may cause changes in species composition and hence surface cover (Bragg and Tallis, 2001; Holden et al., 2007a). Peatlands cover around 3% (an estimated area of 400 million ha) of the Earth’s land surface (Immirzi et al., 1992; Lappalainen, 1996). They store around half of global soil carbon (Strack, 2008; Yu et al., 2010) and as peatlands are more likely to form in regions with high precipitation excess, they often form in upland areas of the temperate and boreal zones (Gallego-Sala and Prentice, 2013). Thus, in many parts of the British Isles, peatlands occur in the headwater catchments of major rivers (Burt, 1995). There is therefore concern about changes to river regime and flood risk that might be brought about due to degradation of upland peatlands. Peatlands might both attenuate and increase flood risk in different environmental settings or at different times of the year (Acreman and Holden, 2013; Bullock and Acreman, 2003), but understanding of upland peatland management and land cover impacts on altering streamflows is still unclear and needs to be improved.

Large areas of the UK uplands are covered by blanket peat. Blanket peatlands typically have high water tables (Price, 1992), and hence the potential for peat to store additional fresh water and act as a buffer to flooding is very limited (Holden et al., 2006). Thus a little rainfall can cause rapid saturation of the peat and lead to the generation of saturation-excess overland flow or rapidly-flowing near-surface throughflow and these flows may dominate the river hydrograph during storm events (Holden and Burt, 2002; 2003b). The river regime of blanket peatlands tends to be very flashy with rapid rising limbs, high flow peaks and very little baseflow (Evans et al., 1999). There are concerns that land management interventions in upland peatlands in the UK may increase flood peaks (e.g. Hess et al., 2010; O'Connell et al., 2004; Parrott et al., 2009; Posthumus et al., 2008; Wheater and Evans, 2009). However, given that these systems are already very flashy in nature it is not clear what impacts such interventions might have. There is also the related problem of the spatial distribution of management interventions. As noted by Holden (2005), the same management intervention may both theoretically increase and decrease the flood peak in the main river channel depending on how the intervention affects the timing of water delivery and its synchronosity from different parts of the catchment. There is therefore a need to understand such issues to support environmental decision making.

In many areas of the UK uplands there has been a history over at least the last 60 years of the loss of vegetation due to overgrazing, atmospheric pollution, wildfire and other interventions (e.g. Bower, 1961; Bower, 1962; Evans, 2005; Holden et al., 2007b; Maltby et al., 1990; Tallis, 1973). Thus a loss of a dense understory of *Sphagnum* or the complete loss of surface vegetation altogether may lead to changes in water movement over peatland surfaces. *Sphagnum* is associated with a much greater surface roughness than bare peat and it therefore has an ability to significantly slow down the velocity of water movement (Holden et al., 2008). Peatland restoration efforts are underway across many degraded upland landscapes and these often seek to revegetate bare peat (Parry et al., in press). Practitioners are very keen to understand whether such revegetation has an impact on river flows that could be used as an additional justification for their work and perhaps yield further investment (e.g. IUCN, 2011). Thus, we need a tool to evaluate the impact on river flow peaks of changes to, and the spatial distribution of, land cover types in headwater peatlands.

TOPMODEL was originally developed by Beven and Kirkby (1979) at the University of Leeds, and initially employed in UK small catchments (Beven et al., 1984). The model is considered as a set of conceptual tools which can be utilised to model the hydrological processes (especially the dynamics of surface and subsurface contributing areas) in a relatively simply way (Beven, 1997). TOPMODEL has been treated as a standard model for hydrological analysis in many European countries (Singh and Woolhiser, 2002) and had a global use, e.g. Lamb et al. (1998) in Norway, Franks et al. (1998) and Saulnier and Datin (2004) in France, Güntner et al. (1999) in Germany, Xiong and Guo (2004) and Chen and Wu (2012) in China, Dietterick et al. (1999) and Peters et al. (2003) in the US, Sivapalan et al. (1997) in Australia, and etc.

The assumptions of TOPMODEL are suitable for the case of blanket peat-covered catchments which are dominated by surface and near-surface flow (Holden and Burt, 2003b). However, the model is not spatially distributed and has no module to represent overland flow movement, so the model cannot describe the impacts of different distributions of vegetation cover change and their impacts on surface flow and downstream river flow. However, TOPMODEL has many advantages which means it could be employed as a good prototype to be modified into a distributed model to simulate land cover change impacts on river flow in upland peat catchments.

## 1.2 Research aim and questions

The aim of this research is to understand the impact of land cover change on river flow in upland peat headwaters. It does so by taking forward a numerical modelling approach building on empirical field data. In order to accomplish this aim, there are three main research questions to be addressed in this thesis.

1. What is the impact of upland management on downstream river discharge, especially on peak flow and timing in upland peat catchments?

2. Can we adequately characterise upland land management impacts as impacts on surface vegetation cover, roughness and hydrological flowpaths that affect the speed and timing of delivery of water to river channels?

3. To simulate the impacts what would be a robust approach? Is a modified TOPMODEL competent to address the two key questions above?

The thesis develops new components of TOPMODEL and tests the revised model across three different headwater catchments. Land cover scenarios are designed to support a series of structured experiments in order to understand how land cover impacts peak flow magnitude and timing.

## 1.3 Organisation of the thesis

The work in this thesis will be presented in the order of: literature review, model establishment, scenario experiments and summary of findings. Chapter 2 will review the science base for understanding land management impacts on river flow and hydrological modelling. The development of a new distributed version of TOPMODEL which can represent and simulate spatially distributed land cover change impacts on river discharge will be presented in Chapter 3 whilst the model will be tested based on an upland peat catchment, Trout Beck, in Chapter 4. In Chapter 5, a series of land cover scenario modelling experiments are performed to explore three hypotheses of land cover change impact on river flow and they are modified to three principles of land cover change impact informed by the results of the scenario experiments. These three principles, which can be treated as recommendations for land managers interested in delaying and reducing flow peaks, will be applied and tested in another two upland peat catchments (the Wye catchment and the East Dart catchment) through land cover scenario modelling in Chapter 6. Chapter 7 brings together the main findings of this thesis and discusses potential future research opportunities.

# Chapter 2
# Headwater peatlands, land cover impacts and flow models

## 2.1 Introduction

This chapter is a review covering three main areas: i) the impact of land management on runoff production processes; ii) the UK uplands and blanket peat as a case study; and iii) modelling approaches to catchment hydrology and runoff production. The main driver for the choice of material being reviewed here is research question 1 (from Chapter 1) being asked by the land manager and academic community about the potential impacts of upland management, and particularly upland peatland restoration and management on downstream flood risk.

## 2.2 What do we know about land management impacts on hydrological processes, leading to changes in river flow?

### 2.2.1 Introduction

The impact of human activities on hydrological systems in the landscape (e.g. rivers, lakes, wetlands,  coastal marshes, etc.) have led to a set of global scale “syndromes” of change (Meybeck, 2004). These activities have been substantially impacting the landscape, including through agriculture, urbanization, and changes in forest cover all over the world. Land-use interventions influence almost any hydrological process element (Buytaert et al., 2006). In particular, surface and near-surface hydrological processes have been extensively impacted in many parts of the world due to changes of land management on the land surface (Allan et al., 1997; Bounoua et al., 2002; Malmqvist and Rundle, 2002). In the UK, for example, there can be very few rivers considered “pristine” and totally unaffected by human activities (Hannaford and Marsh, 2008). .

Different types of land management affect the hydrological cycle in different ways. There can be an increase in local surface runoff due to modern agricultural land-use management (O'Connell et al., 2007). Grazing animals can produce not only on-site impacts (i.e. changes in soil properties and vegetation cover), but also off-site impacts (i.e. downstream runoff and water quality) (Bilotta et al., 2007). Conservation tillage leads to smaller amounts of storm-driven runoff and more baseflow in some deep-loess hills (Kramer et al., 1999). Deforestation can also influence the hydrological cycle, e.g. total annual water yield and storm runoff of a catchment (Douglas, 1999). .

Flood frequency change is of wide concern and may be impacted by changes of all hydrological elements that lead to changes in river flow. In the UK many urgent efforts are being made to try to understand whether changes in upland moorland management can be used to alleviate downstream flood risk. Agencies (e.g. the Environment Agency and the Scottish Environment Protection Agency) are keen to determine the magnitude of such changes and wonder if they should invest in upland moorland management strategies for flood mitigation.

The soils of upland peat catchments in the UK are dominated by organic soils of which blanket peat is typical in many headwaters. The common land management in peatlands includes grazing, burning and drainage (Ramchunder et al., 2009). Heavy grazing in peatlands may potentially increase flood risk, because sheep tracks are compacted and infiltration capacities are reduced so that infiltration-excess overland flow becomes more common (Holden et al., 2007b). The carrying capacity of peatlands is low so vegetation cover can easily result removal of vegetation cover by even low density grazing, and this may leads to soil erosion and reduction in surface roughness and speeds up overland flow (Holden et al., 2008). Drainage in peatlands can increase and decrease flood peaks due to two mechanisms with converse effects on hydrological response (Holden et al., 2004). Water table lowered by ditches can provide extra soil storage capacity for rainwater and reduce saturation-excess overland flow in the early stages of a storm, while higher flow velocities in ditches speed up the delivery of surface water from hillslopes into streams. Afforestation on peatlands can increase interception after canopy closure and lower the water table by transpiration, which may lead to reduction of streamflow (Shotbolt et al., 1998). Rotational burning decreases the relative depth to the water table (Worrall et al., 2007), which could increase overland flow production in response to rainfall. There are several land-use management factors influencing different stages of hydrological processes which may lead to flood peak timing and magnitude changes in river channels.

Flood risk influenced by land use management should be understood to improve land use decision making and ecosystem service evaluation. There are still limited knowledge with the complicated interactions of topography, vegetation cover, soils and their spatial and temporal variations for land management impact on river flow. Thus, many challenges are in this area.

This section firstly attempts to provide a review concerning our knowledge about how land management alters hydrological process, particularly the river flow and the flood regime. Following this, some of the main gaps and challenges in our understanding of mechanisms of flood change due to land management will be discussed.

### 2.2.2 Runoff pathways

There are several different runoff pathways on hillslopes, some of which could be affected by land-use activities. Figure 2.1 illustrates the main hillslope runoff pathways (Holden, 2008).

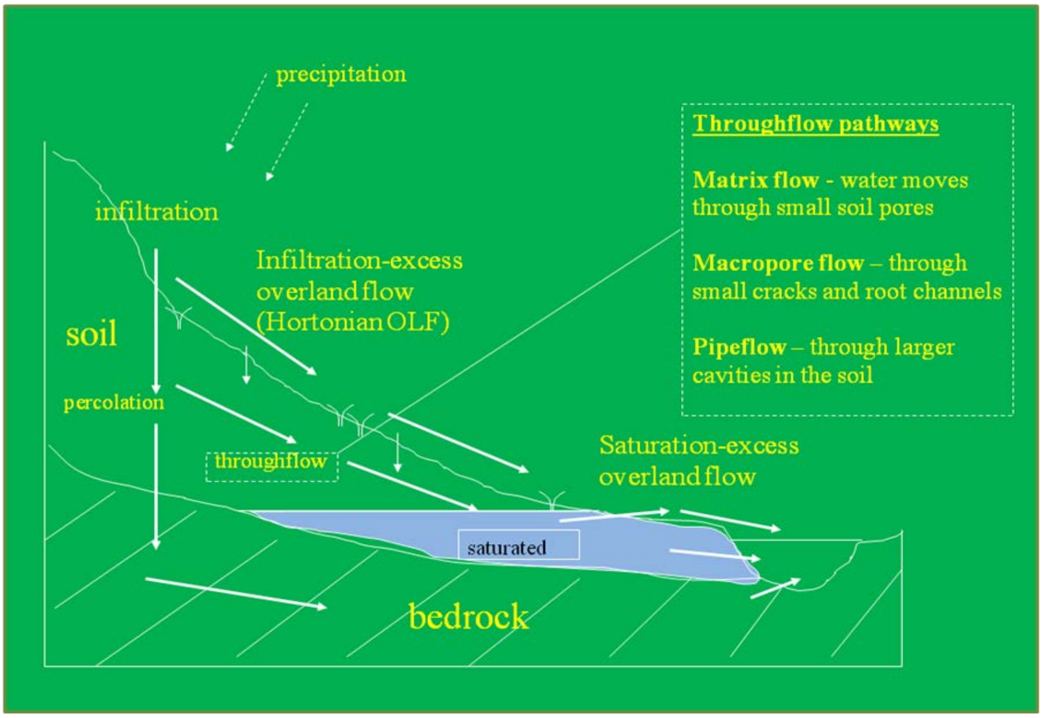


**Figure 2.1** Hillslope runoff pathways (from Holden, 2008).

#### 2.2.2.1 Infiltration

The process of water entry into the surface of a soil is Infiltration, which is a vital component in the hydrological cycle, especially in runoff production, and is mainly impacted by land cover and soil properties. The maximum infiltration rate is called infiltration capacity, which determines (along with rainfall intensity) the proportion of incoming rainfall that go into the soil and the proportion becomes infiltration-excess overland flow. The infiltration capacity of a soil commonly reduces more and more slowly and then reaches a relatively stable or quasi-stable rate during a storm event (Holden and Burt, 2002; Phillip, 1957). Different land use and management activities affect infiltration capacities at both saturated stable state and through time during rainfall events (e.g. in urbanized areas the infiltration capacities are normally low due to the impermeable land surface).

#### 2.2.2.2 Infiltration-excess overland flow

If surface water supply is greater than the rate of infiltration into the soil then surface storage will occur. With the increasing of the surface water storage during the event, the surface depressions are filled and then overland flow occurs. This is the well-known Hortonian overland flow (i.e. infiltration-excess overland flow) mechanism, and Horton (1933; 1945) considered that infiltration-excess overland flow was the only source of storm runoff.

In fact, infiltration-excess overland flow is rarely observed in temperate areas (except urban areas) due to the high infiltration capacity of soils and the normally low rainfall intensity, so it is only generated in exceptional storms. However, in semi-arid areas, infiltration-excess overland flow is more widespread and frequent because of their sparse vegetation, well-developed soil crusts and more intense rainfall events (e.g. northern China). Infiltration-excess overland flow genarates on spatially localized parts of a hillslope and thus only parts of the hillslope or catchment may produce infiltration-excess overland flow rather than the whole hilslope or catchment. This is known as the concept of partial contributing area (Betson, 1964).

#### 2.2.2.3 Saturation-excess overland flow

When infiltration occurs, the available pore space in soil is filled by infiltrating water. If there is enough infiltrating water, all of the pore spaces are full and the soil is saturated. At this time, the water table is at the land surface. Thus any extra water can lead to the appearance of overland flow, which is called saturation-excess overland flow. This can occur during rainfall events even at low intensities, and can persist long after rain has stopped (Kirkby, 1988). For instance, it may happen at the bottom of a hillslope or on thin soil with few pore spaces (Holden, 2012).

In a catchment, the parts (area) producing saturation-excess overland flow vary through time and this is the concept of variable source area (Hewlett, 1961; Hewlett and Hibbert, 1963). For instance, in wet seasons, larger areas in a catchment will be saturated and there will be a greater possibility of the generation of saturation-excess overland flow than in dry seasons. If a storm event begins in a catchment with dry antecedent wetness condition, a limited area will produce saturation-excess overland flow. Then, as rainfall continues more and more areas of the catchment are getting saturated (e.g.

valley bottoms). A larger area of the catchment generates saturation-excess overland flow.

#### 2.2.2.4 Throughflow

Water infiltrating into the soil travels vertically and laterally downslope; this is called throughflow. Water deliver through the very fine pore spaces of soil as matrix flow, or move through macropores as macropore flow, or through soil pipes known as pipeflow.

Water can move through the matrix of soil whether it is saturated or unsaturated on hillslopes. Water movement though saturated soil under gravity is normally estimated by Darcy’s law. The rate of movement is proportional to the hydraulic gradient and the saturated hydraulic conductivity which varies with soil type and depth. Sandy soils generally have a higher hydraulic conductivity than clay ones. Hydraulic conductivity is commonly greatest close to the soil surface, where porosity is greatest, and reduces with depth. However, for peat soil, hydraulic conductivity does notvary significantly with soil depth (Holden and Burt, 2003a). Water can also deliver in unsaturated soil from wetter zones to drier zones, driven by both gravity and gradients in soil moisture tension. .

Water moving through larger pore spaces in soils is macropore flow or pipflow, and macropores are pores larger than 0.1 mm in diameter while pipes might be larger than 1 mm in diameter (Holden, 2012). Macropores promote subsurface flow when they are connected and continuous over sufficient distances (Beven and Germann, 1982). Water can preferentially move through them, so macropores can influence runoff production. Studies in peatland catchments have shown that over 30% of throughflow moves through macropores (Baird, 1997; Holden, 2009; Holden et al., 2001). Natural soil pipes and pipeflow can be found in different environments such as rainforest (e.g. Sayer et al., 2006), loess (e.g. Zhu, 2003), etc. Pipeflow also has an important role in peatland hydrology. A field study in a deep blanket peat catchment in Northern England indicated that 13.7% of streamflow was produced by pipeflow over a period of one and a half years (Smart et al., 2013).

### 2.2.3 How land management affects runoff production

Land management practices impact several hydrological processes and this section deals mainly with runoff production processes.

#### 2.2.3.1 Agriculture

Tillage and harvest practices, surface and underground drain networks, field boundaries in agricultural catchments affects their hydrology, especially their responses to rainfall events.

The greatest impact of agriculture on runoff processes is usually on soil surface condition, especially infiltration and subsequent infiltration-excess overland flow. Undisturbed soils have much higher infiltration capacity than soils in agricultural land. Once cultivated, the soil surface becomes compacted where they are laid bare to raindrop impact, until the next crop develops a protective cover (Burt and Slattery, 2005). Hence, infiltration capacity may decrease to give more possibilities of infiltration-excess overland. For instance, research on traditional shifting agriculture in the central Spanish Pyrenees (Lasanta et al., 2006), using many experimental plots between 1992 and 2003, demonstrated that shifting agriculture increased infiltration-excess overland flow and the active shifting agriculture plot has nearly twice surface runoff coefficient of abandoned shifting agriculture plot. Grazing animals can also lead to the increase of this type of overland flow, due to compaction which reduces infiltration. Tractors can compact the soil surface and cause concentrated zones of infiltration-excess overland flow. Concentrations of overland flow down the track can make accelerated formation of rill and gully (O'Connell et al., 2007).

Saturation-excess overland flow has a strong relationship with climatic conditions and the soil characteristics of the catchment, but also to farming methods. Some tillage implements like the moldboard plough compact the soil below their working depth, when they lift and loosen the soil above the depth. Thus plough pans (tillage pan) can be formed by repeated use of these implements at the same depth and it significantly reduces hydraulic conductivity near the pans and can increase saturation-excess overland flow. Burt and Slattery (2005) indicated that some soils with a high bulk density plough pan will absorb 60 mm water in 24 h, while other similar soils without a plough pan absorb more than 3 times that amount of moisture in the same period based on a study of the Texas High Plains. Arable terracing, which is popular in mountain areas, can also improve the premature formation of saturated areas and increase saturation-excess overland flow (e.g. the research of Gallart et al. (1994) in Mediterranean mountains).

Generally, soil macroporosity in agricultural lands is usually less developed than that in natural lands such as grassland (Holden and Gell, 2009). However, cultivation can reduce subcritical water repellency by two to three times in arable lands (Hallett et al., 2001). Dye tracing tests have shown that the conducting macroporosity for arable plots is largely comprised of inter-aggregate voids resulting from ploughing (Jarvis et al., 2008). This may change runoff in agricultural lands by increasing macropore flow.

Agricultural buffer zones between fields and watercourses have often been applied to trap sediment and pollutants (Sliva and Williams, 2001). There has been some research on the impacts of agricultural riparian buffer zones on river flow (e.g. Lowrance et al., 2007). It may be that in some circumstances such buffer zones attenuate flow if they are wide enough and if the vegetation cover provides a greater surface roughness than the cropland. However, such impacts have never been tested in peatland catchments before.

#### 2.2.3.2 Change of forest cover

Forests influence the supply of water in streams and the regularity of their flow (Zon, 1927). There are many researches around the world (e.g. Bosch and Hewlett, 1982; Bruijnzeel, 2004) which show that afforestation reduces streamflow peaks and increases lag times as enhanced evapotranspiration increases storage capacity of the soil while canopy interception also reduces the water volume reaching the stream. Conversely deforestation has opposite impacts (Bruijnzeel, 2005b). For example, Germer et al. (2009) showed that storm flow discharge was 18% of rainfall in pasture but only 1% in forest in a study on a small Amazon catchment. After forest removal, due to the increased amount of precipitation reaching the ground and the decreased uptake of moisture from soil, the source areas of saturation-excess overland flow can expand. Viramontes and Descroix (2003) reported that progressive degradation of soils and vegetation due to deforestation increased the ratio of the flood runoff coefficient to the base runoff coefficient in a catchment in northern Mexico. Forest management activities such as harvesting also influence runoff process (Bruijnzeel, 1992; Bruijnzeel, 2005a) and recovery from such influence may take many decades (Bruijnzeel, 2005b). For instance, soil compaction from machinery results in large volumes of localised infiltration-excess overland flow which effectively act as an extension of the regular drainage network (Grip et al., 2004).

In some areas there is work to afforest riparian zones in order to increase landscape roughness in the flood plain and attenuate flow downstream with modelling studies suggesting that some moderate scale benefits could be achieved (e.g. Anderson et al., 2006; Darby, 1999). Woody debris dams are being actively encouraged in some upland systems within stream channels to improve habitat diversity (Pitt and Batzer, 2012) and to slow flow and retain more water (Thomas and Nisbet, 2012). However, the idea of investigating surface roughness of riparian buffer zones in upland peatlands in order to reduce flood peaks has not hitherto been considered,

#### 2.2.3.3 Urbanization

Urbanization is one of the outcomes associated with economic development and population growth all over the world. However, negative hydrologic consequences can often occur due to catchment imperviousness and connectivity. The main materials of the ordinary urban pavement are impervious bitumen, cement and brick etc., and the infiltration capability of these is approximately zero. The performance of these kinds of land surface mostly break the process of the natural hydrological cycle, and exclude the subsoil from the rainfall-infiltration process (Berne et al., 2004; Booth et al., 2004). The ordinary pavement increases the velocity of flow and reduces the delay time for the surface runoff reaching streams.

Urbanization also disturbs hydrologial connectivity. Buildings, streets and roads in cities break the natural runoff pathways, which leads to redistribution of overland flow producing areas. This may bring a distinct change to the amount and timing of streamflow peaks. Research on hydrological effects of urbanization in China by Cheng and Wang (2002) revealed that three decades of urbanization had increased the peak flow by 27% and the time to peak was decreased by 4 hr in many urban areas.

#### 2.2.3.4 Flood synchronicity

Land management impacts the timing of water delivery, so that the flood peaks may coincide from different tributaries. Hence, the flood peak may go either up or down following land management change depending on the position and the distribution of the interventions in the catchment. The same land management practice may have a different impact depending on where in the catchment it occurs, because it impacts the timing of water delivery to the main channel and so a spatial approach is needed (e.g. Figure 2.2). A case regarding forest harvesting in eastern United States (Hornbeck et al., 1993) also illustrates this issue; the cutting of 24% of the forest basal area from catchment 2 at Leading Ridge caused a nearly two-times larger increase in streamflow than cutting 33% of catchment 4 at Hubbard Brook or catchment 2 at Fernow. This is because of the different cutting positions of these catchments. The cutting at Leading Ridge consisted of a single block in the lowest part of the catchment; at Hubbard Brook the cutting was conducted through a series of strips located half way up the catchment, while that at Fernow involved harvesting trees from all over the catchment. The position of the cutting can impact hydrographs in forest catchments.

Thus any models of land cover change impacts on streamflow response must consider the spatial distribution of the land cover change and the timing of water delivery to the main stream channel. This information directly informs the thinking needed for the work later in this thesis when applied to the specific case of headwater peatlands.

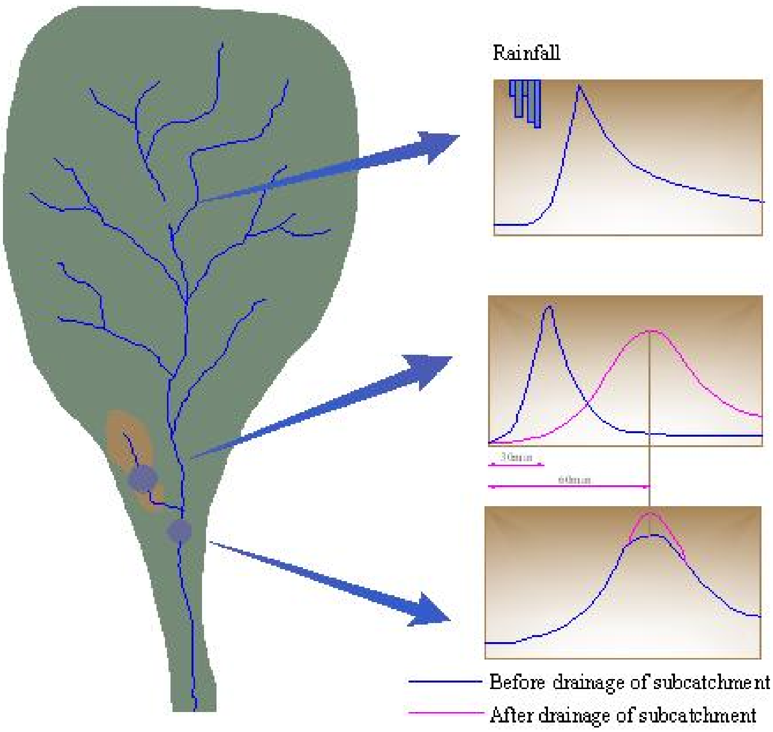


**Figure 2.2** A schematic showing an example of the flood synchronicity issue (from Holden, 2012).

## 2.3 Effects of UK upland land management on local and downstream floods

### 2.3.1. Introduction

Around the UK there have been significant changes in land use and management since 1940s. The agricultural land areas reduced gradually with the average annual decrease of 15400 ha between 1983 and 2008 (equivalent to a rate of 1% per decade) (Bibby, 2009). Nevertheless, the transfer of land use (e.g. form cultivation land to farm woodland) and the changes of forms of cultivation, grazing, afforestation and deforestation widely occurs, perhaps resulted by the drive for self-sufficiency in food production and the effects of the Common Agricultural Policy (O'Connell et al., 2007).

O'Connell et al. (2007) summarized agricultural land-driven changes on hydrology including: “accelerated loss of hedgerows and subsequent creation of larger fields; cultivation practices causing deeper compacted soil; land drains connecting the hill top to the channel; cracks and mole drain feeding overland flow to drains and ditches; unchecked wash-off from bare soil; plough lines, ditches and tyre tracks concentrating overland flow; tramlines and farm tracks which convey runoff quickly to water courses; and channelized river with no riparian buffer zone”.

In Britain, uplands cover around one-third of Britain's land surface. Since the 1950s, land-use interventions such as conifer plantations, acid grasslands and so-called 'improved' hill pastures have replaced many of the more natural upland habitats. Land use activities in uplands, such as grazing, drainage and burning may impact upland hydrology. This section of the review discusses changing upland management practices and their impact on runoff generation and local and downstream flooding in the UK.

### 2.3.2. Upland soils and land cover in the UK uplands

UK uplands are mainly covered by organic soils which occupies over 11 % area of England and Wales and occur predominantly in upland areas (Atherden, 1992). These organic soils range from raw peats and earthy peats to organo-mineral soils such as stagnohumic gleys, humic gleys, etc. (see area proportion and distribution of organic soils in England and Wales in Table 2.1 and Figure 2.3) (Holden et al., 2007c). Stagnohumic, raw peats and stagnopodzols are the most important soil types in terms of covered area. Most organic soils in England and Wales are associated with semi-natural vegetation (Holden et al., 2007c). There have been large changes in the management of landscapes dominated by organic soils with increased drainage, grazing, afforestation and liming, which has led to changes in the vegetation cover of these soils. Organic soils normally have high water contents and are subject to shrinkage upon drying, so these land management has led to not only changes in the vegetation cover of these soils but also the hydrological cycle in upland areas.

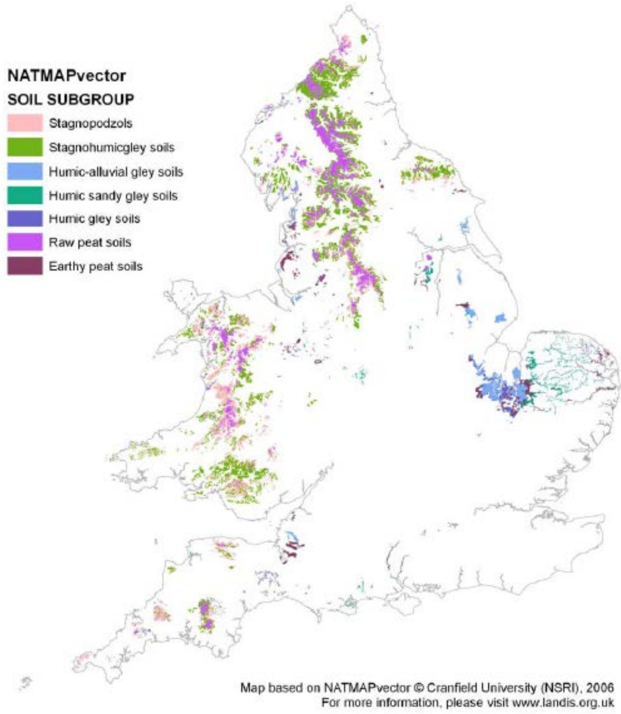


**Figure 2.3** Distribution of organic soils in England and Wales.

**Table 2.1** The major organic soils of England and Wales (from Holden et al., 2007c).

| Soil | Soil group | Area (km$^2$) | Proportion of England and Wales (%) |
|---|---|---|---|
| Peat | Raw Peat | 3575 | 2.6 |
| | Earthy Peat | 1014 | 0.7 |
| Organo-mineral | Stagnopodzol | 3566 | 2.5 |
| | Stagnohumic gley | 5420 | 3.9 |
| | Humic-alluvial gley | 1076 | 0.8 |
| | Humic sandy gley | 566 | 0.4 |
| | Humic gley | 502 | 0.4 |
| Total | | 15719 | 11.3 |

In upland areas, plant growth on organic soils is limited by many factors, e.g. soil acidity, low nutrient availability, low temperatures and short summers. The predominant vegetation normally varies with soil type. Organo-mineral soils are usually covered by heath-type vegetation dominated by *Nardus* or *Molinia* grasslands, and blanket peat sustains moorland vegetation dominated by *Calluna*, *Erica, Eriophorum* and *Sphagnum* spp. (Floate, 1977). These vegetation types often supports low density populations of sheep and deer, and in some areas there is periodic burning. These native plant communities modified by human activity are considered as semi-natural vegetation or rough grazings as which approximately 70 % of UK upland areas are classified (SOAFD, 1995).

Peat is extremely slowly decaying organic matter that has accumulated under saturated conditions. Peatlands are more likely to form in upland areas of the temperate and boreal zones with high precipitation excess or in lowland areas where shallow gradients impermeable substrates or topographic convergence maintain saturation (Holden et al., 2004). Major classification of peatland is based on its source of nutrient and water. Bogs, for which the supply of water and nutrients are dominated by rainfall, are ombrotrophic peatlands; while fens, which depend on groundwater for water and nutrient support, are minerotrophic peatland (Charman, 2002). Peatlands are most common in the uplands of the UK and cover many headwater areas. Peat is classified as a deposit of at least 30 cm depth in England and Wales (50 cm in Scotland) containing more than 50% organic carbon (Holden et al., 2007c). The peat areas can reach 13% of Britain and most are in Scotland (2.6 million ha) (Milne and Brown, 1997). the dominant peatland in UK is blanket bog, covering 87 % of UK peatland area (Holden et al., 2007c). Blanket bog normally occurs on the gentle slopes of upland plateaux, ridges and benches and it represents around 10–15% of the world's blanket peat resource (Tallis, 1998).

UK blanket peatlands have been changed and managed by human activities since their development began around 9000–5000 BP, with the felling of upland tree cover and grazing (Simmons, 2003). Today there are many land management activities within the uplands which impact on water and soil processes. UK upland peatlandshave been particularly subject to drainage (and more recently drain-blocking), grazing, burning and afforestation with some infrastructural impact from roads and tracks. These interventions will impact peatland hydrology but with unclear potential impacts on streamflow in the uplands.

### 2.3.3. Land management impacts on upland hydrology in the UK

#### 2.3.3.1 Drainage and drain-blocking

UK has a long history of peatland drainage and it is a key intervention for British agriculture (Williams, 1995). More than 50% of agricultural activity is conducted on land that has been drained (Newson, 1992). Table 2.2 gives a short description of the history of UK peatland drainage (Holden et al., 2004).

**Table 2.2** Brief history of major peatland drainage in the UK (from Holden et al., 2004).

| Period | Action |
|---|---|
| **From 1600** | Drainage began in Britain accompanying land tenure, enclosure and reclamation of the Anglian Fens. |
| **1600-1900** | Most drainage activity had focused on 'improving' fenlands for agriculture by lowering the water table. |
| **From 1900** | Drainage was also directed towards flood alleviation; Expansion in ditching, tile draining and channelization activity was huge. |
| **From 1945** | Government grants for expansion in drainage works paid at 70%, particularly in agriculturally marginal upland areas; About 190000 ha of deep peatland and 315000 ha of shallow peats have been afforested with coniferous plantations. |
| **1960-1980** | Most of the upland drainage of blanket peats took place, particularly in the English Pennines; The peak rate of drainage was estimated to be 100 000 ha per year. |
| **1990-present** | Large-scale damming of upland drains in blanket peat |

During the middle of the last century, there were two apparently conflicting hypotheses on impacts of peatland drainage on flooding. One was that increased drainage density would increase flow rates to the main stream channel (e.g. Conway and Millar, 1960). The other was that drainage lowered water tables and increased the storage potential for new rain inputs and therefore would reduce flood risk Burke (1967). However, McDonald (1973) noted that the study catchments of Conway and Millar (1960) and Burke (1967) lack comparability, because the peat at one site was much more *Sphagnum*-rich than the other while Robinson (1980) noted that there were very different drainage densities and topographies between sites. Lane and Milledge (2013) have recently shown through a modelling approach that the net effect of travel times to the stream impacted by artificial drainage networks in blanket peat can be negligible depending on the configuration of the drains as drain routes can be less direct than overland flow routes across the hillslope. Both Lane and Milledge (2013) and Ballard et al. (2011) have strongly suggested, from modelling studies, that overland flow roughness is likely to be a more important factor in determining land management impacts on blanket peatland streamflow peaks rather than whether there are surface drains or not. Thus, the influence of widespread drain blocking through the use of dams spaced at regular intervals along drains which has been implemented in blanket peatlands over the past 15 years has yielded little evidence of impacts on streamflow (Acreman and Holden, 2013) except for isolated, but not entirely convincing, examples (e.g. Wilson et al., 2011).

#### 2.3.3.2 Grazing

Grazing may have impacted upland peatland hydrology in the UK particularly for total runoff and overland flow. Sansom (1999) reported that the annual water yield had increased by 25% with the sheep numbers doubled to 24000 in the period between 1944 and 1975 in the north Derwent catchment. Grazing can lead to compaction of soil and decrease of infiltration capacity so infiltration-excess overland flow becomes more common in these grazed peatlands. Both the value and actual spatial distribution of livestock may significantly decrease vertical connectivity and increase lateral connectivity for water, and hence increase both the spatial and temporal frequency of overland flow (Zhao, 2007). Grazing can also result in a reduced water storage capacity of the peatland soil and thus may give more opportunities to saturated-excess overland flow, e.g. the research in a small catchment in Dartmoor (Meyles et al., 2006). Hence, grazing may bring flashier runoff generation in upland peatlands.

Because of the low carrying capacity of the upland system, vegetation cover can easily be removed by grazing leading to erosion and a reduction in surface roughness increaing overland flow velocities. For instance, *Sphagnum*, with its dense branching and uniform structure with depth, has been lost from many peatlands through environmental change including enhanced grazing (Holden et al., 2007b). This may have an impact on overland flow travel times potentially leading to shortened stream lag times. Indeed even if a peatland surface remains fully vegetated, field results suggest that if the vegetation type is altered then flow velocities could change, causing alterations in the timing of runoff delivery from slopes to streams (Holden et al., 2008).

#### 2.3.3.3 Burning

Rotational burning which supports the grouse moor industry has impacted surface vegetation cover across large areas of the UK uplands including peatland headwaters (Hobbs and Gimingham, 1987; Holden et al., 2007b; Thompson et al., 1995). The main aim of burning is to produce a mosaic distribution of vegetation with different ages, by which the habitat diversity can be increased for populations of grouse, sheep and deer. Grouse shooting produces large income to land owners. It is considered to be about £10 million annually for England and Wales alone (Ward et al., 2007) and indirectly contributes some £192 million to the UK upland economy (PACEC, 2006).The grouse-shooting activities are suggested to have been associated with an increase of new burns in upland regions of England especially after the Moorland Regeneration Programme in 2001 (Yallop et al., 2006). For burning practices in UK uplands, there are protocols that are recommended. For instance, in the Defra Heather and Grass Burning Code (Defra, 2007), there is guidance about not burning within 5 m of watercourses and to avoid extending a burn patch more than 25 m along the bank of a watercourse. In other words, there is a suggestion that a buffer strip should be applied around streams when undertaking burning. On the other hand, for burning patch size, burning in a way that the exposes a single area of more than 0.5 hectares of bare soil is strongly advised against in the Defra Heather and Grass Burning Code. However, the hydrological impacts of patch size or of buffer strips have not been investigated in these upland peatland systems.

A few studies have been conducted to explore the influence of burning on water flow in peatland catchments. Fisher (2006) observed that the rate of steady state infiltration was 78% lower for a moorland patch that had been burned that year compared with another strip that was burned 15 years previously. Similarly, Mallik et al. (1984) indicated that the rate of infiltration on a burned plot was decreased up to 74% compared to an unburned plot. They considered this was due to the fact that the ash particles on the burned plot clogged the soil pores in upper soil layer, and thus the density of larger pores is reduced, with a concomitant increase in the density of smaller pores. Holden et al. (2014) found a significant reduction in macropore flow and hydraulic conductivity associated with patches that had been burned more recently compared to those that had been burned more than 15 years since data collection or compared to those with no burning. These results are all in agreement suggesting that burning could enhance overland flow production. However, as blanket peatlands are dominated more by saturation-excess rather than infiltration-excess processes further work on burning impacts on water table behaviour is required. Clay et al. (2009) reported shallower water table and more surface flow in more recently burnt plots. Holden et al. (2014) found significantly greater (two-fold) bulk densities of peat in more recently burnt plots suggesting that soil-holding potential will have declined and hence saturation would be more readily achieved.

Vegetation changes in burned areas may also lead to effects on hydrology. The removal of the vegetation cover may reduce surface roughness and enable faster water flow velocities. However, further work is required on burnt plots to establish such effects.

Compared with small rotational fires, wildfire is more severe and destructive and therefore may have greater impacts on hydrology. Wildfire is believed to be have been common since late Devonian times in most vegetation zones throughout the world (Schmidt and Noack, 2000). Many surveys (e.g. DeBano, 2000) suggest that fire-induced water repellency of soils leads to increased overland flow, runoff and soil erosion following fire. The removal of vegetation and litter from already highly repellent soils by wildfire allow the effects of repellency to become much more prominent (Shakesby et al., 2003). Thus the presence of high repellency levels before fire and its relationship to vegetation types could be key for impacts of fire on peatlands hydrology. .

Overall the hydrological impacts of fire upon soils and hydrological processes require further research in the uplands of the UK.

### 2.3.3.4 Coniferous afforestation

Over the last decades, one of the major land use changes in UK uplands is the conversion of semi-natural vegetation to plantation forest dominated by coniferous species, particularly in upland areas of Wales, Scotland and the North Pennines. Sitka spruce is the dominant species as it is well suited to the climate and soils with good yields. Lodgepole pine competes better with heath vegetation and is grown above 600 m (Rudeforth et al., 1984). Much plantation forestry occurred in the 1970s and 1980s and encouraged by technical advances and tax incentives even though the planting of these areas is previously considered unsuitable (Shakesby et al., 2000). Generally coniferous afforestation influences the local soil regime. For example, it can increase peat dry bulk density and decrease water content compared with those in peatlands without forest (Thompson, 1987).

Runoff is affected by coniferous afforestation on blanket peat. Streamflow tends to increase in both total and in flow peaks. It increased low flows in the beginning years (perhaps 20 years) with drainage and initial planting then water yield decreases as the forest matures (Robinson, 1986). Forest evaporation may be another key factor in hydrology of upland peatlands. In parts of Plynlimon, mid-Wales, there are some of the highest forest evaporation records in the world (Stott and Marks, 2000) and the value is much higher than that in upland grassland (Shuttleworth and Calder, 1979). Thus increased transpiration and interception may cause a much greater lowering of water table than drainage alone (Marc and Robinson, 2007), and this may also decrease the water yield of the catchment in mature plantations. McCulloch and Robinson (1993) indicated that flood peaks should be reduced by forests, except for the effects of drainage and forest roads. In some instances the effect of drainage and forest roads may be much bigger than that of afforestation so a particular outcome of afforestation on river flow may not be confirmed. Robinson and Dupeyrat (2005) concluded that the potential of forests to reduce peak flows in UK uplands is much less than that has been widely declared and they might have a limited impact in managing regional or large-scale flood risk. Hence, the impacts of afforestation in upland areas on river discharge are not quite clear now.

#### 2.3.3.5 Broadleaf afforestation

Even though there seem to be pressures to reduce coniferous afforestation, mixed leaf woodlands are increasing in upland catchments and in riparian zones in UK (Gimingham et al., 2002). Interception losses from broadleaf woodland are lower than those from coniferous forestry but higher than those from upland peatland vegetation, and this may reduce water yields when extensive broadleaf afforestation is conducted in headwater catchments (Holden et al., 2007b).

Riparian forests were planted during the major program of upland afforestation in 1940-1980s in UK (Broadmeadow and Nisbet, 2004), but the main aspects of research on riparian buffer zone forest in the UK are the impacts on soil erosion and water quality rather than on flow attenuation.

#### 2.3.3.6 Tracks/roads

Very few published researches is available on how tracks or roads affect peatland hydrology in UK uplands (Grace et al., 2013). However, there is increased demand for more access tracks to be created for activities such as shooting and windfarm infrastructure in the upland catchments. The track may compress the peat and subside slowly through time and it thus may become a more direct source of overland flow and a localised drainage for the surrounding areas (Grace et al., 2013) (additionally, tracks are usually accompanied by drains). On the other hand, the restriction in throughflow below the track will impact flows upslope and downslope of the track itself and such effects have been observed on tracks made by scientists going to routine monitoring points in peatlands (Robroek et al., 2010).

## 2.4 A brief review of catchment hydrological models

### 2.4.1 Introduction

Numerical modelling is a powerful scientific method with a wide range of applications. Processes naturally occurring in the system can be modelled to examine what might happen under scenarios, so models can be considered as an experimental laboratory. Models are also very useful when the content of a theory is developing, and they can give simulations to corroborate findings and ideas. It can even help to deal with some currently unmeasurable processes and components of the system. Much recent progress in hydrological sciences is closely connected to modelling approaches.

The catchment hydrological model aims to simulate and predict the hydrological behaviours in catchments for purposes from watershed management to engineering design (Singh, 1995), and it is normally used to model flood events, hydrograph form, flow delay, inundation etc. Hydrological modelling has a long history and can be tracked back to the 19$^{th}$ century for the design of infrastructure, e.g. canals, drainage systems, dams and bridges. Hydrological modelling started to involve the development of concepts, theories and models of individual components of the hydrologic cycle in the 1960s, and overland flow, subsurface flow, channel flow, infiltration, evaporation, interception, etc. became the main topics for hydrological modelling.

Developing a hydrological model normally involves a process with following steps: i) data collection and analysis; ii) establishing a conceptual model representing the hydrological elements and processes aimed at; iii) translating the conceptual mode into a new mathematical model; iv) calibrating the mathematical model with some historical data by adjusting various coefficients; and v) validating the model with another historical data.

### 2.4.2 Classifications of catchment models

There are many methods to classify catchment hydrological model. A basic one is about the classification of conceptual and empirical models. The conceptual model works in some way approximating the physical processes (Clarke, 1973).

Considering the effect of antecedent conditions of catchments, continuous models were developed. These model include modules representing continuous hydrological elements (e.g. soil moisture, groundwater, interception etc.), distinguishing it from un-continuous models (e.g. event-based models). One of the earliest continuous catchment hydrological models is Stanford model - Hydrologic Simulation Program Fortran (HSPF).

Another key classification of catchment models is deterministic models and stochastic models. A deterministic model gives a single set of output variables for a simulating run, but allowing uncertainty in the input, parameter or output. Stochastic models includes stochastic algorithms for hydrological simulation. It sometimes can improve the computational efficiency, even though may bring extra uncertainty.

For now, another most essential classification of catchment hydrology models is based on the differences between lumped models and distributed models. The lumped models treat a catchment as a single unit without any consideration of the spatial pattern of the characteristics and process in the catchment. Conversely, distributed models deal with hydrological processes involving spatial pattern. Further on, if a distributed model is a network of connected lumped models it is a distributed integral model, whereas a distributed model involving spatially-distributed hydrological calculations is a distributed differential model.

For distributed models which usually use conservation equations derived from the Reynold’s transport theorem to represent the water flow, there is another series of model categories including physical, analytical and empirical distributed models based on the solutions of these partial differential equations which has no closed form solution (Todini, 2007). The model solving the full physically based equations with numerical techniques is referred as physical. Some models instead use simplifying assumptions to derive closed form solutions of the governing conservation equations, and these models are referred as analytical. If the representation of a water flow process is not derived from the governing physically based conservation equations, then it is referred as empirical. Empirical approaches are based on experimentally determined relationships such as linear regressions.

**Table 2.3** Principles of model classification.

| Classification | Principle |
|---|---|
| conceptual or empirical model | including physical processes |
| continuous or un-continuous model | including continuous simulating time step |
| deterministic or stochastic model | including uncertainties |
| lumped or distributed model | including spatial pattern of the characteristics and process |
| statistical model | including probability distributions of inputs and outputs |

### 2.4.3 Currently used catchment models

Many catchment hydrological models are widely used and have varying structures for different modelling purposes. For instance, HSPF (Hydrologic

Simulation Package-Fortran) with its extended water quality module is the standard model adopted by the Environmental Protection Agency of the United States; HEC-HMS (Hydrologic Engineering Centre - Hydrologic Modelling System) is considered as the standard model in the design of drainage systems in US; TOPMODEL and SHE are the standard models for hydrological simulation in many European countries; the Xinanjiang model is popular for catchment hydrological analysis in China; the Tank models are commonly accepted in Japan; and etc.. Table 2.4 shows many commonly used catchment models around world.

HSPF is a physically-based lumped model with a single PERLND (pervious land area) and a single RCHRES (reach reservoir unit) used to simulate hydrologic processes within the catchment (Gallagher and Doherty, 2007). It models the catchment responses of water, sediment, and chemical amounts in a series of vertical storages. The fluxes between the various storages and exchanges with the river reaches are modelled with equations that have parameters determined by measurement and/or calibration (Nasr et al., 2007).

The Soil and Water Assessment Tool (SWAT) model developed by the USDA Agricultural Research Service has international acceptance as a robust interdisciplinary catchment modelling tool. It is a semi-distributed, conceptual model designed to model the transportation of water, nutrient and pesticide at a catchment scale, in which the simulated catchment is subdivided into sub-catchments, river reaches and Hydrological Response Units (van Griensven et al., 2006)

TOPMODEL (Beven and Kirkby, 1979) is a physically-based semi-distributed hydrological model that allows runoff generation predictions to be mapped back into space at any time step (Choi and Beven, 2007). It is also a flexible model which can include new process mechanisms as derived from empirical studies. TOPMODEL has become a basis that underpins many other models that have developed from it. For example, The PESERA coarse scale erosion model for Europe (Kirkby et al., 2008) estimates subsurface flow using TOPMODEL, with topographic properties estimated from local relief (from DEMs) and soil characteristics (saturated hydraulic conductivity and TOPMODEL soil parameter) from the soil type, based on field experience. Hence, a modified TOPMODEL may also be utilized to deal with other catchment issues, such as tackling scaling issues related to understanding small-scale land management impacts at the large scale.

**Table 2.4** Common catchment models (modified from Singh and Woolhiser, 2002).

| Model | Researcher | Feature | Number of papers in Web of Science |
|---|---|---|---|
| Physically Based Runoff Production Model (TOPMODEL) | Beven and Kirkby (1979) | Physically based, semi-distributed, continuous hydrologic simulation model | 394 |
| Stanford watershed Model (SWM)/Hydrologic Simulation Package-Fortran IV (HSPF) | Bicknell, Imhoff et al. (2001; 1993) | Continuous, dynamic event or steady-state simulator of hydrologic and hydraulic and water quality processes | 518 |
| Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS) | HEC (2000) | Physically-based, semi-distributed, event-based, runoff model | 59 |
| University of British Columbia (UBC) Model | Quick (1995) | Process-oriented, lumped parameter, continuous simulation model | + |
| Tank Model | Sugawara (1995) | Process-oriented, semi-distributed or lumped continuous simulation model | + |
| Storm Water Management Model (SWMM) | Huber (1995) | Process-oriented, semi-distributed, continuous stormflow model | 135 |
| Xinanjiang Model | Zhao (1992) | Process-oriented, lumped, continuous simulation model | 53 |
| Systeme Hydrologique Europeen/Systeme Hydrologique Europeen Sediment (SHE/SHESED) | Bathurst, Wicks et al. (1995) | Physically based, distributed, continuous streamflow and sediment simulation | 140 |
| Generalized River Modeling Package—Systeme Hydroloque Europeen (MIKE-SHE) | Refsgaard and Storm (1995) | Physically based, distributed, continuous hydrologic and hydraulic simulation model | 106 |

| | | | |
|---|---|---|---|
| Soil-Vegetation-Atmosphere Transfer (SVAT) Model | Ma and Cheng (1998) | Macroscale, lumped parameter, streamflow simulation system | 282 |
| Soil Water Assessment Tool (SWAT) | Arnold, Srinivasan et al. (1998) | Distributed, conceptual, continuous simulation model | 911 |
| National Weather service-River Forecast System (NWS-RFS) | Burnash (1975) | Lumped, continuous river forecast system | 62 |
| Hydrological Simulation (HBV) Model | Bergstrom (1995) | Process-oriented, lumped, continuous streamflow simulation model | 118 |
| ARNO (Arno River) Model | Todini (1996) | Semi-distributed, continuous rainfall-runoff simulation model | 55 |
| Topgraphic Kinematic Approximation and Integration (TOPIKAPI) Model | Todini (1995) | Distributed, physically based, continuous rainfall-runoff simulation model | 11 |

+ : the words used in these models are too common so that thousands of papers can be found in *Web of Science* and the most of these are not related to hydrology modelling.

### 2.4.4 Data needed by hydrological models

Catchment hydrology modelling normally needs several sorts of data including hydrometeorologic data (e.g. rainfall, snowfall, pan evaporation, etc.), geomorphologic data (e.g. elevation data, river networks, slopes, drainage areas, etc.), agricultural data (e.g. land use, treatment), pedologic data (e.g. soil type, porosity, moisture content, saturated hydraulic conductivity, etc.), geologic data (e.g. stratigraphy data, lithology data), hydrologic data (e.g. stream discharge, flow depth, water table, etc.). For this thesis, the data needed covers most of these sorts of data. The long time series hydrometeorologic data and hydrologic data is important to find big flood events and land use data may be essential to show the land cover change.

### 2.4.5 TOPMODEL

TOPMODEL was a continuous lumped or semi-distributed deterministic hydrological model when it was originally developed by Beven and Kirkby (1979). It was made based on a simple theory of hydrological similarity of points in a catchment, by which the index of hydrological similarity is from the topographic index of Kirkby (1976) and is helpful for computational efficiency. For original TOPMODEL, there are three theoretical assumptions (Beven, 2001; Beven and Kirkby, 1979): (A) There is a saturated zone in equilibrium with a spatially uniform recharge rate over an upslope contributing area and the runoff is spatially constant. (B) The water table is almost parallel to the surface such that the effective hydraulic gradient is equal to the local surface slope. (C) The transmissivity profile may be described by a single-valued function of storage deficit, with a value of runoff when the soil is just saturated to the surface.

The original TOPMODEL is a concise hydrological model which has a major advantage of its limited number of parameters. For storm event simulation, the model may just need the soil hydraulic conductivity decay parameter, the soil transmissivity at saturation, and the uniform flow velocity to run. Thus, the model might be easier to modify with new functions when compared with other models which have many more parameters (e.g. SWAT model), as new functions normally bring additional parameters and the risk of over-parameterization (Perrin et al., 2001).

The saturation-excess overland flow mechanism used in the original TOPMODEL is a good potential match to process dominance in via overland flow in peatland catchments. Some research has used TOPMODEL in UK peatlands. Beven et al. (1984) tested TOPMODEL based on three UK catchments including two peat ones, with reasonable outcomes. Lane et al. (2004) extended the original TOPMODEL with high-resolution digital topographic data in a blanket peat catchment, Oughtershaw Beck, North Yorkshire. A modified TOPMODEL was used by Page et al. (2007) to simulate the chloride signal in peatland catchments within Plynlimon.

The assumptions of TOPMODEL (Beven and Kirkby, 1979) fit the case of blanket peat catchments well, in which river flow is dominated by surface or near-surface flow and there is a rapidly declining rate of flow in the top few centimetres of the soil profile (Holden and Burt, 2002). Although there is flow at depth in blanket peat, it makes negligible contribution during streamflow peaks (Evans et al., 1999; Holden and Burt, 2003a). The model is felt to be widely applicable in catchments dominated by shallow subsurface flow and overland flow, and the limited number of parameters is another advantage of TOPMODEL. Clearly other models could be used in this research programme but, as TOPMODEL fits the peatland case well, this thesis will adopt and modify TOPMODEL to investigate land management impacts on river flow in the UK peatland catchments.

## 2.5 Key factors to be developed for modelling land cover change impacts on hydrographs in peatlands: relationships of overland flow, surface roughness and its distribution

### 2.5.1 Overland flow and surface roughness distribution

River flow in blanket peat catchments is dominated by surface or near-surface flow and there is a rapidly declining rate of flow in the top few centimetres of the soil profile (Holden and Burt, 2002). In particular, saturation-excess overland flow or rapidly-flowing near-surface throughflow may be dominant in river hydrographs during storm events (Holden and Burt, 2002; 2003b). Thus investigating land management influence on overland flow would be beneficial to understand the land management impact on downstream river flow in upland peat catchments.

Surface roughness is a key factor for overland flow velocity and it can largely impact the timing of overland flow movement in a catchment. Thus, change of surface roughness may remarkably influence the hydrograph at the catchment outlet. On the other hand, surface roughness, by influencing the time delay of overland flow on hillslopes, can also affect the volume of overland flow infiltrating into soil. Particularly in storm event, these impacts mean there could be large changes of peak flow timing in river channels and hence change of flood risk.

In natural catchments, surface roughness is usually related to land cover type (e.g. type of vegetation cover, or type of bare soil or rock). Heterogeneous spatial distribution of surface roughness exists due to the heterogeneity of spatial distribution of land cover. This spatial variation of surface roughness obviously influences overland flow delivery timing and vector field on hillslopes (both local and downslope areas) and thus affects downstream hydrographs in the river channel. Further on, as indicated by McDonnell (2013), efforts at a local scale are useless unless larger scale connectivity is considered, so the effect of the distribution of surface roughness may need to be better understood to get connectivity between local surface roughness and downsteam river flow, and thus the relationship of land cover change (including spatial distribution) and flood risk would be clarified.

There are only a few studies on impacts of the spatial variability of surface roughness on hydrographs. An experimental study of Wu et al. (1982) demonstrated that there is an equivalent uniform roughness for a catchment with non-uniform roughness over its surface, but it is only valid for overland flow on a conical-section experimental catchment facility with only two kinds of roughness elements (butyl rubber and butyl rubber covered with gravel). Huang and Lee (2009) conducted scenario modelling research on surface roughness spatial distribution, in which overland flow on a virtual impervious rectangular plane was simulated by a non-inertia wave model, and the result indicated that both the spatial distribution and the range of variability of surface roughness can significantly impact overland flow hydrographs. Maske and Jain (2014) extended the work of Huang and Lee (2009) from the rectangular plane to two conical surfaces (i.e. converging surface and diverging surface). The comparison of the results of these three surfaces also implied that surface roughness distribution has an influence on hydrographs even though the influence may be subject to the geometric features of the surfaces. These studies are helpful to understand the effect of spatial distribution of surface roughness on overland flow process. However, these works, either experimental or modelling, just focused on overland flow movement on the small lab experimental catchment or virtual planes with regular geometric shapes.

As indicated by Holden (2012), the timing and the synchronicity of overland flow delivery and concentration from different parts of a real catchment would be key to understanding impact on hydrographs in river channels. Such processes are related to a few factors mainly including topography and surface roughness (and its distribution) of the catchment. Surface roughness affects timing of overland flow movement everywhere in a catchment combining with catchment topography, so it is difficult to address the impact of roughness and its distribution alone from the findings of the studies described above which had simple-shaped experimental catchments. Thus, the study on impacts of the spatial distribution of surface roughness on hydrographs and flood risk should be conducted based on real catchments, even though these previous experiments may give some useful hints.

Land cover data with high resolution is difficult to obtain and field experiments with changing land cover in real catchments can be very expensive. Additionally variation between real rainfall events can create difficulties in identifying impacts on hydrographs induced by land cover change. However, through a modelling process land cover scenarios designed to represent different patterns of land cover distribution are much easier to develop, and storm events for different scenarios can be kept the same to eliminate the influence of precipitation variation. Thus, a modelling study with land cover scenarios would be an efficient method to understand the impacts of land cover change on river flow.

Modelling land cover impacts on overland flow delivery needs to ensure surface roughness is linked to vegetation cover. Very little work has been done on this issue in peatland catchments. Holden et al. (2008) explored the relationships between flow velocity, vegetation cover, slope, and water depth based on field data in blanket peat catchments. The research developed an empirical overland flow velocity forecasting model which can predict the in-situ overland flow velocity considering the local slope and overland flow depth for three typical vegetation covers (*Sphagnum*, *Eriophorum* and bare peat) of peatlands. This can be employed in a new model to represent the overland flow velocity field in peatland catchments, and that will be a new modelling method to understand and predict impacts of land cover change and distribution on downstream river flow in peatland catchments.

### 2.5.2 Land cover scenarios

Land cover scenarios with different spatial distribution patterns of land cover should be designed to clarify which parts of the catchment are more sensitive to land cover change impacts on river flow, and which spatial pattern of land cover can provide more influence on hydrographs. This section will discuss for the research needs for land cover scenario design.

#### 2.5.2.1 Riparian buffer zone

The riparian buffer zone is the interface between hillslopes and river channels, and the last land surface overland flow moves through before entering water courses in a catchment. Runoff from riparian zones is often dominant in hydrographs between storm events, throughout small runoff events and in the early stage of large events as determined by tracer experiments in real catchments (McGlynn and McDonnell, 2003).

Revegetation and eco-restoration is being conducted in riparian areas for many peat catchments. Nevertheless, there is very little research on the impact of vegetation cover change of riparian areas on hydrographs in river channels. However, a review of a few published modelling studies may be helpful to infer the impacts even though they focused on general distribution of surface roughness in imaginary surfaces rather than the surface roughness of riparian areas in real catchments. An overland flow modelling study with a rectangular plane (1% slope) of Huang and Lee (2009) found that a scenario with decreasing surface roughness in a downstream direction had a slightly earlier but much lower flow peaks compared to the scenario with downslope-increasing surface roughness (the two scenarios maintained the same average surface roughness). Maske and Jain (2014) also made similar conclusions for a range of surface slopes (1% to 3%). If the rectangular surfaces in these two studies are imagined to be a hillslope in a real catchment, this finding seems to imply that high surface roughness on headwater areas is more positive than high roughness on riparian areas to reduce flow peak, It also implies that low surface roughness on upslope areas brings more peak volumes than that on downslope areas. Connecting this point to vegetation cover change in a real upland peat catchment, it means that re-vegetation efforts on headwater areas is more effective to attenuate flood peaks than that on riparian areas and loss of vegetation cover on headwater areas may have a more negative impact on flood risk than that on riparian areas. However, this conclusion seems to be contradictory to the common view of hydrological performance of riparian areas, for which the riparian areas are considered as important parts in catchments for flood attenuation. These factors require testing for the upland blanket peat case.

The concentration of overland flow can also remarkably impact hydrographs in a catchment, and the concentrating process is related to the topography of a catchment. The most concentrated overland flow passes through riparian areas before flowing into river channels. Very few studies, combining catchment topographic features, are on the impact of land surface roughness distribution. Maske and Jain (2014) conducted a modelling experiment, with surface roughness distribution scenarios similar to those mentioned above on rectangular planes, for diverging and converging conical surfaces. The result of the diverging conical surface, on which overland flow diffuses downstream, is consistent with the previous results on rectangular planes. Nevertheless, for the converging conical surface, the resultant hydrographs showed there was no obvious difference between the scenarios with increasing and decreasing surface roughness in a downstream direction (keeping the same area-weighted average surface roughness). This conclusion reveals that the advantage of high roughness on headwater areas may be offset by concentration of overland flow on a converging plane, indicating that the surface roughness change on downstream areas is more efficient to impact overland flow due to the flow concentration on converging surfaces.

Therefore, it seems that there are two converse mechanisms for the impact of the distribution of surface roughness on hydrographs:

1. High surface roughness in the headwater area restricts increasing overland flow velocity and makes it easy to maintain low velocity in downstream areas, while the low surface roughness in the upslope area leads to high overland flow velocity and it is hard to restrict this in downslope areas.

2. The converging shape of a catchment makes the downstream areas (e.g. riparian areas) have larger efficiency for overland flow velocity change by land cover roughness.

Scenarios therefore need to be designed and modelled to explore which menchanisms dominate in upland peat catchments. This would be helpful to inform whether any practical land management work should focus on protection and restoration of riparian zones in these catchments for flood alleviation.

#### 2.5.2.2 Patch size

Bare peat without any vegetation in peatlands widely exists due to removal of vegetation due drivers such as to pollution, burning and over-grazing. These no-vegetation patches are often distributed through UK upland peat catchments in a mosaic shape with different patch sizes. For burning patches, the Defra Heather and Grass Burning Code (Defra, 2007) strongly advises that a single area of bare soil produced by burning should be no more than 0.5 ha. This is helpful to prevent soil erosion but the impacts of bare peat patch size on river flow is still not well understood. On the other hand, for peatland restoration work, determining whether the patch size for re-vegetation has impacts on flood alleviation is also interesting for optimization of these efforts. Large bare patches may have better landscape connectivity across them, than a series of small bare patches will have across that same part of the landscape. In terms of overland flow velocity and volumes this connectivity could be very important. Hence, the size of land cover change patch would be worthy to investigate for its impacts on river flow.

#### 2.5.2.3 Slope

Slope, determined by topography, plays a vital role for in-situ overland flow velocity. The relationship between overland flow velocity, slope and surface roughness can be represented by the Manning's equation and Darcy–Weisbach equation which have been widely accepted. However, these equations focus on local impacts of surface roughness on overland flow processes combined with a slope effect and the combined impacts of these two factors on downstream river flow are not clear. In real catchments, heterogeneity of the spatial distribution of gradient exists, and especially the gradient range is quite large in upland peat catchments. Similar land cover change on areas with distinctive gradients may bring different influences on river flow, but the difference of impacts on river flow between land cover change in steeply sloped areas and that in gently sloped areas is still not well understood, to the author's knowledge. Thus, scenarios would need to be produced to investigate whether steeply sloping areas are more sensitive to land cover change impacts on river flow in a catchment, than gently sloping areas.

## 2.6 Summary

This chapter provided a general overview concerning land management impacts on runoff and streamflow from peatland headwaters in the UK. Surface conditions appear to be crucial controls on streamflow in headwater peatlands. The land cover of such peatlands is affected by management activity. Even research into the impacts of drains on streamflow in peatlands is beginning to suggest that the wider surface roughness of the peatland might be a more important factor in determining streamflow response than the presence or absence of drains. Thus a landscape-scale approach to peatland surface cover might be an appropriate way to consider how management interventions could influence streamflow peaks. Holden et al. (2008) offered the first empirical evidence of the effects of vegetation type on overland flow velocities in peatlands, which may be significant for river flow. The dominance of *Sphagnum* led to the slowest velocity but water flows were substantially faster through sedges and fastest over bare peat. Grayson et al. (2010) have provided the first evidence at a medium-sized catchment-scale (11.4 $km^2$) that changes in vegetation cover (i.e. moving from bare peat to revegetated peat) over parts of a catchment can result in changes to the flood peak and other hydrograph characteristics. They indicated that the period of maximum extent of the area of bare peat corresponded to higher discharge peaks while natural revegetation in the catchment was associated with lower discharge peaks and that the hydrographs were also flashier during the periods of most bare peat and less so as revegetation has progressed through time

The spatial distribution of landscape features such as the drainage network, topography and variation in surface cover may be important in determining the streamflow peak response of management interventions due to flow synchronosity effects which mean that the same cover change might have different impacts depending on where in the catchment the changes occur. Hydrological processes are spatially and topographically controlled. Therefore, there may be sensitive parts of a catchment where management (e.g. grazing) will have a much greater impact on stream flow (e.g. by compacting valley bottoms) than in other parts of the catchment. Distributed hydrological modelling may bring more support for land managers through providing guidance to optimize expenditure in different parts of the catchment. For instance, the role of sheep tracks reminds us that if we are to understand the environmental impacts (and make reliable predictions) of reductions in grazing then we need to use spatial modelling techniques that incorporate topographical processes rather than simply rely on lumped models (Fleming, 2002). Furthermore, practitioners are keen to understand whether there are locations in the catchment that might have more favourable river flow peak attenuation results if they revegetate bare peat or if they encourage a more dense *Sphagnum* understory. Thus a spatial modelling approach is required to address this problem. TOPMODEL is a well-known hydrological model used around the world. Its underlying assumptions match the case of blanket peatlands well. However, it requires modification in order to be used to deal with spatially distributed overland flow variations and land cover change across headwater catchments. Model data needs and lack of detailed information on impacts of multiple management interventions on peatland properties and hydrology are important factors to take into consideration when developing a suitable modeling approach for studying how land cover change impacts stream flow in peatland headwater catchments. Thus, there may be a series of key considerations for the new modelling approach as follows:

- Spatially-distributed structure of the model to represent spatial land cover change in a catchment.
- A module to separate subsurface flow and overland flow which is sensitive to land cover change.
- A module to describe overland flow movement on hillslopes, involving representing in-situ land cover impacts on overland flow delivery and routing of the overland flow.

The development of a distributed catchment hydrological model with these considerations in order to address the key question posed by this thesis, as outlined in Chapter 1, will be presented in Chapter 3.

# Chapter 3
# Model development

## 3.1 Introduction

The main purpose of the project is to understand the impact of land-cover change in upland peat catchments on downstream hydrographs. For this aim, there are two major tasks for the model development. First, a spatially distributed model is needed to identify and handle the variety of spatial patterns of land cover in the catchment. The other prime assignment is to establish an overland flow delay module which can distinguish the various influences of land cover on surface water delivery on hillslopes because the majority of stream discharge in blanket peatlands is derived from surface flow (Holden and Burt, 2003b). It is thought that downstream discharge from peatlands might be sensitive to surface vegetation cover (Ballard et al., 2011; Holden et al., 2008; Lane and Milledge, 2013) and this may be fruitful to investigate rather than more traditional studies of impacts on river flow of individual land management strategies such as drainage which have often resulted in equivocal conclusions. TOPMODEL has been selected as a suitable prototype because of its excellent performance in hydrological modelling in many UK upland catchments (e.g. Beven et al., 1984; Fisher and Beven, 1996; Page et al., 2007).

## 3.2 Original TOPMODEL rationale

TOPMODEL was initially developed by Beven and Kirkby (1979), applying concepts from Kirkby (1976), and it was a continuous lumped or semi-distributed hydrological simulation model in its early stages. The original TOPMODEL mentioned in this section refers to version 9502 which was coded with the computer language of FORTRAN 77 by Keith Beven at Lancaster University in 1995. Figure 3.1 gives a basic structure of original TOPMODEL.

The basic version of TOPMODEL is based on three theoretical assumptions (Beven, 2001; Beven and Kirkby, 1979): (A) There is a saturated zone in equilibrium with a spatially uniform recharge rate over an upslope contributing area and the runoff is spatially constant. (B) The water table is almost parallel to the surface such that the effective hydraulic gradient is equal to the local surface slope. (C) The transmissivity profile may be described by a single-valued function of storage deficit, with a value of runoff when the soil is just saturated to the surface.

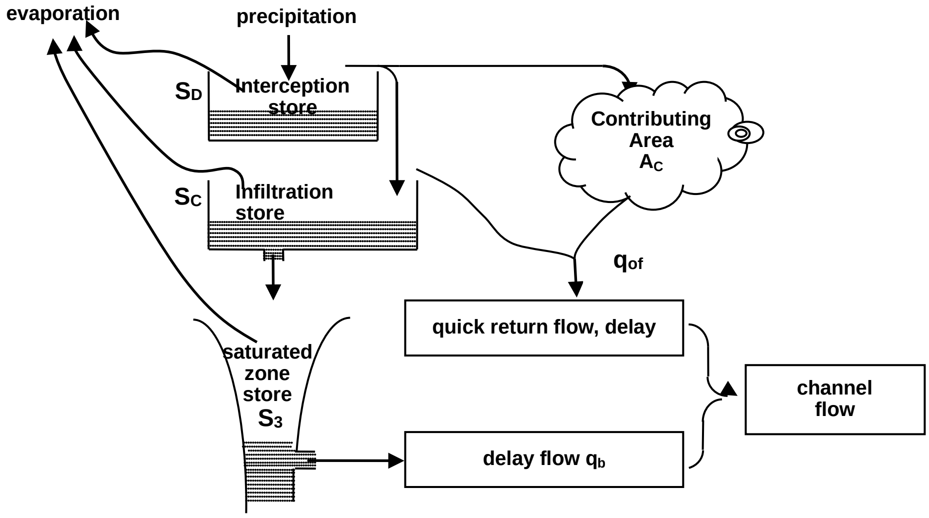


**Figure 3.1** Structure of original TOPMODEL (from Beven and Kirkby, 1979).

Kirkby (1997) provided a classical approach to the rationale of TOPMODEL from the continuity equation based on strictly necessary assumptions. A brief review of the deduction is presented below in order to demonstrate the theoretical base of the original TOPMODEL and leads to a proceeding approach for developing a distributed TOPMODEL.

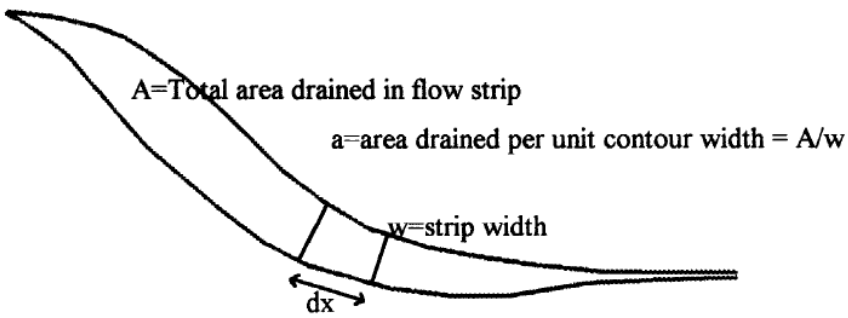


**Figure 3.2** Definition sketch for flow strip (from Kirkby, 1997).

As seen in Figure 3.2, there is a flow strip with variable width in which the horizontal distance follows a curvilinear path down the line of greatest slope in a catchment. Due to the water balance equation (Equation 3.1), we get Equation 3.2:

$$\text{inflow} - \text{outflow} = \text{net decrease in soil moisture deficit}$$

Equation 3.1

$$dt\left[waj-\left(wa+d\overline{wa}\right)\left(j+dj\right)+iwdx\right]=-wdD\ dx$$

Equation 3.2

in which, *w* is flow strip width, *x* is horizontal distance, *D* is soil moisture deficit, *a* is area drained per unit contour width, *i* is net rainfall density, *j* is discharge per unit area (i.e. runoff rate), and *aj* is discharge per unit contour width.

Rearranging and dividing throughout by $w$ *dx dt*, we have:

$$a\frac{\partial j}{\partial x}+\frac{j}{w}\cdot\frac{\partial\left(aw\right)}{\partial x}-\frac{\partial D}{\partial t}=i$$

Equation 3.3

Using the geometric identity of Equation 3.4,

$$\frac{1}{w}\cdot\frac{\partial\left(aw\right)}{\partial x}=1$$

Equation 3.4

we consequently get Equation 3.5 which is a completely general statement of hydrological continuity for the flow strip:

$$a\frac{\partial j}{\partial x}-\frac{\partial D}{\partial t}=\left(i-j\right)$$

Equation 3.5

Here, the two assumptions are chosen for the first time in the procedure in order to develop the expression of flow strip discharge. It is assumed that (i) flow strip discharge is proportional to slope gradient (assumption B above), and (ii) the discharge is related to some function of soil moisture deficit (assumption C above).

The first assumption is an equivalence of Darcy's law which is a good approximation for most subsurface flow except that of macropore and pipe flow underground. For overland flow, it is separated from subsurface flow by most versions of TOPMODEL. If we further assume that the effective hydraulic gradient is equal to the hillslope surface gradient (i.e. water table is always parallel to the land surface) or perhaps to fixed proportion to surface slope, the slope data for this assumption is totally topography-related and hence more accessible than piezometric gradient in most real catchments.

The second assumption may be summarized in Equation 3.6 for a suitable function *f*

$$q = aj = \Lambda f\left(D\right)$$

Equation 3.6

Formally, we may invert this to have Equation 3.7 for another function $\Phi$:

$$D = \Phi\left(aj / \Lambda\right)$$

Equation 3.7

where $\Lambda$ is slope gradient.

Now, another assumption (assumption A above) is indispensably made that discharge per unit area (i.e. *j* in equations) is spatially uniform, which means term $\partial j / \partial x$ in Equation 3.5 equals zero. If a consistent solution to the equation is needed, the net rainfall addition, *i*, and the term $\partial D / \partial t$, must also be spatially invariant (i.e. must not change with position in the catchment).

Calculating the term $\partial D / \partial t$ with Equation 3.8 and 3.9, we have Equation 3.10:

$$\frac{\partial D}{\partial t} = \frac{\partial \Phi\left(aj / \Lambda\right)}{\partial\left(aj / \Lambda\right)} \frac{\partial\left(aj / \Lambda\right)}{\partial t}$$

Equation 3.8

$$\frac{\partial\left(aj / \Lambda\right)}{\partial t} = \left(aj / \Lambda\right) \frac{1}{j} \cdot \frac{dj}{dt}$$

Equation 3.9

$$\frac{\partial D}{\partial t} = \left(aj / \Lambda\right) \frac{\partial \Phi\left(aj / \Lambda\right)}{\partial\left(aj / \Lambda\right)} \cdot \frac{1}{j} \cdot \frac{dj}{dt}$$

Equation 3.10

In Equation 3.10, the term

$$\left(aj / \Lambda\right) \frac{\partial \Phi\left(aj / \Lambda\right)}{\partial\left(aj / \Lambda\right)}$$

is itself a function of $\left(aj / \Lambda\right)$ and must also vary with time alone, and not with position. Since *a, j* and $\Lambda$ are time-constant at any point (*j* has been assumed it is spatially uniform), the only suitable form for this term is, in general, a constant, which we will call *-m*. The function $\Phi$ must then take the form of a logarithm. At its most general, we have Equation 3.11 and Equation 3.12:

$$D = \Phi\left(aj / \Lambda\right) = -m \ \ln\left(aj / \Lambda q_0\right)$$

Equation 3.11

$$\frac{\partial D}{\partial t} = \left[ (aj/\Lambda) \frac{d\Phi(aj/\Lambda)}{d(aj/\Lambda)} \right] \cdot \frac{1}{j} \frac{\partial j}{\partial t} = -\frac{m}{j} \cdot \frac{\partial j}{\partial t}$$

Equation 3.12

For the logarithmic form, the appropriate spatial form of the continuity equation (Equation 3.13) is obtained, together with the relationship between deficit and runoff (Equation 3.14):

$$\frac{dj}{dt} = \frac{j}{m}(i - j)$$

Equation 3.13

$$D = -m \ln(aj/\Lambda q_0) \quad \text{or} \quad q = aj = \Lambda q_0 \exp(-D/m)$$

Equation 3.14

Equation 3.14 defines both the discharge ($q = aj$) and the soil water deficit to saturation ($D$) at every point in the catchment. With $D$=0 at soil saturation, $q_0$ is the discharge per unit width at saturation on unit slope gradient. This may vary from place to place within the catchment without violating the other assumptions.

We can also define the runoff required to produce local saturation, which varies from place to place. Setting D = 0 in Equation 3.14, it gives

$$j_* = \frac{\Lambda q_0}{a}.$$

Equation 3.15

where $j_*$ is discharge per unit area at saturation.

Getting Equation 3.15 back to Equation 3.14, the formulation of $j$ can be

$$j = j_* \cdot exp(-\frac{D}{m}).$$

Equation 3.16

where $m$ is a soil depth parameter, invariant over the flow strip and over time, which shows how quickly discharge falls off with depth. At deficit D, the lateral saturated hydraulic conductivity is

$$K(D) = \frac{aj}{\Lambda} \cdot \frac{1}{m} = \frac{q_0}{m} \exp(-D/m)$$

Equation 3.17

This is the rationale of original TOPMODEL, and the main hydrological calculation process is based on these equations. For the time delay of flow in the original TOPMODEL, a simple uniform parameter of mean time delay for both overland flow and subsurface flow is adopted as it is only a lumped or semi-distributed model.

## 3.3 Distributed TOPMODEL

To tackle the spatial distribution of different land cover types, the model should be distributed and calculate hydrological behaviour individually in every cell from DEM (Digital Elevation Model) data. Meanwhile, subsurface flow and overland flow should be separately treated in the distributed TOPMODEL, especially in different delay modes, to reveal the land cover impact on the stream hydrograph. Figure 3.3 illustrates the processing of a distributed TOPMODEL which will be discussed in detail in the following sections.

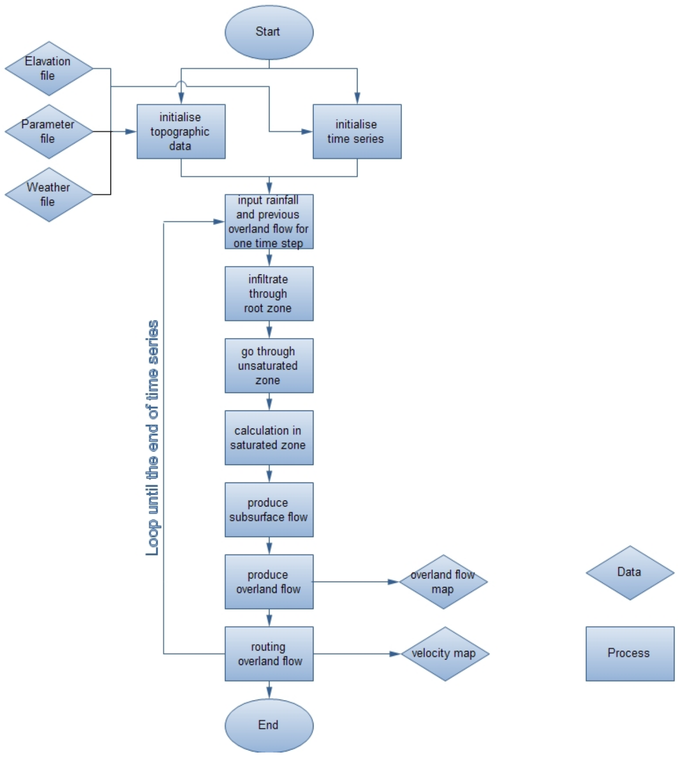


**Figure 3.3** Processing order of distributed TOPMODEL.

### 3.3.1 Subsurface flow module in distributed TOPMODEL

The rationale of TOPMODEL needs to be extended for the distributed model, so the hydrological equations should be downscaled from catchment scale to cell scale (probably 10m). The new elementary equations should represent hydrological behaviour cell by cell in a catchment.

From the general statement of hydrological continuity (Equation 3.5) and the logarithmic assumption (Equation 3.11 and Equation 3.12),

$$a\frac{\partial j}{\partial x}-\frac{\partial D}{\partial t}=\left(i-j\right)$$

Equation 3.5

$$\frac{\partial D}{\partial t}=-\frac{m}{j}\cdot\frac{\partial j}{\partial t}$$

Equation 3.12

we have

$$a\frac{\partial j}{\partial x}+\frac{m}{j}\cdot\frac{\partial j}{\partial t}=\left(i-j\right)$$

Equation 3.13a

Here, i and j are assumed spatially uniform in a DEM cell for distributed model. Thereby, the continuity equation with in a cell is also Equation 3.13, and a solution can be obtained as Equation 3.18. Equation 3.13a is the generality of Equation 3.13 which remains valid if i and j vary spatially:

$$\frac{dj}{dt}=\frac{j(i-j)}{m}$$

Equation 3.13

$$\ln\left(\frac{j}{i-j}\right)=\frac{it}{m}+c$$

Equation 3.18

where *C* is an unknown constant need to be solved.

We want to acquire the key equations for a cell in distributed TOPMODEL, and the solution of Equation 3.13 in a time interval (it is assumed that the topographic and soil properties are uniform in a cell.). If $j_0$ is defined as discharge per unit area at the beginning of a time interval, the boundary condition of Equation 3.13 is

$$\text{at } t=0,\ j=j_0\,.$$

Bringing it into Equation 3.17, *C* is solved as Equation 3.19:

$$C=\ln\left(\frac{j_0}{i-j_0}\right)$$

Equation 3.19

Taking it back to Equation 3.17, we have Equation 3.20:

$$\ln\left(\frac{j}{i-j}\right)=\frac{it}{m}+\ln\left(\frac{j_0}{i-j_0}\right)$$

Equation 3.20

Solving *j,* it is

$$j=\frac{j_0}{\frac{j_0}{i}+(1-\frac{j_0}{i})\cdot exp(-\frac{it}{m})}$$

Equation 3.21

Equation 3.21 is the expression of *j* for a cell at time *t* within a time interval.

From Equation 3.16, *D* can be calculated by Equation 3.22:

$$j = j_* \cdot exp(-\frac{D}{m}) .$$

Equation 3.16

$$D=m\cdot\ln\left(\frac{j_*}{j}\right)$$

Equation 3.22

Hence, if $D_0$ is defined as deficit at t=$t_0$ and $D_1$ is deficit at the end of time interval, we get

$$D_0=m\cdot\ln\left(\frac{j_*}{j_0}\right)$$

Equation 3.23

$$D_1=m\cdot\ln\left(\frac{j_*}{j_1}\right)$$

Equation 3.24

where $j_1$ is discharge per unit area at the end of a time interval.

In terms of water balance (i.e. net rainfall plus decrease of deficit equals runoff), total runoff in a time interval may be received by Equation 3.25:

$$TF=i\cdot\Delta t+(D_1-D_0)=m\ln\left(1+\frac{j_*}{i}exp\left(-\frac{D_0}{m}\right)\cdot\left(exp\left(\frac{i\cdot\Delta t}{m}\right)-1\right)\right)$$

Equation 3.25

where *TF* is total runoff for a grid, and $\Delta t$ is time interval.

However, Equation 3.25 should be implemented without modification only in the case for which the grid is never over-saturated (i.e. overland flow is never produced) in the time interval, because Equation 3.23 and Equation 3.24 (from Equation 3.16 and previously Equation 3.14) are defined to express runoff below the land surface and are hence only applicable for subsurface flow.

In the case where saturation is reached within a time interval $\Delta t$, it is assumed that net rainfall intensity is constant during the time interval, and heavy enough to saturate the cell and produce overland flow at some time $t_*$ within the time interval.

If we suppose, at time t*, the soil just reaches saturation (i.e. deficit just equals zero and the total runoff rate is discharge at saturation, $j_*$), we have Equation 3.26 from Equation 3.21:

$$j_* = \frac{j_0}{\frac{j_0}{i} + (1 - \frac{j_0}{i}) \cdot exp(-\frac{it_*}{m})}$$

Equation 3.26

Solving it gives Equation 3.27 which is valid during the time interval, if $i > j^* > j_0$:

$$t_* = \frac{m}{i} \ln\left( \frac{j_*(i - j_0)}{j_0(i - j_*)} \right)$$

Equation 3.27

Before t*, the cell is not at saturated, the moisture deficit is continuously decreasing and there is no overland flow, so that Equation 3.25 is applicable. Hence, substituting Equation 3.27 into Equation 3.25, the amount of subsurface flow from $t = 0$ to $t = t_*$ is

$$SSF_1 = m \ln\left( 1 + \frac{j_*}{i} \cdot \left( \frac{j_*(i - j_0)}{j_0(i - j_*)} - 1 \right) \right) = m \ln\left( \frac{i - j_0}{i - j_*} \right).$$

Equation 3.28

Between t* and the end of time interval, the grid is continuously saturated due to the assumed continuing rainfall at the constant rate for the time step, and consequently the subsurface flow rate consistently equals $j_*$ in this period. Subsurface flow in this stage is

$$SSF_2 = j_* \cdot (\Delta t - t_*)$$

Equation 3.29

In addition to subsurface flow, the surplus net rainfall transforms to saturation-excess overland flow whose amount is determined by Equation 3.30, and this is also the total overland flow within the time step:

$$SOF = i \cdot (\Delta t - t_*) - SSF_2 = (i - j_*) \cdot (\Delta t - t_*)$$

Equation 3.30

Total subsurface flow in the time interval is the sum of that in the two sub-stages (shown as Equation 3.31).

$$SSF = m \ln\left(\frac{i - j_0}{i - j_*}\right) + j_* \cdot (\Delta t - t_*)$$

Equation 3.31

The deficit at the end of the time step is zero due to its saturation at that point.

The case of a continuously saturation cell (i.e. the status which starts at saturation and undergoes huge net rainfall, so that the cell keeps saturated during the whole time interval) can be treated as a particular situation in the saturated case as above. The subsurface flow is calculated from the density of discharge at saturation through the time interval, leaving the other part of runoff as overland flow.

All equations for subsurface flow in a cell, which is the base of the distributed modification for TOPMODEL, have now been derived, and they will be used in the module for subsurface water behavior and overland flow generation.

### 3.3.2 Overland flow module in distributed TOPMODEL

The runoff delay in the original version of TOPMODEL is treated by a lumped method using a constant general channel flow velocity and a hillslope velocity. Field measurements in blanket peat have shown that overland flow may be significantly slower than assumed in the original TOPMODEL (Holden et al., 2008), requiring the delay to be formed from a more explicit overland flow routine.

In order to simulate the overland flow movement and the land surface impact on it, an overland flow module is developed, being a new component to be added to the original TOPMODEL. After getting the overland flow volume from every cell in the model, the overland flow module controls the computation of spread and concentration of overland flow and derives the time consumed in this process. Routed overland flow water can then be re-involved in the hydrological calculation in down-flow slope cells, providing delayed local inputs to combine with subsequent rainfall in a spatially variable pattern. In the representation of overland flow, the time delay is calculated separately for each cell that generates or receives surface flow, providing an interactive relationship between subsurface flow and overland flow.

#### 3.3.2.1 Overland flow routing algorithm

The main assignment of the overland flow routing algorithm is to provide an overland flow distribution for every step of simulation and to support the calculation of overland flow delay. The multiple-direction flow algorithm is employed as a theoretical base to represent the overland flow routing procedure in the overland flow module. This routing algorithm is a multiple direction flow version of D8 (deterministic eight node) algorithm (O'Callaghan and Mark, 1984) which allocates all flow to the grid neighbouring cell with the steepest slope after considering the slopes to all eight neighbouring cells. The multiple-direction flow algorithm was firstly developed by Quinn et al. (1991), which allows flow dispersion in hillslope routing processes. The water in a cell is split to its every lower neighbour cell and the fractions of water amount are determined by slope weights. The fraction of flow given to the neighbour *i* is given by Equation 3.32:

$$Fr_i = \frac{S_i}{\sum_{i=1}^{8} S_i}$$

Equation 3.32

where $S_i$ is the gradient in direction i, $Fr_i$ is the flow fraction in direction i, and i is from 1 to 8 representing the eight directions of eight cells. However, this algorithm tends to cause undesirable dispersion of flow in valley bottoms as stream channels should normally be well defined (Gallant and Wilson, 1996). This can be overcome by switching to a single flow path algorithm when the contributing area exceeds a certain value. In the distributed TOPMODEL, the problem may be solved by defining a channel network in the DEM of the catchment (i.e. setting a series of cells on river lines as channel cells with high flow velocity in which there is no water split process). This will be discussed in following section.

The DEM data should be modified in advance with a pond-filling process in which the elevation of every cell with no lower neighbour cells is increased to the average value of its neighbours' elevations, since the pond water is not the issue this model wants to tackle. Meanwhile, a ranking procedure based on elevation value in the modified DEM map is firstly needed for all cells in the catchment. The Quick Sorting Algorithm (Hoare, 1962; Sedgewick, 1978) is used to sort the cells in decreasing order of elevation value as a preparation before the entire hydrological calculation in the model.

The routing algorithm is used for every cell in a time step throughout the whole period of the simulation. In each time step the model algorithm runs through every cell in the area, beginning with the highest cell (i.e. the peak point in the catchment) and ending with the lowest one (i.e. the outlet of the basin after the pond filling). This sequencing is required to ensure that all overland flow produced by higher cells has been included in the calculation for lower cells in the catchment during the same time step.

Within each time step the calculation for an individual cell begins by applying the rainfall, together with any overland flow from upslope, to estimate the infiltration, overland flow production, subsurface flow and updated local saturation deficit using a local solution to equation 3.5. These processes do not require the algorithm which then routes the overland flow, part of which may remain in the source cell and part distributed over cells downslope

Two methods of routing the overland flow have been conceptualised. In the first the flow is repeatedly split between all adjacent downslope cells according to the distribution between alternative flow directions, setting up a chain reaction which is computationally inefficient to implement and difficult to parameterise. Alternatively the overland flow generated in each source cell is split into a number of parcels (50-100), each a realisation of the total overland flow which is then followed stochastically, using the flow partitions (equation 3.32) as the basis for selecting a path at random from cell to cell. The velocity of each parcel is calculated from the overland flow depth and the local gradient at each step of the flow path, using Manning’s equation (3.35). The velocity calculated in this way is then interpreted as the probability that the path will terminate within the time step in each cell traversed. When all parcels have been followed to the ends of their respective paths, they are combined (and weighted) to give the destination distribution for all the overland flow generated in the source cell at the end of the time step.

The stop condition in the routing process for a single water parcel is also probabilistic. At each step along the path of an overland flow parcel, the velocity, $v$, is calculated from Equation 3.36, in which the depth is the depth of flow generated in the source cell and the gradient is the local gradient between successive cells on the flow path. It follows that, for this step, the mean travel distance in a time step $\delta t$ is $v\delta t$. Applying an exponential distribution which is equivalent to assuming a constant probability of stopping per unit distance, the probability of stopping within one cell, of dimension $\delta x$, i.e. stopping within the current cell may be written as

$$P = 1 - exp[-\delta x/(v\delta t)]$$

Equation 3.33

and the outcome determined randomly.

Water parcels after the routing process from a cell can stop in many downslope cells which cover a relatively extensive area with various flow path distances. Therefore, this leads to a consecutive and smooth distribution of overland flow travel distance for a cell, which helps to smooth out rapidly fluctuating runoff concentrations downslope. This stochastic algorithm has been preferred to the more complex chain reaction process, and implemented within the model code.

After running through all cells (from high to low) in the catchment, the overland flow in the outlet cell is the overland flow output of the catchment in current time step. This flow includes overland flow produced in current time steps in the area near the outlet and in former steps away from it, and overland flow running in the hillslope cells would be a part of overland flow output or a part of subsurface flow output due to the re-infiltration.

#### 3.3.2.2 Time delay process and its equations

The time delay process of water movement on real hillslopes is a process of velocity variation induced by acceleration and friction, which are driven by topographic factors and land surface features. The equations for delay time of overland flow (or the equations for velocity of overland flow) should hence be related to surface gradient, flow depth, and land surface cover.

The Darcy-Weisbach equation (as Equation 3.34) can be utilized as an expression of land surface resistance to overland flow, which provides a theoretically-based way to build relationships among overland flow velocity, gradient, flow depth and the friction factor in upland peatlands backed up by empirical observations (Holden et al., 2008):

$$V^2 = \frac{8g}{f} dS$$

Equation 3.34

where $S$ is the surface slope and, $v$ is the mean velocity of overland flow, $d$ is overland flow depth, $g$ is gravitational acceleration, and $f$ is the dimensionless friction factor. $f$ can be related to the ratio of water depth, $d$ to an effective roughness diameter, *k*, which can be described by a empirical equation 3.35.

$$\frac{1}{\sqrt{f}} = A + 1.77\ln\left(\frac{d}{k}\right)$$

Equation 3.35

where *A* is an empirically defined constant.

Combining Equation 3.34 and 3.34, overland flow velocity will be related to flow depth and slope gradient with a couple of constants but the expression may be complex. From the work of Holden et al. (2008), when we have 10 < *d/k* <10000 there is a relationship of $f^{-0.5} \sim (d/k)^{1/6}$ which is consistent with Manning's equation.

Thus it is simplified as

$$v = k_v \cdot d^{2/3} \cdot S^{1/2}$$

Equation 3.36

where $k_v$ is a suitable constant based on Equation 3.34 and 3.34. This is a succinct form of velocity calculation in which water depth will be obtained in every cell at every time step through the running process of the model. Gradient can be gained through an analysis of elevation data before the hydrological simulation.

The algorithms describing overland flow movement have been presented in this section. The new model thus has the ability to represent land cover change impacts on overland flow in fully distributed fashion.

## 3.4 Summary

The distributed modification of TOPMODEL was developed in this chapter. This was a considerable undertaking which took around 18 months of research time. The original basic method for treating subsurface flow is inherited from the original TOPMODEL, but the equations are downscaled to suit the grid cell formulation of the distributed model. A new distributed overland flow module has been developed to simulate the overland flow movement on the land surface, in which the impact of land cover change on overland flow can be represented. The module employs the multiple-direction flow method and the equations of roughness for overland flow with stochastic algorithms.

**Table 3.1** Physical meanings of major parameters in the new model.

| Parameter | Physical meaning |
|---|---|
| $m$ (m) | Active depth for subsurface flow |
| $k_v$ | Velocity parameter of overland flow |
| $K$ (m/hr) | ‘Notional’ hydraulic conductivity of soil |

This new distributed version of TOPMODEL can now be tested in order to assess its suitability for performing land cover change experiments in upland catchments. The model will be tested in next chapter.

# Chapter 4
# Test of the distributed TOPMODEL

## 4.1 Introduction

The distributed version of TOPMODEL has been described in chapter 3, setting out the distributed modelling structure and the new overland flow movement component. The model now needs to be tested prior to its application in upland peat catchments. The aim of this chapter is, therefore, to test the distributed model based on the upland peat catchment, Trout Beck at Moor House National Nature Reserve in the north Pennines of England.

Section 4.2 presents the process of model calibration and validation in the Trout Beck catchment with real summer storm events. Section 4.3 presents a comparison of results between the distributed TOPMODEL and the original TOPMODEL. A summary of the model testing results is then given in section 4.4 at the end of the chapter.

## 4.2 Model test in the Trout Beck catchment

### 4.2.1 The study site and rainfall events for model testing

The Trout Beck catchment at Moor House National Nature Reserve (54°41’ N, 2°23’ W) is in northern England, covering an area of 11.4 km$^2$ (see Figure 4.1) with the elevation ranging from 842 m to 533 m AOD. It is one of the headwaters of the River Tees. The catchment was chosen as a test site because i) the catchment has a long series of hourly data of outlet river flow and weather so there are much data for many storm events which can be used for model tests, and the data from 1993 to 2009 was obtained for use in this project from the Environmental Change Network. ii) much research on peatland processes has taken place at the site (possibly more than at any other site in the world) and thus there is good scientific context and the modelling work will also provide useful information for future studies at the site; and iii) there was suitable topographic data from the site.

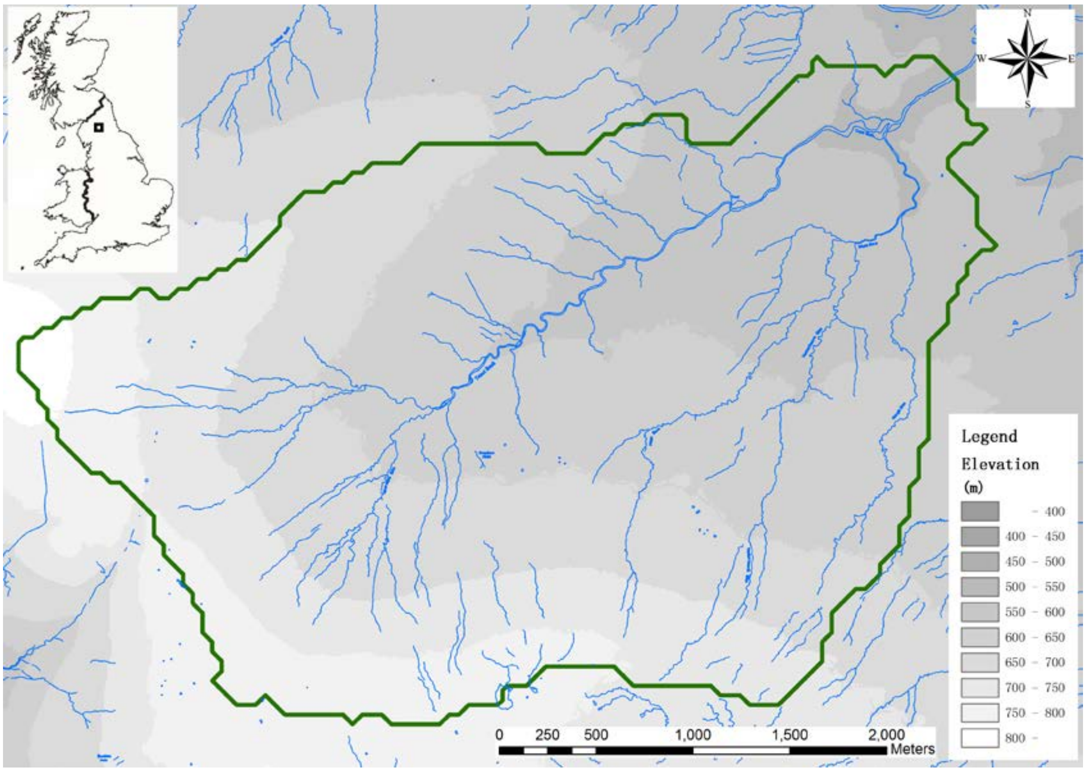


**Figure 4.1** Location and map of Trout Beck catchment.

Glacial boulder clay in the catchment lies on Lower Carboniferous sequences of interbedded limestone, sandstone and shale (Johnson and Dunham, 1963). Around 90% of the catchment area is covered by blanket peat with a typical depth of 1-2 m (Evans et al., 1999). The peat suffered severe erosion in the 1950s, but large areas have revegetated since then, and bare, eroded peat is now restricted to a few areas (Cundill et al., 2007). A recent field investigation shows that bare peat occupies 9.4% of the surface in the catchment (from unpublished data from the North Pennines AONB Partnership; see Chapter 7).

The climate of the catchment is classified as sub-arctic oceanic (Latter et al., 1998), with an annual average temperature (1931–2006) of 5.3 °C (Holden and Rose, 2011), and a mean annual rainfall of 2012 mm (records from 1951 to 1980 and 1991 to 2006) (Holden and Rose, 2011). 43% the annual precipitation falls between April to September (Grayson et al., 2010). Climatic data have been recorded at Moor House since 1931, the longest record for any UK upland site (Holden and Adamson, 2001).

To avoid freezing and melting problems and the lower reliability of winter precipitation records due to snowfall, rainfall events for model calibration and validation are selected from summer-half years (from 1993 to 2009). Figure 4.2 summarises the yearly maximum of hourly summer rainfall.

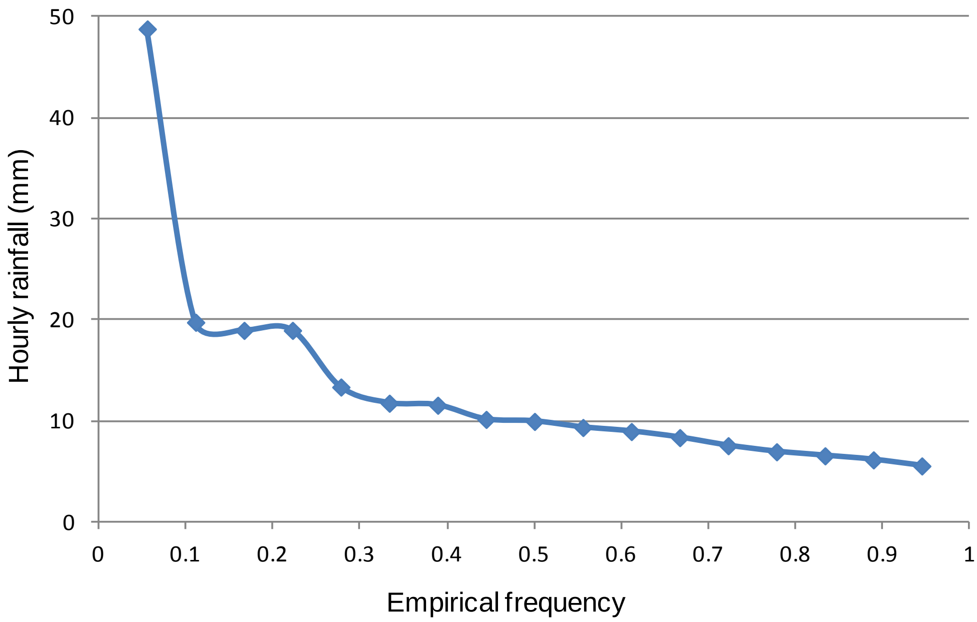


**Figure 4.2** Empirical frequency of hourly rainfall intensities of yearly maximum from 1993 to 2007.

A one-week period commencing from 16th August 2004 (105 mm total rainfall) has been chosen as a suitable period for calibration. It includes a storm event with 19.4 mm precipitation in one hour and represents an approximately 10-year return period estimated from the empirical frequency of events (Figure 4.2). Another wet week near to the calibration period is selected as the validation period commencing from 8th August 2004 (128 mm total rainfall). The Penman-Monteith equation (Monteith, 1965) is employed to estimate the evapotranspiration during the calibration and validation periods.

Prior to the procedure of calibration and validation, a simple test of the simulation stability for the distributed TOPMODEL is needed due to the stochastic algorithm utilized in the overland flow module of the distributed model. A parameter set is picked to run the model for five times during the calibration period. The five modelled hydrographs are almost overlapping (see Figure 4.3), and the largest difference of flow value between the hydrographs is less than 1%. It is concluded that the stochastic algorithm in the model is stable enough for model application for real storm events. The model calibration and validation can therefore be operated in the next step.

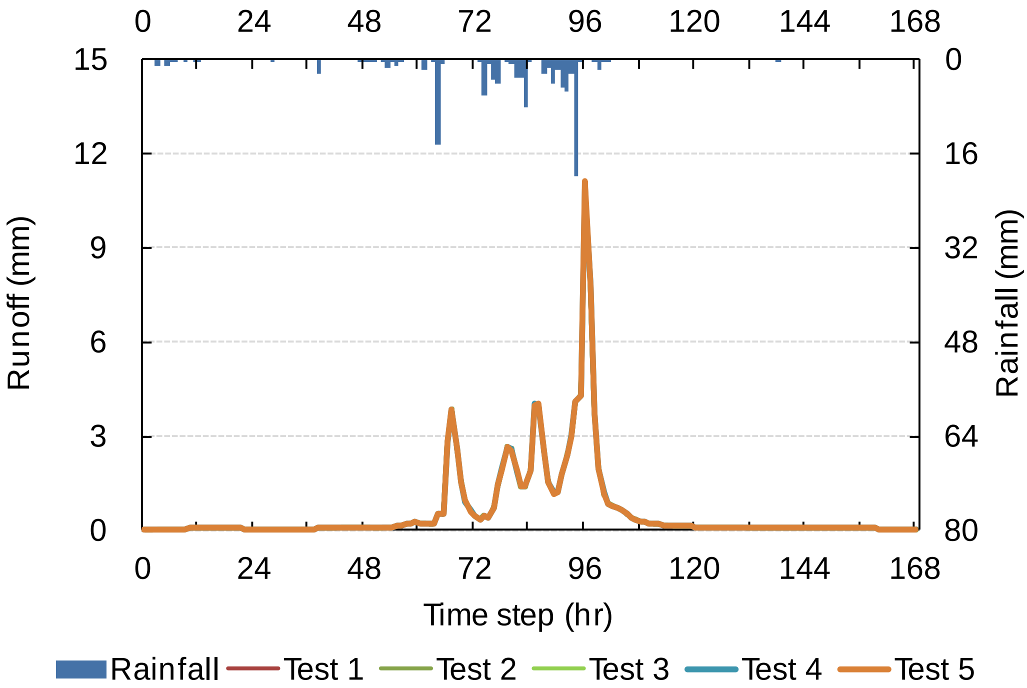


**Figure 4.3** Hydrograph results of a stability test of the distributed TOPMODEL.

### 4.2.2 Method of model calibration and validation

The distributed TOPMODEL is tested in the catchment of Trout Beck in this section through the procedure of calibration and validation. An approach from the GLUE (the generalised likelihood uncertainty estimation) framework is introduced for this procedure. In order to assess the uncertainty which is inherent in any hydrological simulation (Cameron et al., 1999), the GLUE framework was established by Beven and Binley (1992). The GLUE method rejects the concept of an optimum or best parameter set for a system, and all parameter sets are assumed to have an equal likelihood of being acceptable estimators of the system (Beven and Binley, 1992; Cameron et al., 1999). From a specified parameter space, many parameter sets are picked using Monte Carlo simulation. The performance of each parameter set is evaluated by likelihood measures to assess prediction of the parameter set. There is a rejection of some parameter sets as non-behavioural after the assessment. The acceptance of the existence of multiple behavioural parameter sets has been called equifinality (Beven, 1993), which should be accepted as a generic problem in modelling rather than simply reflecting the problem of identifying the "true" model in the face of uncertainty (Cameron et al., 1999). This framework is widely used to estimate uncertainty and evaluate results in hydrological modelling (e.g.

Aronica et al., 2002; Blasone et al., 2008; Franks et al., 1998; Freer et al., 1996; Immerzeel and Droogers, 2008; Shen et al., 2012).

Around 300 of model runs were completed for preparation of the test in this chapter. Because of the time-consuming run of the distributed TOPMODEL, the number of simulation runs for calibration and validation must be limited. Thus, the three crucial parameters of $m$, $K$, and $k_v$ in distributed TOPMODEL are only taken into account in the test process. $m$ is the active depth for subsurface flow; $K$ is a 'notional' hydraulic conductivity of soil in the model ($K \times m$ is the transmissivity). $m$ and $K$ are key parameters for the generation of subsurface flow and overland flow. $k_v$ is the velocity parameter of overland flow which controls the speed of overland flow movement. These three parameters are the most important ones to impact timing of water delivery in catchments and the hydrograph at the outlet in the model. Due to the shortage of field observations of these parameters, they are assumed to be homogeneous throughout the catchment for the purposes of the test.

The experience from other TOPMODEL applications (Beven, 1997; Kirkby, 1997) can be used to narrow the parameter space and so restrict the number of calibration runs needed. In order to avoid uneven distribution of parameter sets in parameter space caused by such a limited number of runs, the parameter sets are scanned systematically in the parameter space (as shown in Table 4.1), giving 90 sets of parameters for calibration.

**Table 4.1** Parameter space for the model calibration.

| Parameter | Parameter ranges | | |
|---|---|---|---|
| | Lower value | Upper value | Increment |
| $m$ (m) | 0.003 | 0.018 | 0.003 |
| $k_v$ | 10 | 50 | 10 |
| $K$ (m/hr) | 100 | 300 | 100 |

$m$ is the soil depth parameter; $k_v$ is the velocity parameter of overland flow; $K$ is a hydraulic conductivity of soil.

Comparing the simulated hydrographs with the observed one, the Nash-Sutcliffe efficiency (the measure of likelihood) of each simulation result was calculated. The 20% of simulated hydrographs with the highest efficiency are then used to compose an envelope band of hydrographs which is compared to the observed runoff through the calibration period.

These top 20% parameter sets were picked to run the model through the validation period. The same top 20% of parameter sets were then used to created envelope bands of the validation storm and compared to the observed hydrograph of the validation period.

### 4.2.3 Result of calibration and validation

For the flow calibration, the Nash-Sutcliffe efficiency for each simulation run is computed to measure the likelihood. Figure 4.4 shows the Nash-Sutcliffe efficiency distribution against the parameter *m* and *Kv* for *K* = 100 m $hr^{-1}$, and the highest values of efficiency are located within the orange envelope area.

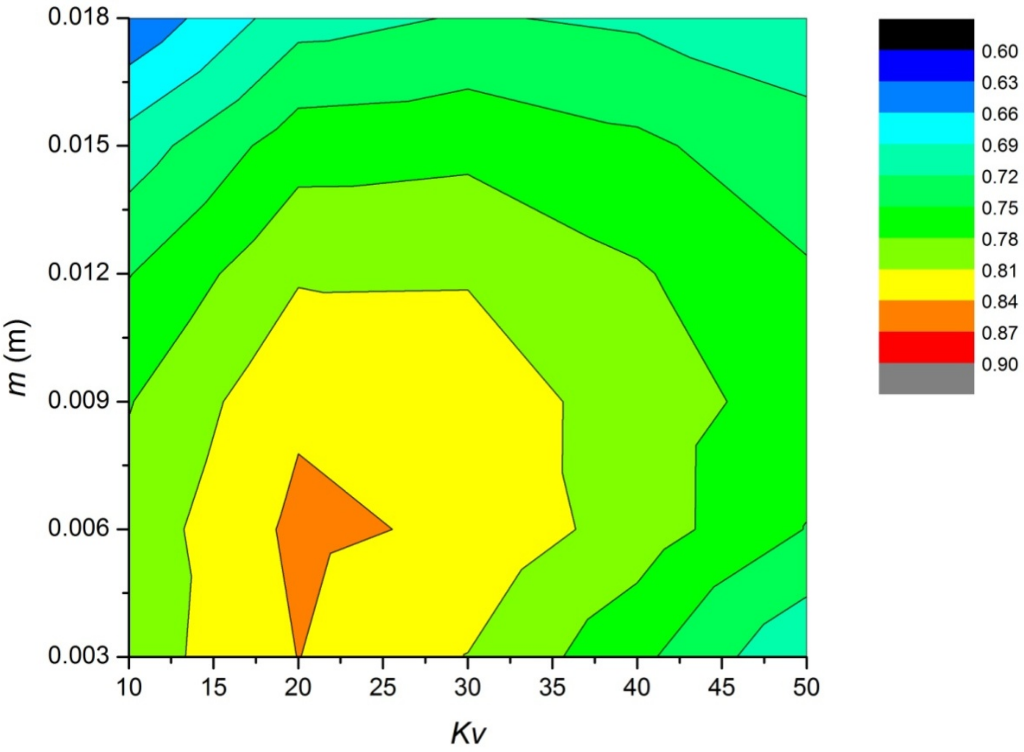


**Figure 4.4** Nash-Sutcliffe efficiency distribution of simulation runs with *K* = 100 m $hr^{-1}$ in calibration.

After completing the simulation runs using these calibration procedures, the top 20% hydrograph band is plotted in Figure 4.5. The Nash-Sutcliffe efficiency for the single best-fitted hydrograph, the upper boundary of the band, and the lower boundary of the band have been picked and calculated to represent the model performance during the calibration period, as shown in Table 4.2.

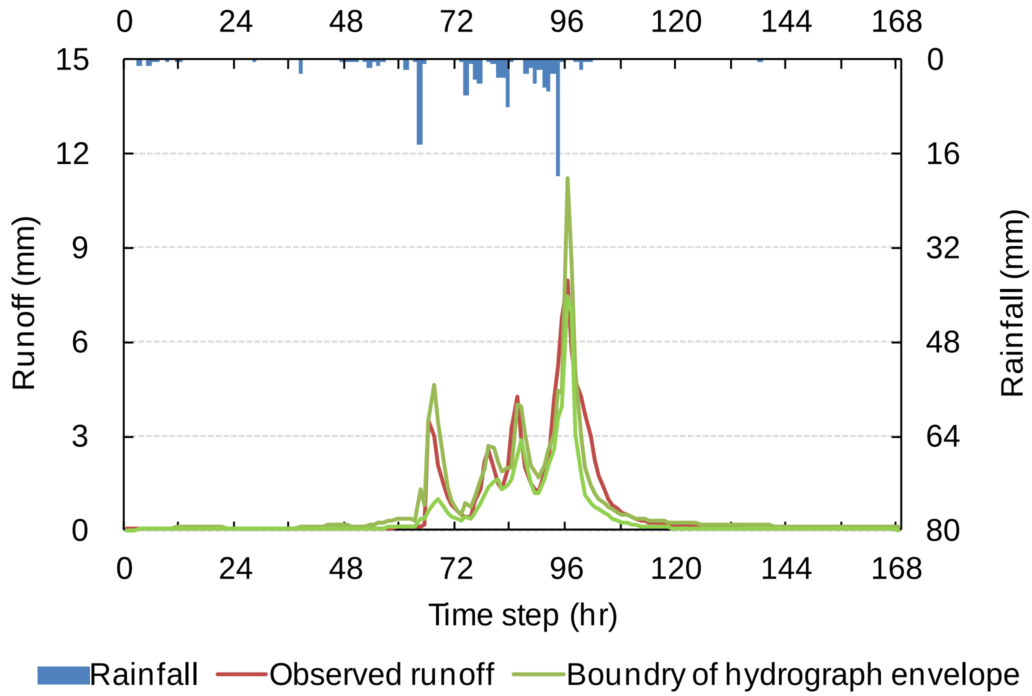


**Figure 4.5** Comparison of the observed runoff and the top 20% simulation hydrograph band in the calibration period.

**Table 4.2** Nash-Sutcliffe efficiency of the hydrograph band in the calibration.

| Hydrograph | Efficiency |
|---|---|
| Highest fitted hydrograph | 0.851 |
| Upper boundary | 0.833 |
| Lower boundary | 0.785 |

The top 20% parameter sets in the calibration are run in the model during the validation period. The band of resulting hydrographs is illustrated in Figure 4.6, and the Nash-Sutcliffe efficiency of the representative curves is shown in Table 4.3.

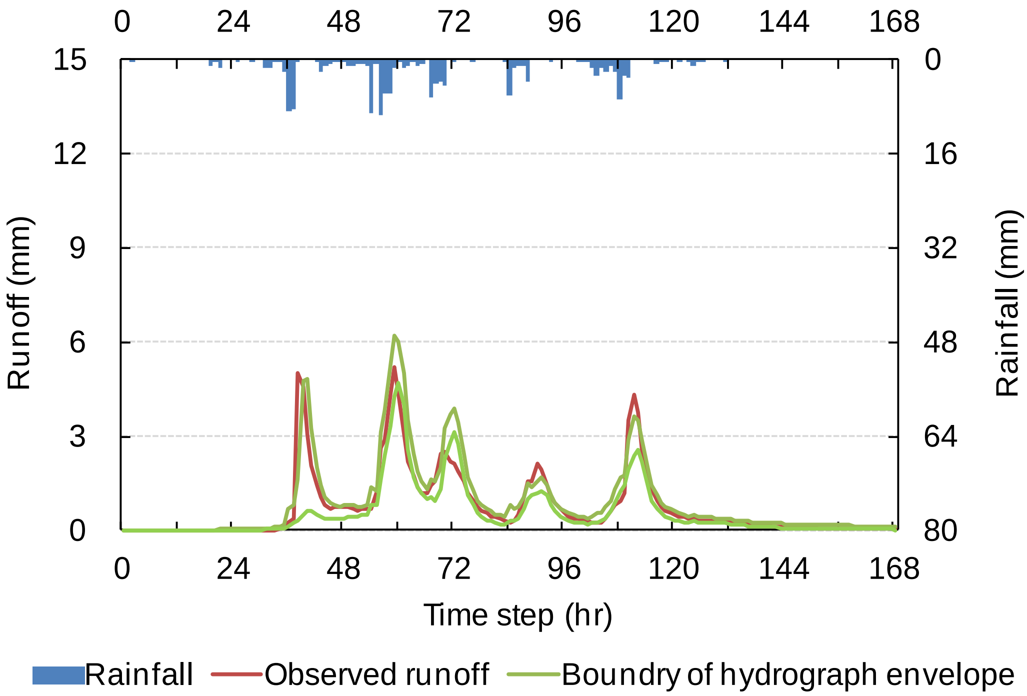


**Figure 4.6** Comparison of the observed runoff and the hydrograph band in the validation period.

**Table 4.3** Nash-Sutcliffe efficiency of the hydrograph band in the validation.

| Hydrograph | Efficiency |
|---|---|
| Highest fitted hydrograph | 0.833 |
| Upper boundary | 0.778 |
| Lower boundary | 0.644 |

The model performance is satisfactory in the testing process since the Nash-Sutcliffe efficiency of the top 20% simulations in the calibration is over 0.78, and that in validation is more than 0.64. The two hydrograph bands of calibration and validation span most of the observed hydrographs in the two periods. This test result demonstrates that the distributed TOPMODEL can simulate runoff well for the Trout Beck catchment. The distributed TOPMODEL performances are compared to the original version of TOPMODEL in the next section.

## 4.3 Comparison of the distributed TOPMODEL and the original TOPMODEL

To compare the distributed TOPMODEL to the original TOPMODEL, the same modified GLUE procedure has been applied to the Trout Beck catchment data with the same storm events for calibration and validation, applying the original version of TOPMODEL. The physical means of *m* and *K* are same as those in the distributed TOPMODEL. *v* is the uniform velocity of runoff. All three parameters are homogenous for the catchment due to the lumped configuration of the original TOPMODEL. Parameter ranges of *m* and *K* are kept from the test in the distributed TOPMODEL, and Table 4.4 shows the parameter space for the original TOPMODEL, in which there are 90 parameter sets.

**Table 4.4** Parameter space for the calibration of the original TOPMODEL.

| Parameter | Parameter ranges | | |
|---|---|---|---|
| | Lower value | Upper value | Increment |
| *m* (m) | 0.003 | 0.018 | 0.003 |
| *V* (m/hr) | 800 | 1600 | 200 |
| *K* (m/hr) | 100 | 300 | 100 |

After modelling runs for calibration, the hydrograph band constituted with the top 20% efficiency results is illustrated in Figure 4.7. Using these top 20% parameter sets in flow validation, the hydrograph band is produced as plotted in Figure 4.8. Table 4.5 shows the Nash-Sutcliffe efficiency of the hydrograph bands in the calibration and validation runs.

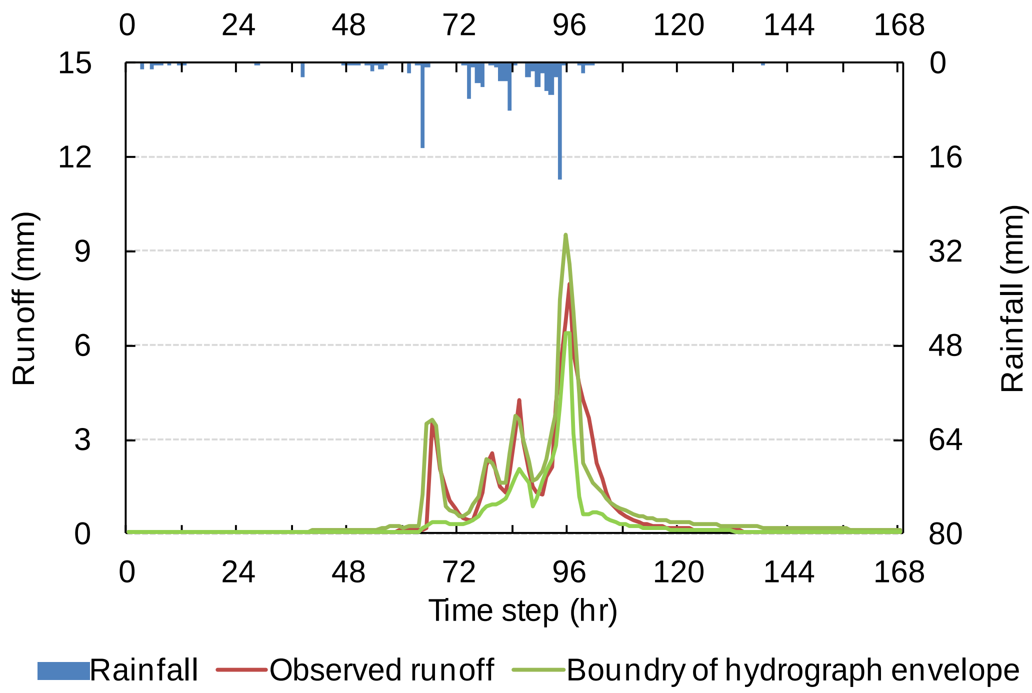


**Figure 4.7** Comparison of the observed runoff and the top 20% simulation hydrograph band in calibration period for the original TOPMODEL.

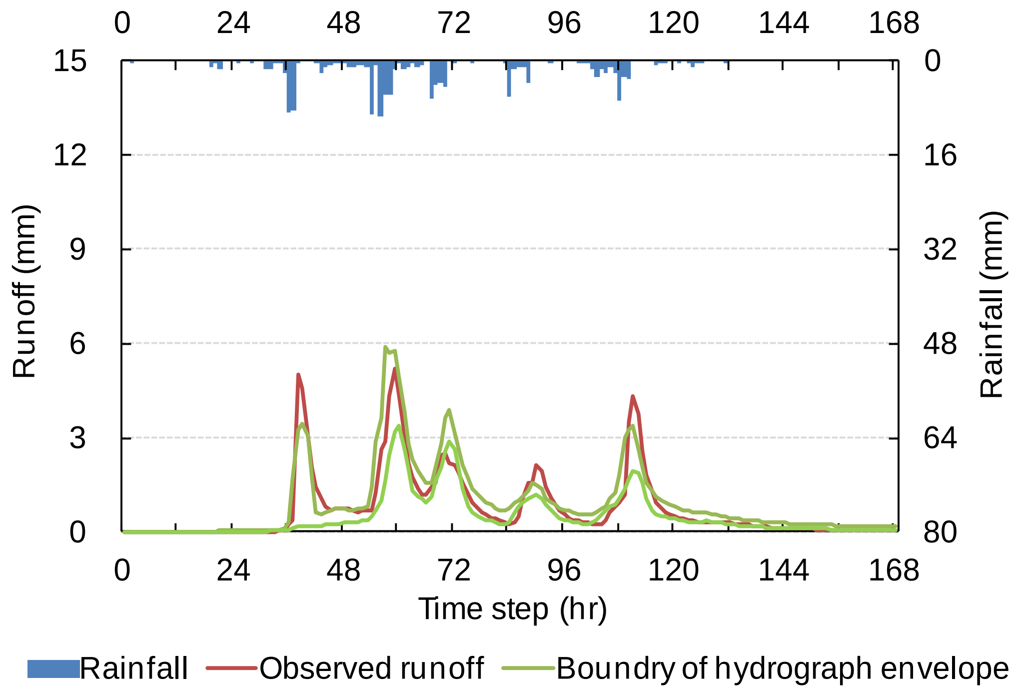


**Figure 4.8** Comparison of the observed runoff and the hydrograph band in validation period for the original TOPMODEL.

**Table 4.5** Nash-Sutcliffe efficiency of the hydrograph band in the calibration and validation for the original TOPMODEL.

| Hydrograph | Calibration efficiency | Validation efficiency |
|---|---|---|
| Highest fitted hydrograph | 0.860 | 0.797 |
| Upper boundary | 0.853 | 0.772 |
| Lower boundary | 0.683 | 0.533 |

Comparing the test results of the distributed TOPMODEL and the original TOPMODEL, the calibration hydrograph bands are quite similar for the two models. The Nash-Sutcliffe efficiency of the highest fitted hydrograph and the upper boundary in the results of the original TOPMODEL is slightly better than the distributed model. However, for the validation results, the hydrograph band of the distributed TOPMODEL envelopes more parts of the observed hydrograph. Nash-Sutcliffe efficiency of all three representative curves for the band of the distributed TOPMODEL is distinctly better than that for the original TOPMODEL (see Table 4.6). This comparison implies that the new distributed TOPMODEL performed better than the original version in this catchment, and the distributed configuration and the new overland flow module seem to improve the model's ability to predict river flow. Clearly this is in addition to the benefits developed in chapter 3 including the spatial distribution and the fact that users of the new model can also determine overland flow volumes and velocities across any point in the catchment for each time step used.

**Table 4.6** Comparison of result hydrograph bands of the distributed TOPMODEL and the original TOPMODEL for the validation period.

| Hydrograph | Validation efficiency | |
|---|---|---|
| | The distributed TOPMODEL | The original TOPMODEL |
| Highest fitted hydrograph | 0.833 | 0.797 |
| Upper boundary | 0.778 | 0.772 |
| Lower boundary | 0.644 | 0.533 |

However, the cost of the distributed model is time of model runs. The simulation of the distributed TOPMODEL takes about 20 min per run (a simulation week) using an Intel i7 Processor (4 core 2.0 GHz), while the original one takes less than 2 seconds for a run. In the distributed TOPMODEL, actual running time consumed for an individual modelling time step mainly depends on the overland flow contributing area which is related to the rainfall amount in the current time step and the overland flow contributing area formed in the previous time steps. A larger contributing area means that more cells are under calculation for the overland flow routing and re-infiltration in the overland flow module, and that, for an individual cell in the contributing area, the overland flow route has more chance to be extended. These distributed overland flow calculations are more time-consuming than the subsurface flow calculation.

## 4.4 Summary

In this chapter, the distributed TOPMODEL is tested with a modified GLUE method for real summer storm events in the upland peat catchment of Trout Beck. The model behaves reliably for simulating flow in both calibration and validation periods. Comparison of the distributed TOPMODEL with the original TOPMODEL using the same calibration and testing procedures indicates that the distributed TOPMODEL is more robust than the distributed TOPMODEL in the simulation under summer storm events. Therefore, the distributed TOPMODEL will be employed for land cover scenario experiments in next chapter.

# Chapter 5
# Land cover scenarios

## 5.1 Introduction

UK upland peatland catchments are often dominated by sedges such as *Eriophorum*, shrubs such as *Calluna* and mosses such as *Sphagnum*. These vegetation cover types have their unique characteristics (e.g. vegetation density) by which they influence overland flow movement (Holden et al., 2008). Many land management practices may change these land cover types and patterns (Holden et al., 2007b) in some extreme cases changing vegetated land to bare peat. There is extensive bare peat in many locations in headwater catchments in the UK uplands (Holden et al., 2007c). These changes may generate significant impacts on river flow in upland peatland catchments. Thus, this chapter aims to locate these hydrological impacts of land cover change and gives suggestions as to possible land management interventions for flood reduction in headwater peatland catchments.

In previous chapters, the distributed TOPMODEL has been established and tested and gives sound simulation in the 11.4 $km^2$ Trout Beck catchment. More importantly, the model shows adequate sensitivity to different types of land cover and the overland flow module, even though it contains a statistic-based algorithm for surface flow routing for individual cells, produces stable modelling results at the catchment outlet in short time steps (e.g. 0.1 hr interval). Indeed it can still maintain the stability using a shorter time interval and smaller area but this is out of scope for this research project. It is now possible with the model to simulate and investigate subtle aspects of overland flow processes on hillslopes, the land cover impact on overland flow and the consequent hydrograph changes in river channels.

To model the impact of land cover change in upland blanket peat on downstream flow, different types of scenarios are needed to represent different land-cover patterns. In this chapter, groups of land-cover scenarios, designed based on three main hypotheses given below, are modelled by the distributed TOPMODEL to investigate how the differences of land-cover patterns impact the hydrograph at the catchment outlet. The work helps to locate which parts of the catchment might be most contributory to peak flow, and to establish an efficient method to evaluate land cover impacts on river flow. The three specific hypotheses have been formulated to test catchment response to land cover changes. These hypotheses are based on ideas from the ideas discussed in section 2.5 but have never been tested in headwater peatlands before. Each hypothesis has been 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.

Hypothesis (1): A wider bare peat buffer strip nearer to the river channels brings a higher peak and reduced delay to the peak; conversely, a wider buffer strip with higher density vegetation (e.g. *Sphagnum*) leads to a lower peak and postpones the peak. In both cases, buffer strips surrounding downstream channels have a greater effect than further upstream.

Hypothesis (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 catchment; 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 catchment outlet.

Hypothesis (3): Bare peat on steep slope areas, where overland flow predominantly moves faster, gives a faster response and higher peak value at the catchment outlet, while high density vegetation or re-vegetation on a steep slope area has a larger positive impact on peak river flow delay and reduces the size of peak flow.

General modelling settings and scenario formulation are presented in section 5.2. Scenario groups according to each hypothesis are presented and discussed respectively in sections 5.3, 3.4 and 5.5. Section 5.6 gives a summary of scenario results and the conclusion for this chapter. Around 150 different model runs were conducted to perform the work of this chapter.

## 5.2 Scenario setting

All land cover scenarios in this chapter are formulated based on the Trout Beck catchment (54.683° N, 2.383° W, 11.4 $km^2$) in Northern England; the upland peatland catchment referred to in previous chapters. Around 90% of the catchment area is covered by blanket peat.

For scenario formulation, the complicated status of land cover in the catchment is simplified resulting in a uniform *Eriophorum*-covered scenario which is treated as a ‘normal’ condition in the experimental scenario runs (in fact, *Eriophorum* dominates the vegetation cover in the catchment). This normal scenario is applied as a standard to evaluate the modelling results of other land cover scenarios in this chapter. Other land cover change scenarios are created by changing part of the *Eriophorum* land cover to other types of vegetation cover. The overland flow parameter (i.e. a vegetation-roughness-related parameter defined in chapter 3) of *Eriophorum* cover is defined as the standard for all types of vegetation cover, and the relative overland flow parameter to this standard parameter is used for each type of vegetation. 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.

There are many groups of land cover scenarios respectively focusing on the three hypotheses of land cover change impact, so each group is deliberately formulated to represent an aspect of a hypothesis in the experimental design. To represent the land cover change, some scenarios include bare peat areas in which the overland flow velocity parameter is five times greater than the normal scenario while other scenarios contain a *Sphagnum* area in which the overland flow velocity parameter is half that of the normal one. This relationship between the overland flow velocity parameter (a type of roughness parameter) of *Sphagnum*, *Eriophorum*, and bare peat is based on the research of Holden et al. (2008). Land cover change over 5 to 20% of the catchment area will be mainly evaluated in this chapter, rather than a larger proportion of the catchment which might not practically represent likely real land cover change. Tens of scenarios were tried to find suitable patterns of land cover type and a suitable proportion of the catchment for each scenario group. The selected different patterns of scenarios will be compared and analysed within the same scenario group to examine their differing impacts on river flow and the factors associated with these impacts Comparisons of scenario peak flows are reported to the nearest percent, quoting, for example, how a scenario peak is 6% higher than the normal peak.

A one hour rainfall pulse with a uniform rate of 20 mm $hr^{-1}$ (2 mm per 6-min) is the precipitation input used in scenario modelling runs. This is similar to the greatest hourly rainfall rate in the storms, which are summer events, in the Trout Beck rainfall record and which were used in the calibration and validation periods for the distributed TOPMODEL in the last chapter. This simple pattern of precipitation helps to track the possible tiny differences in modelling responses of various scenarios.

For time series of scenario modelling the time step is set as 0.1 hr to identify possible minor differences between scenario results. There is a 10-step warming-up stage for the model at the very beginning of the scenario run prior to a 10-step constant rainfall event. Another 80 steps follow the storm in the entire modelling period of 100 time steps. Most scenario hydrographs shown within the figures in this chapter just present the first 60 time steps to focus on the rising and falling limbs around peak time and ignore the last 40 steps which just contain the very low level recessional part of the hydrographs. The catchment outlet flow at the start in each case is set as annual average flow volume, and there is no overland flow on the hillslope at the starting time step. All these settings, including parameter set and time series, will be employed in all scenario modelling runs in order to retain consistency and convenience of scenario comparison and analysis throughout this chapter.

A set of model parameters, by which the result from the simulation gives good fitness (> 0.8) in terms of Nash-Sutcliffe efficiency in modelling tests in the last chapter, is picked as the practical parameter set to be used in all scenario modelling runs.

## 5.3 Buffer strip scenarios

From hypothesis (1), this section aims to evaluate the impact of land cover change in buffer strips on river flow. The buffer strip mentioned in this section is a band with different land covers (bare peat or *Sphagnum*) compared to the ‘normal’ condition (*Eriophorum*), and every section of the strip has a similar position on the hillslope or relative to the river channel. Riparian buffer zones are common in hydrological and ecological research works (e.g. Burt et al., 1999; Cirmo and McDonnell, 1997; Gregory et al., 1991; McGlynn and Seibert, 2003) but it is also useful to understand whether slope position matters for buffer strips when it comes to flood flow generation in blanket peat. Given hypothesis (1), the impact on river flow of the buffer strip size, buffer strip position on the hillslope, and the size of channel branch matched to the buffer zone, will be demonstrated by various groups of land cover scenarios, in which the buffer strip may be covered by high-density *Sphagnum* or by bare peat versus *Eriophorum*-covered parts of the catchment under ‘normal’ conditions.

### 5.3.1 Riparian buffer strip scenarios

The riparian buffer zone is the nearest strip to the river channel, and is the. It is the last land surface that overland flow passes prior to entering the river channel. Runoff from riparian zones often dominates between storm events, throughout small runoff events and in the rising limb of large events

(McGlynn and McDonnell, 2003). A well-vegetated riparian buffer zone may largely mitigate the loss of sediment and nutrients from water flow through the processes of deposition, absorption and de-nitrification (Burt et al., 1999; Cirmo and McDonnell, 1997; Grabs et al., 2012; Surridge et al., 2007). Moreover, the riparian buffer zone is also essential for good ecological functioning of the aquatic and surrounding terrestrial ecosystem in a catchment (e.g. Gregory et al., 1991).

For peatland catchments, saturation-excess overland flow dominates storm flow (Holden and Burt, 2003b). The riparian buffer zone is considered to be a significant contributing area of saturation-excess overland flow in a storm event and thus vulnerable to vegetation degradation and soil erosion in peatlands. Modelling the bare buffer zone scenario and the well-vegetated scenario is beneficial to understanding how the buffer zone affects overland flow processes and river flow in peatland catchments.

It is normally believed that a riparian buffer zone with high density vegetation can mitigate in-situ overland flow production. However, for catchment outlet flow, it is still not quite clear how much the riparian buffer zones with various land cover types affect river flow in blanket peat peatland, especially considering the synchronization of surface water movement. Thus, a series of buffer zone scenarios of differing buffer strip size were created to examine the impacts of riparian buffer zones. Each scenario has a riparian buffer strip with a different area (5%, 10%, and 20% area of the whole catchment, respectively), which is assumed to be covered by bare peat or *Sphagnum* with other parts of the catchment remaining in normal condition (see Figure 5.1). These scenario buffer strips close to the river channel are not designed to represent the natural riparian buffer zone around the river in the catchment. They may partly cover the area of the hillslope and are formulated to investigate the change of overland flow field in near river areas and its influence on river flow. The main river channel that was chosen in the catchment to be surrounded by the buffer zone is comprised of cells of which the accumulative upslope area is greater than 1.2 $km^2$ (it equals 3000 cells in DEM map which is identical to the topographic data used in previous chapters). The impact of other river channel sections being chosen will be discussed in section 5.3.3.

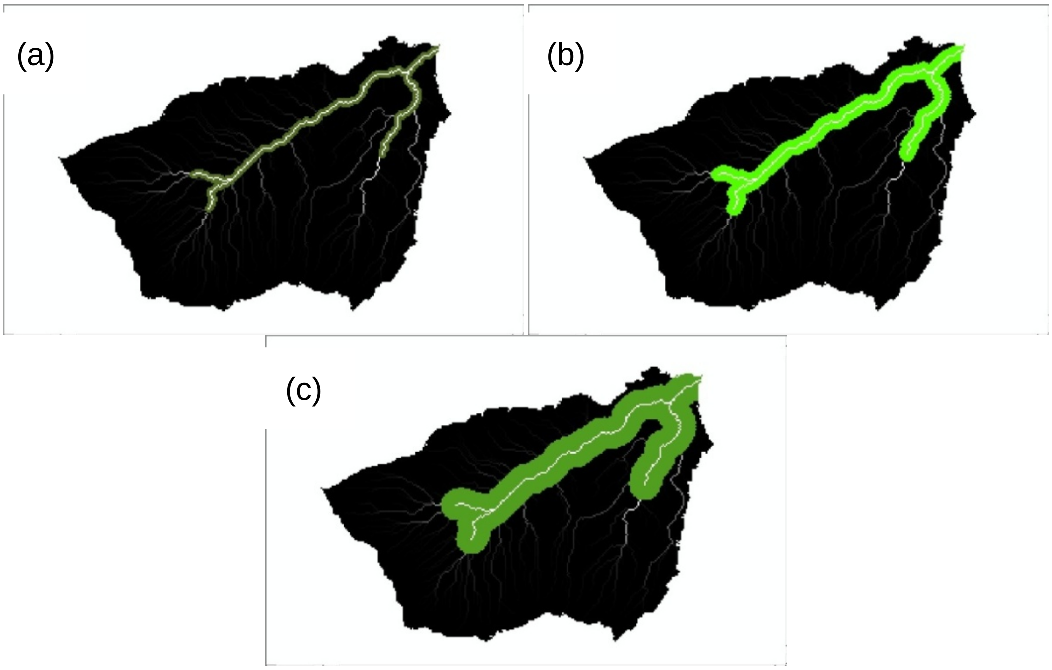


**Figure 5.1** Scenarios of riparian buffer zones with a different proportional area of the catchment; (a) 5% area, (b) 10% area, (c) 20% area.

In the first group of riparian buffer strip scenarios, buffer strips are assumed to be covered by bare peat removing all vegetation from buffer strips. Comparing the simulation result of the normal scenario, in which nothing is removed or changed for land cover, with the buffer zone scenario modelling outcome it is possible to quantify how much the river flow is affected by the absence of riparian buffer zone vegetation. Meanwhile, this comparison may equivalently be seen to be a quantitative assessment of the benefits of restoring vegetation on areas of bare peat close to river channels.

From the scenario modelling result (Figure 5.2), the bare peat strip increases peak flow and pushes peak time forward. A larger bare peat strip scenario clearly produces an earlier flow peak than smaller ones. Faster overland flow driven by bare peat in the catchment near the main channel stem means surface water has less time to stay on the hillslope prior to reaching the river channel, so overland flow has less opportunity to re-infiltrate into ground, becoming subsurface flow which is much slower than surface flow. Thus, more bare peat area means more overland flow and then quicker response flow in the river channel. The rising limb of each hydrograph for the bare buffer strip scenario is about two time steps earlier than the normal one, and the more bare peat the strip has, the earlier rising limb it gives.

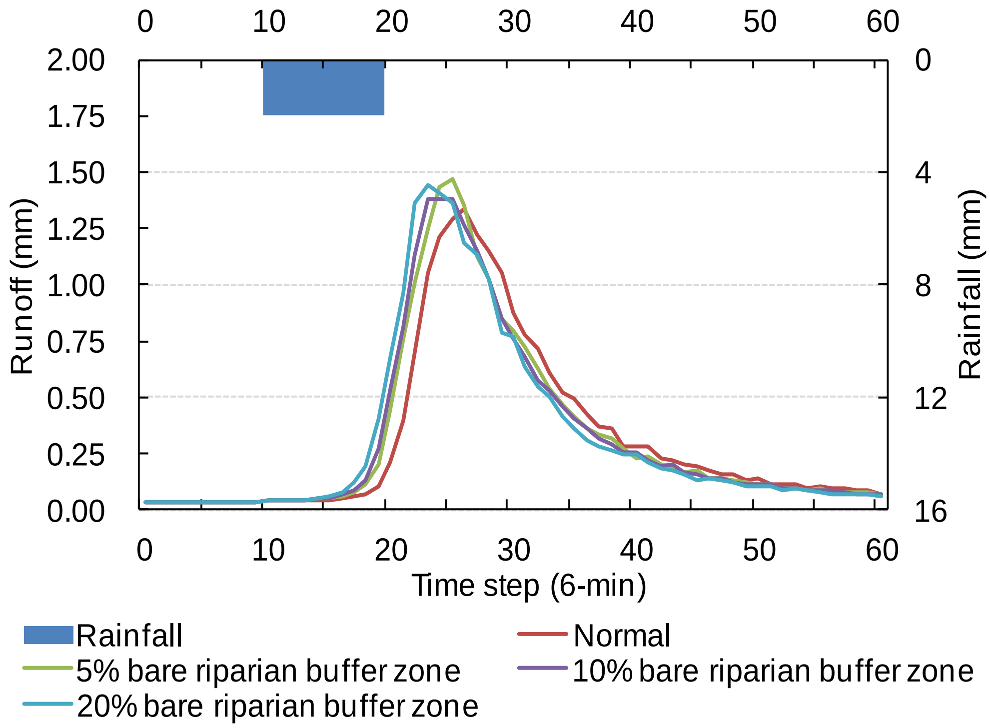


**Figure 5.2** Hydrographs of the bare riparian buffer strip scenario group.

However, as Figure 5.2 shows, the larger bare peat strips may not always give the greatest peaks (e.g. 10% scenario versus 5% scenario). This could be due to the synchronization of overland flow concentration, even though the 10% scenario has an earlier peak than the 5% one. The riparian buffer strip may not break the original synchronism of overland flow concentration on the hillslope due to its down slope position near to the stream channel which is the last place where concentrated overland flow moves through. The narrow riparian buffer strip (5% bare area scenario) affects overland flow only close to the channel, so it has the least opportunity to impact overland flow synchronism. Yet, it still influences overland flow prior to the stream channel. However, it may be that much bigger riparian bare strips (e.g. area proportion >20%) may bring earlier and bigger peak flows.

Another scenario, which contains an outer buffer strip with a 10% bare peat area (see Figure 5.3) is introduced to be compared with other riparian bare buffer scenarios. In the modelling result (see Figure 5.4), it appears that the bare area closest to the channel has more impact on river flow. The 10% area buffer strip nearer to the river channel gives an earlier peak than the 10% outer bare strip scenario, even though they have an identical area of the bare strips. Moreover, the hydrograph of the 10% outer bare buffer strip scenario produces a peak even later than that of the 5% bare riparian buffer zone scenario. These results show that the 5% bare area close to the river channel plays a very key role in changing river flow. Meanwhile, it implies that the buffer strip position may also conspicuously impact river flow, which will be discussed in section 5.3.2.

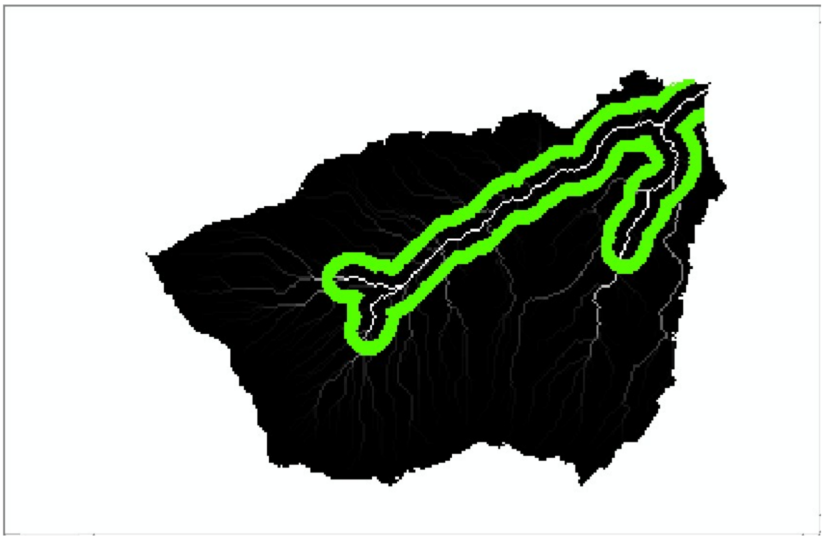

**Figure 5.3** Scenario of 10% outer bare peat buffer strip.

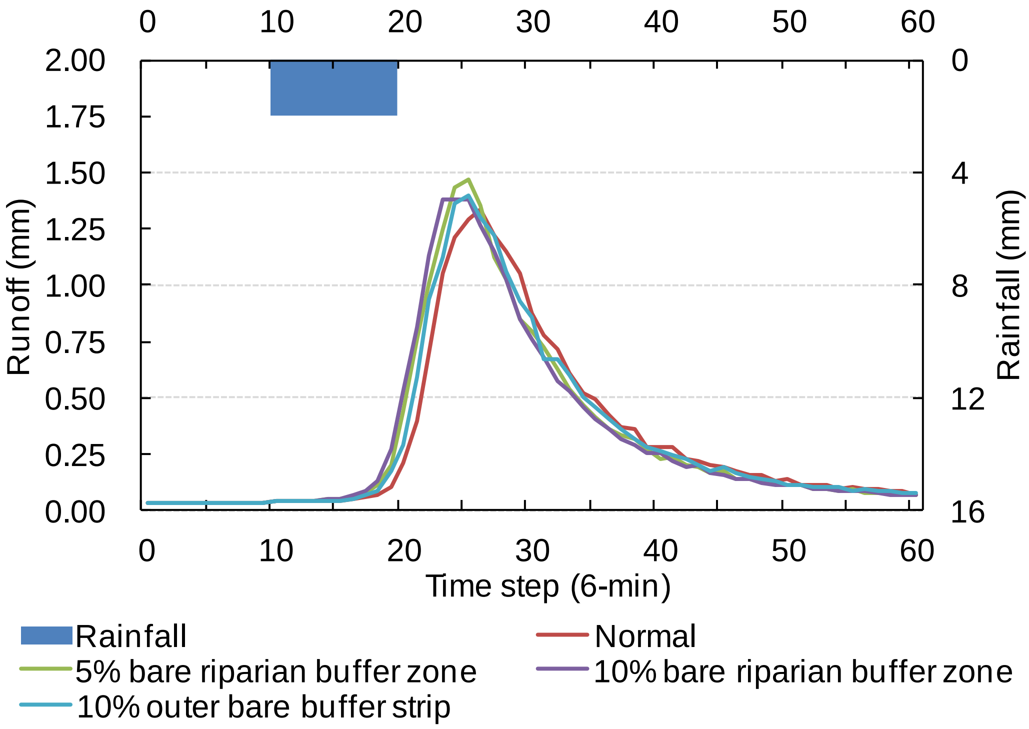


**Figure 5.4** Hydrographs of riparian and outer bare peat buffer strip scenarios.

In another group of scenario simulations, buffer strips where land cover is changed to high density *Sphagnum* are used to check whether high intensity restoration has a strong effect on the hydrograph. The results from the simulation (see Figure 5.5) indicate that *Sphagnum* strips definitely reduce and delay river flow peaks and a larger *Sphagnum* strip scenario produces a later and lower flow peak than a smaller *Sphagnum* strip.

Overland flow on the *Sphagnum* area, contrary to the bare peat area, is slower than that in a normal condition and thus there is more time to transport flow on the land surface and then more chance for water to infiltrate into the soil to become subsurface flow. This delays the catchment response to rainfall and lowers the peak flow in the river.

The size of the *Sphagnum* riparian buffer strip influences river flow. A larger buffer strip gives more effect, which is consistent with hypothesis (1). On the other hand, the buffer strip position may be influential in land cover change impacts on stream flow as mentioned earlier in this section, which involves another aspect of hypothesis (1). The next section will discuss the issue of buffer strip position.

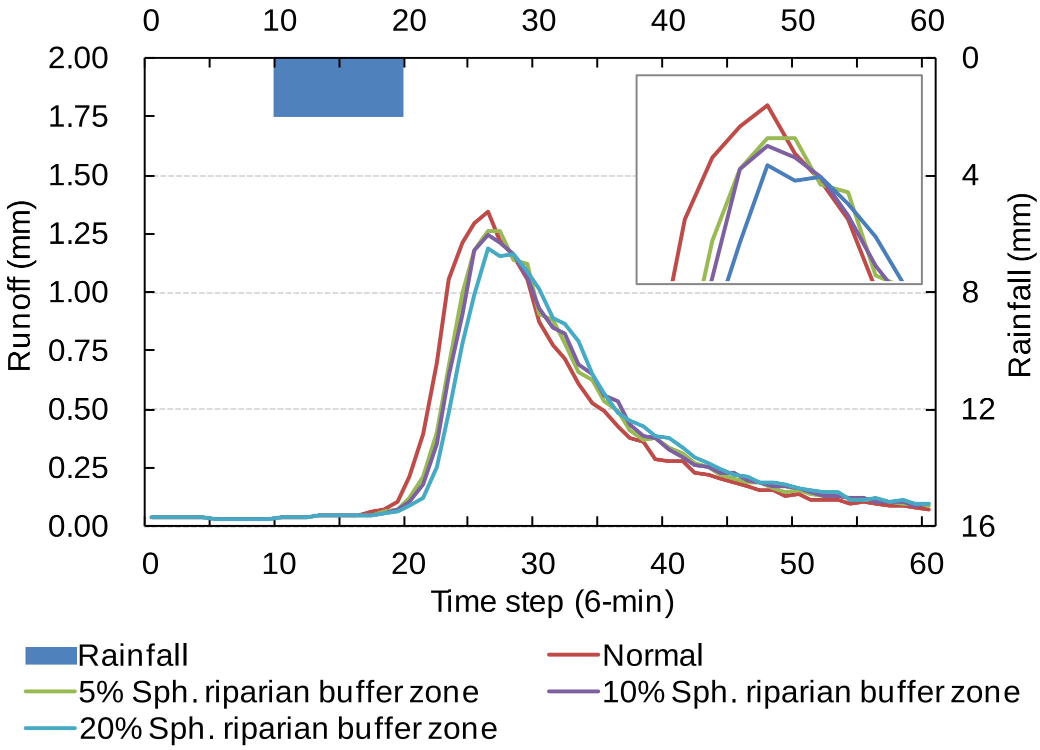


**Figure 5.5** Hydrographs of the riparian *Sphagnum* buffer strip scenario group.

### 5.3.2 Impact of hillslope position of the buffer strip

This section aims to check part of hypothesis (1), discussing the impact of the buffer strip position on stream flow at the catchment outlet. As shown above, land cover change on riparian buffer strips strongly impacts river flow in the Trout Beck catchment. We now turn to whether land cover change on the riparian buffer strip gives the largest effect on stream flow in a peatland catchment compared to more distant buffer strips from the main channel stem.

A group of scenarios representing riparian buffer strips, mid-hillslope (or mid-catchment), and headwater buffer strips, respectively, in the Trout Beck catchment (10% area see Figure 5.6, and 20% area see Figure 5.7) are organised to model their hydrological performance and then to illustrate the influence of buffer strip position. Both bare peat buffer strips and *Sphagnum* buffer strips will be modelled and analyzed in this scenario group.

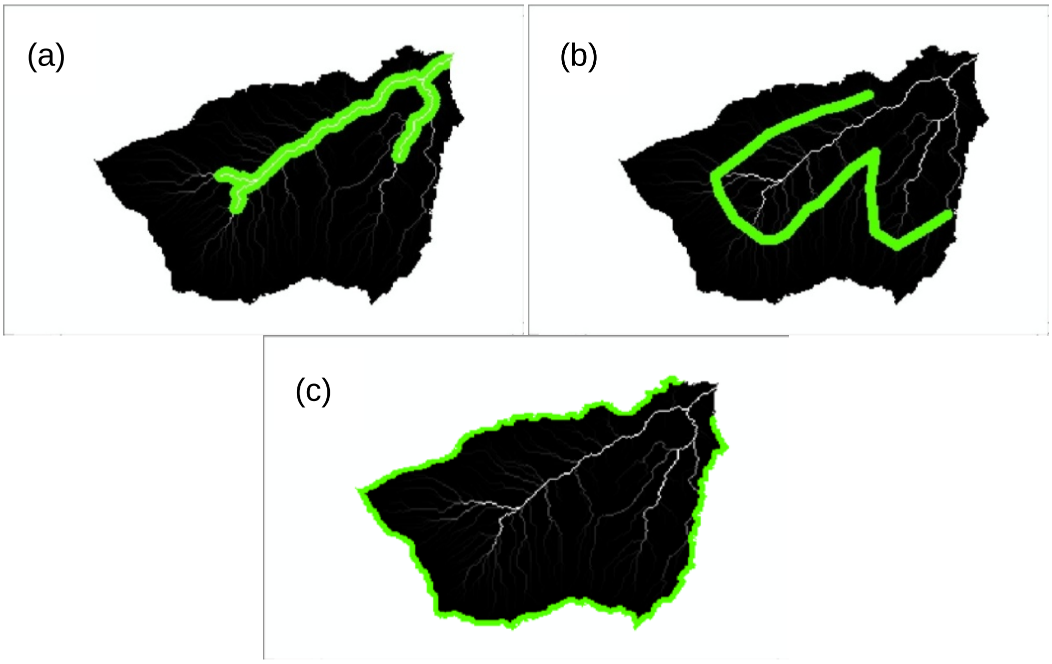


**Figure 5.6** Scenarios of buffer strips with a 10% area in different positions on the hillslope: (a) riparian buffer strip, (b) mid-catchment buffer strip, (c) headwater buffer strip.

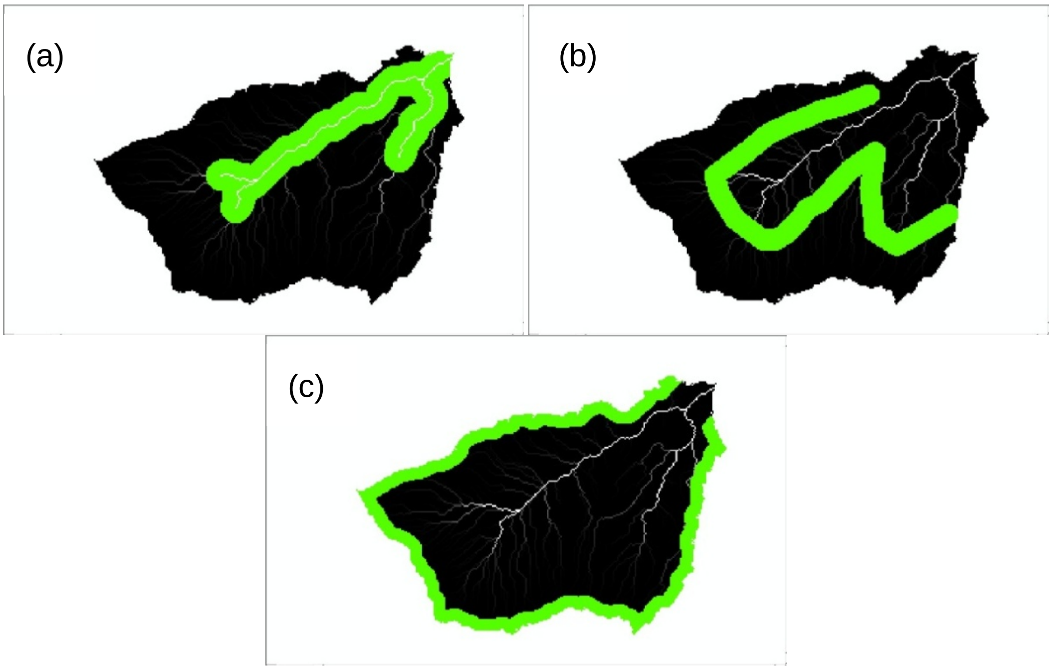


**Figure 5.7** Scenarios of buffer strips with a 20% area in different positions on the hillslope: (a) riparian buffer strip, (b) mid-hillslope buffer strip, (c) headwater buffer strip.

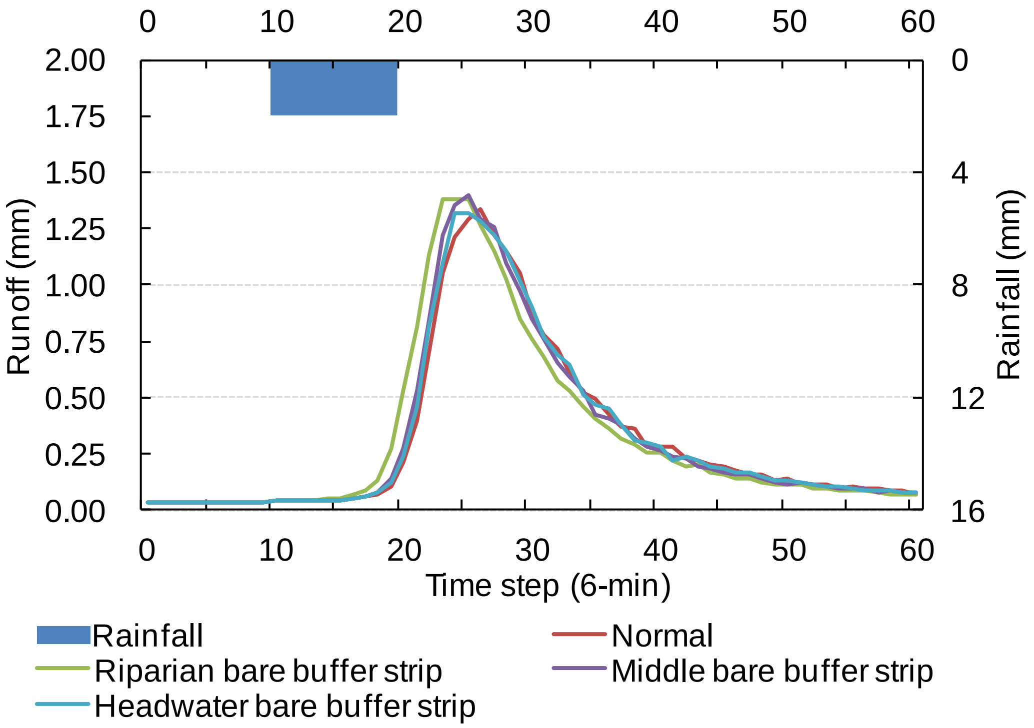


**Figure 5.8** Hydrographs of 10% area bare peat buffer strip scenarios in different positions.

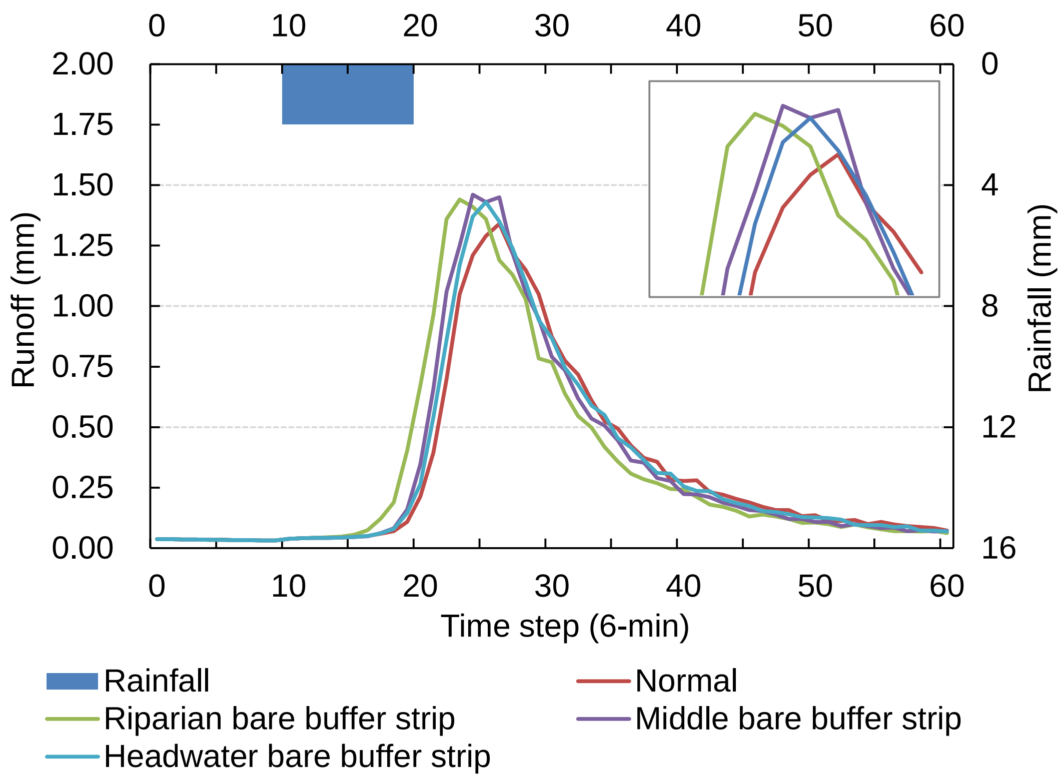


**Figure 5.9** Hydrographs of 20% area bare peat buffer strip scenarios in different positions.

From the hydrographs of the bare peat buffer strip scenarios (see Figure 5.8 for 10% bare peat area, and Figure 5.9 for 20% bare peat area), the riparian bare peat buffer strips result in much earlier rising limbs than those of the mid-slope and headwater buffer strips. Meanwhile, the riparian *Sphagnum* buffer strip has later rising limbs and lower peaks than those of the other two strips (as shown in Figure 5.10 for 10% *Sphagnum* area, and Figure 5.11 for 20% *Sphagnum* area). The mid-catchment buffer strips have a larger impact on river flow than the headwater ones, even though the difference is not as marked as the difference between the riparian buffer strips and the other two. The headwater buffer strips give the lowest impact on river flow, especially for *Sphagnum* land cover. Therefore, it can be concluded, at least for the case study catchment, that a buffer strip nearer to river channels has more influence on river flow, which supports hypothesis (1).

The mid-catchment buffer strips may break the land cover integration of the entire catchment and affect the synchronization of overland flow concentration on the hillslope. Hence, there seems to be a tendency that the middle buffer strips split their flow peaks to two peak points in the hydrographs of the two 20% area scenario sets (as shown in Figure 5.9 and Figure 5.11).

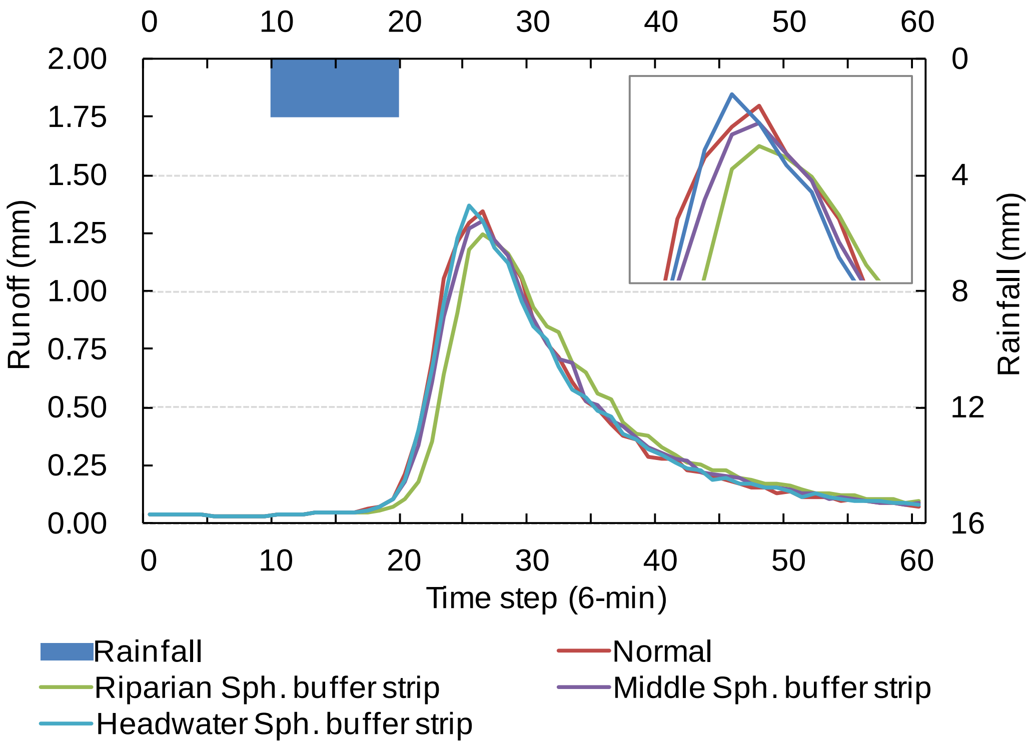


**Figure 5.10** Hydrographs of the 10% area *Sphagnum* buffer strip scenarios in different position.

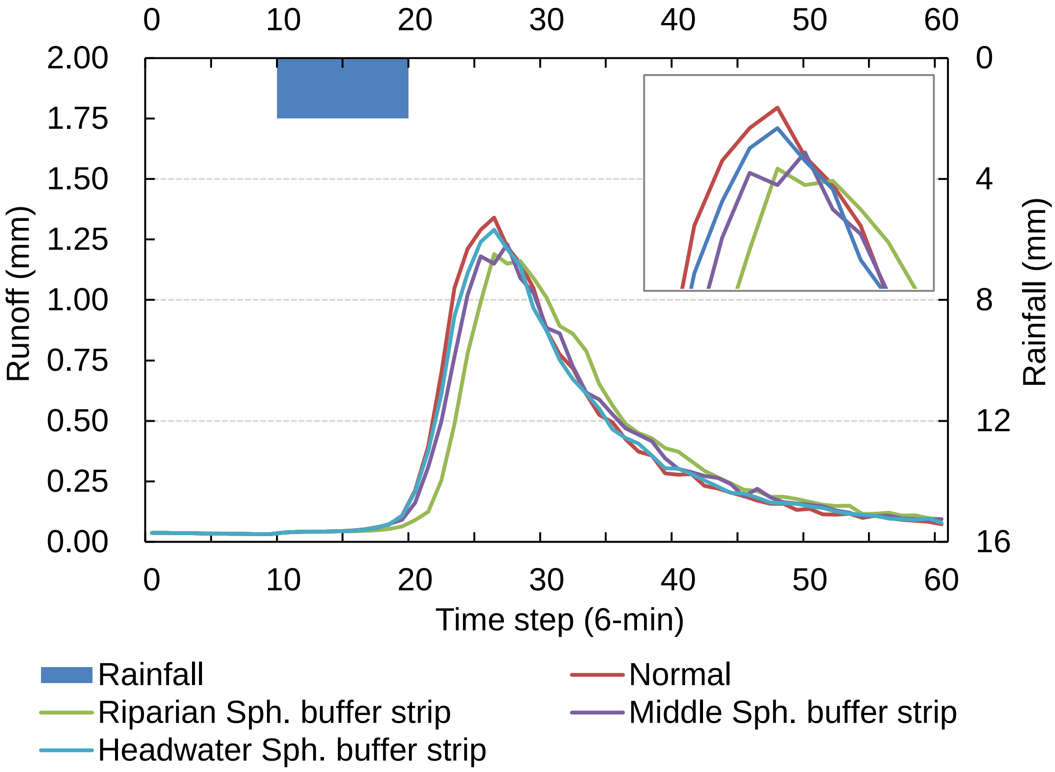


**Figure 5.11** Hydrographs of the 20% area *Sphagnum* buffer strip scenarios in different position.

Overall, the area close to the main stream is the most effective to diminish and delay the flood peak. Thus, the results from Trout Beck suggest that a buffer zone close to the stream channel is the most efficient area to relieve flood risk by re-vegetation in a peatland catchment.

The river channel network was chosen before the riparian buffer strip scenarios were formulated. However, different river channel sizes change the shape of the associated riparian buffer strips and may alter their impact on stream flow. The next section will focus on whether the stream channel network size affects the impact of the riparian buffer strip on river flow.

### 5.3.3 Riparian buffer strip scenarios based on river channel networks of varying branches

The riparian buffer strips, which have been shown to be influential in overland flow movement and river flow earlier in the chapter, are based on a chosen downstream part of the river channel network determined by a set upslope contributing area (see section 5.3.1). However, the broadness of river network which is surrounded by a riparian buffer zone (retaining the identical area for the buffer strip) may play a notable role in affecting stream flow. This last aspect of hypothesis (1) will be explored in this section.

In a peatland catchment, the stream channel network can be complicated with headwater gully streams that periodically flow. Different thresholds of accumulative upslope areas used to define a stream channel in a DEM means there can be many river channel network scenarios that are modelled. A high threshold gives a downstream network and a low threshold defines a broader and upslope-connected network. Therefore, there are some simple principles to select the threshold for the riparian buffer strip scenario formulation. If the threshold is too big (e.g. greater than $1.5km^2$), a very short and downstream channel network is defined and the matched riparian buffer strip may cover a large area near the catchment outlet in the 20% buffer strip scenario due to the constriction of the terrain near the outlet for the catchment of Trout Beck. This area may have a great proportion of hillslope area, which deviates from the original definition of the riparian buffer zone scenario. Conversely, providing a very small threshold (e.g. less than $0.05km^2$), there may be a very narrow buffer strip along an extended and broad channel network in the 10% area buffer strip scenario, which could be narrower than the resolution of the DEM data (20m×20m grid employed in this project) and hard to represent. Thus, a 3000-cell threshold and a 250-cell one, which do not lead to the negative situations mentioned above, were chosen in this group of scenarios as they still maintain a serviceable distinction of channel network patterns for the scenario comparison, while a 500-cell is selected as an intermediate threshold for a medium buffer strip scenario in this comparison group. Based on these three thresholds of channel networks, a group of scenarios representing riparian buffer strips surrounding different river channel networks was organised to assess their impacts on river flow. The patterns of the scenarios are illustrated in Figure 5.12 for a 10% area and Figure 5.13 for a 20% area. The buffer strips are also assumed to be covered by bare peat and *Sphagnum* for experimental scenario runs as in previous sections.

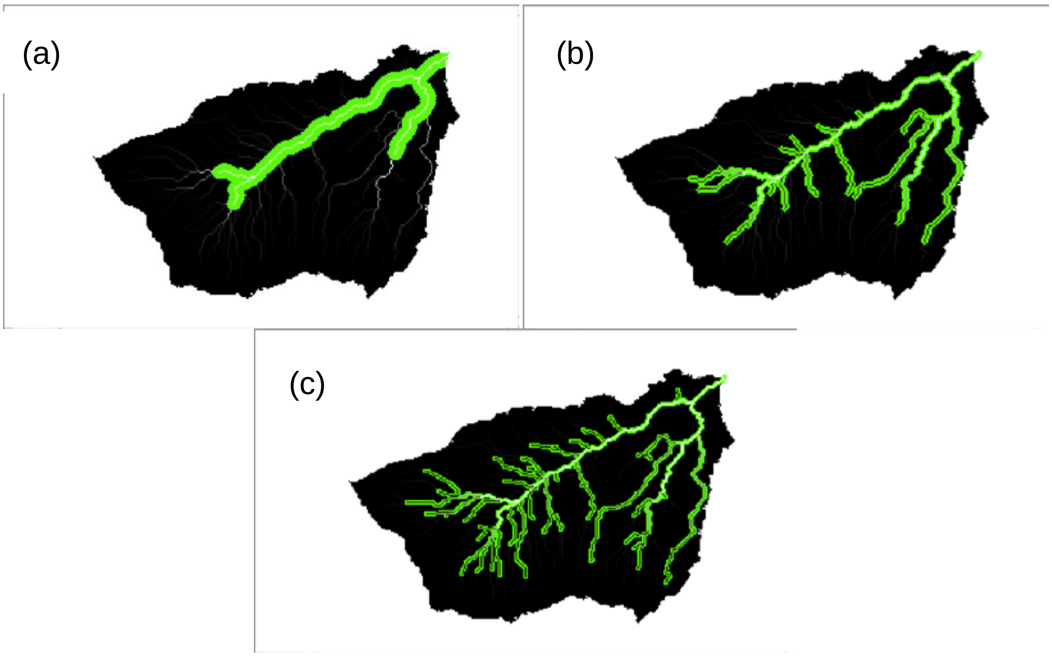


**Figure 5.12** Scenarios of 10% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions; (a) 3000-cell accumulative area, (b) 500-cell accumulative area, (c) 250-cell accumulative area.

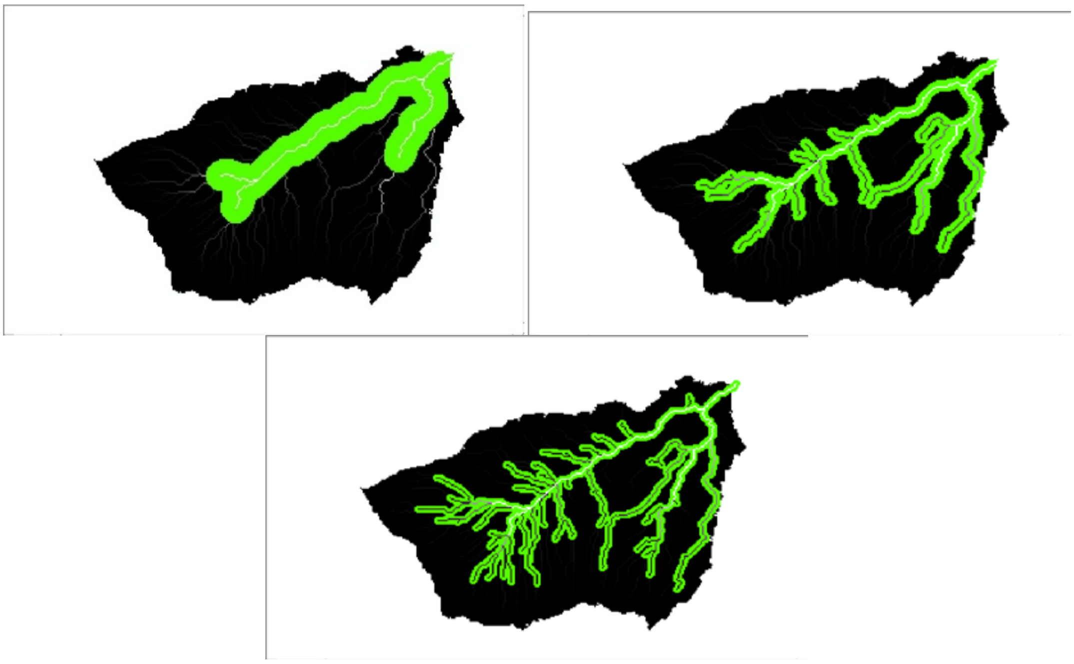

**Figure 5.13** Scenarios of 20% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions; (a) 3000-cell accumulative area, (b) 500-cell accumulative area, (c) 250-cell accumulative area.

From the results for bare buffer strip scenarios (as shown in Figure 5.14 and Figure 5.15), narrower bare peat strips surrounding a longer stream network produce a larger peak flow than fatter strips surrounding a shorter network. This is especially pronounced in the 20% area scenario by which the 250-cell scenario yields the highest peak, even though the rising limb hydrographs for each buffer scenario are almost overlapped. For *Sphagnum* buffer strip scenarios (see Figure 5.16 and Figure 5.17), they are not as divergent in behaviour. However, the *Sphagnum* buffer strips surrounding a more branched river network give a later and lower flow peak.

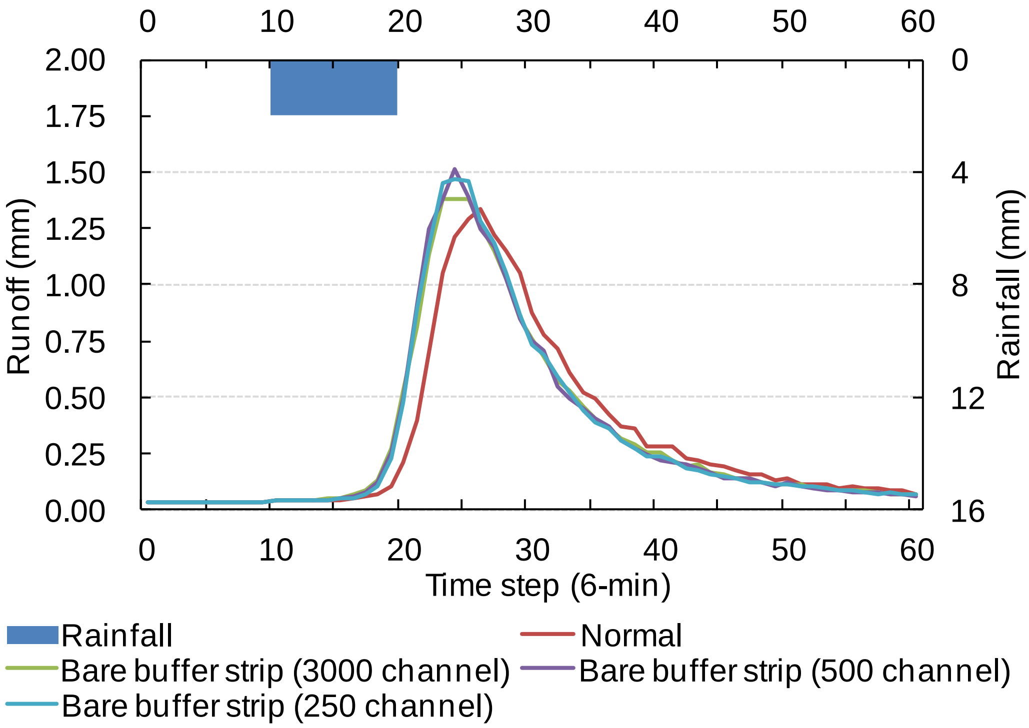


**Figure 5.14** Hydrographs of 10% area riparian bare buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

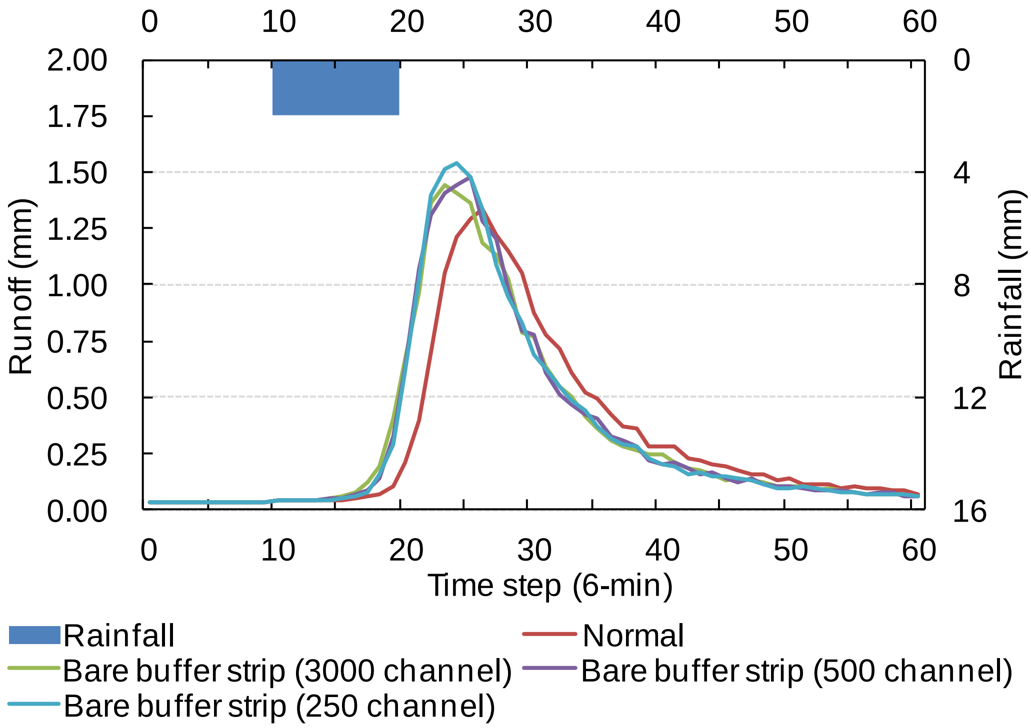


**Figure 5.15** Hydrographs of 20% area riparian bare buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cells= 1.2 $km^2$, 500 cells = 0.2 $km^2$, 250 cells = 0.1 $km^2$.

The outer part of the 3000-cell channel buffer strip has lower efficiency on river flow change than the inner part according to previous results from the riparian bare buffer strip scenario presented in section 5.3.1. It can be considered that a riparian buffer strip based on a more branched channel network (e.g. the 250-cell channel buffer strip) is produced by removing these lower efficiency cells in the 3000-cell channel buffer strip to the upstream riparian buffer strip area. These more efficient bare peat cells encircling a more branched stream network operate to affect overland flow, spreading over a much greater part of the catchment. Thus, it could be speculated that land cover change in the areas close to the stream channel has a more efficient impact when these areas are close to is an upstream network with lower accumulative upslope area. It seems that the buffer strip associated with a more branching stream network, in which cells change overland flow in the region of a low depth of overland flow, is more effective in impacting river flow than a buffer strip just focusing on the downstream area where the overland flow depth might be quite high after a long process of overland flow concentration.

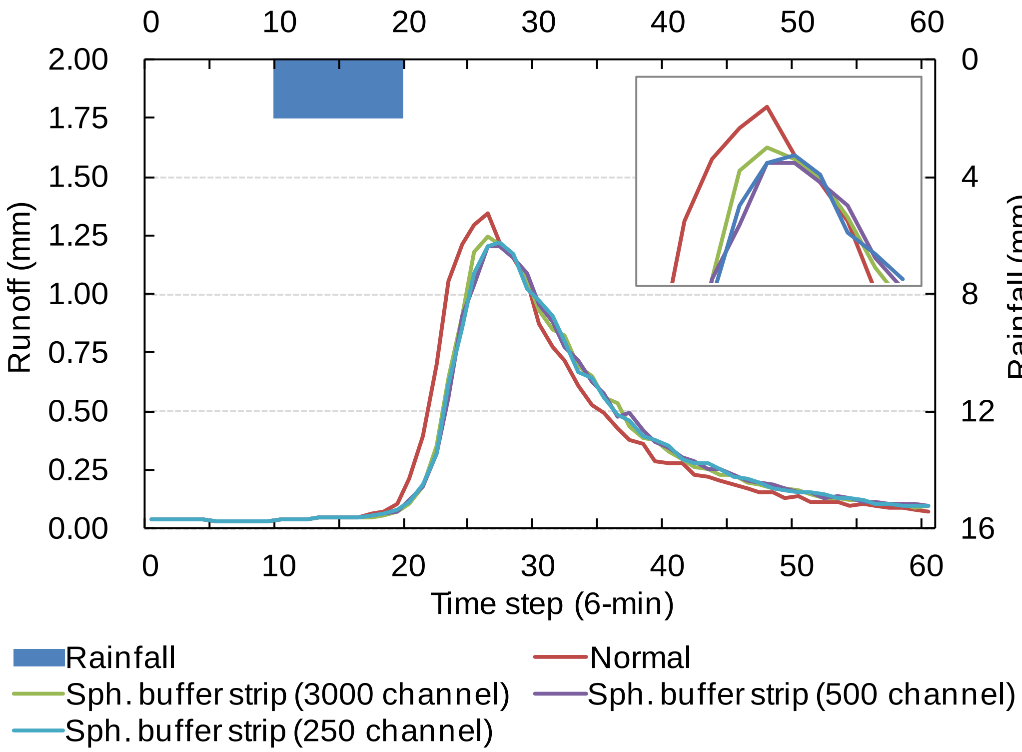


**Figure 5.16** Hydrographs of the 10% area riparian *Sphagnum* buffer strips surrounding different river networks.

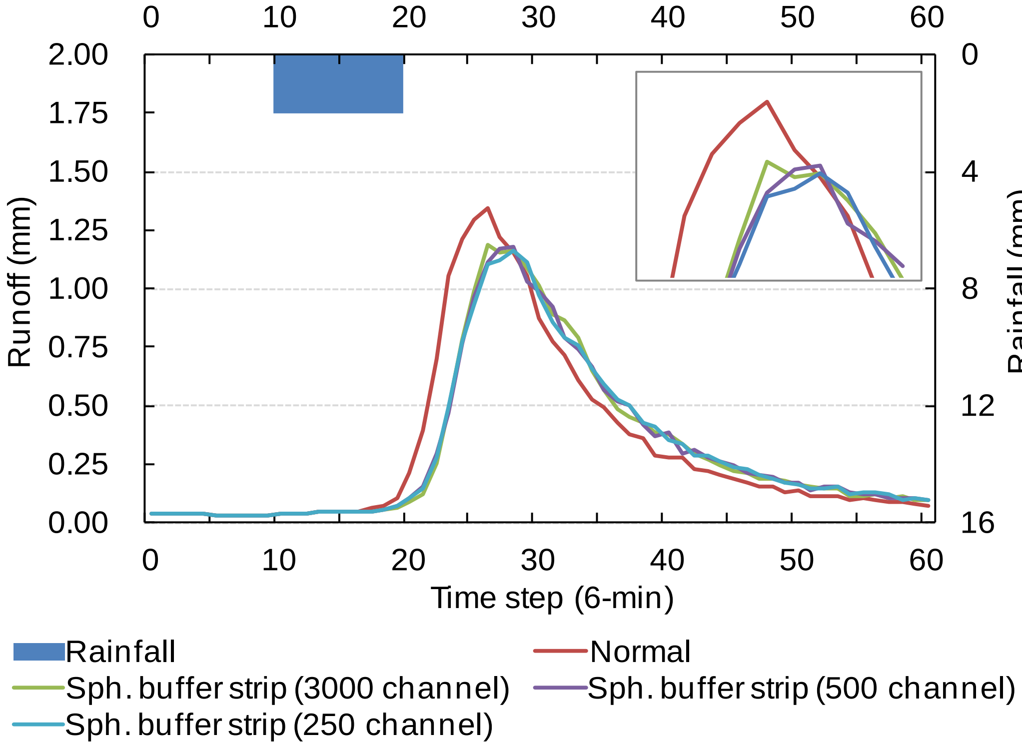


**Figure 5.17** Hydrographs of 20% area riparian *Sphagnum* buffer strips surrounding different river networks.

The *Sphagnum* buffer strip surrounding a more branched river network delays and reduces peak flow compared to a less branched network, but the difference is not as marked as for bare peat. This therefore may not a major advantage for flood risk alleviation. Considering the ease of changing land cover in a more confined block area rather than in a complex narrow strip throughout a peatland catchment, a shift in vegetation from *Eriophorum* to *Sphagnum*, according to the buffer strip scenario of the 3000-cell river network, may be a more economic practice for migrating flood risk than narrow strips associated with a longer channel network. However, it may be possible to encourage *Sphagnum* re-growth along narrow strips around a long channel network and so where possible this should be encouraged to reduce flood risk.

The result of the analysis above is counter to hypothesis (1). 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.

## 5.4 Random patch scenarios

Peatland vegetation deterioration, led by natural or artificial actions (e.g. wild fire, rotational burning and over-grazing), normally takes place in a mosaic pattern of patches throughout a catchment, rather than in one large area such as an entire subcatchment. However, degradation of peatlands has produced a landscape of distributed bare peat patches on the surface which are likely to impact overland flow movement. However, there is still a lack of explicit realization of how these patches impact the downstream river flow or how the differences in patch size influence the catchment outlet hydrograph. Experimental scenario simulations in this section focus on patch experiments. From hypothesis (2), larger patches with changed vegetation are thought to impact river flow peak flow and timing more than the same surface area made into small patches.

Grid land cover change patches are convenient for patch scenario formulation. All patches are picked up randomly based on 2-dimension uniform distribution, and they do not overlap the river channel network in each patch scenario. Figure 5.18, Figure 5.19, Figure 5.20 and Figure 5.21 indicate a group of random patch scenarios with a variety of patch sizes, including 400m$^2$, 1600m$^2$, 6400m$^2$, 10000m$^2$, and 40000m$^2$ patch size scenarios, in the Trout Beck catchment.

While the patch distribution for each size is random it may be that for the very largest patches (100-cell patch scenario), the low number of patches might mean that results are influenced by the specific location on the hillslope of these patches. Thus, for 40000m$^2$ (100 cell) patches, a total of five different scenarios are used each with a different random spatial distribution of the patches (see Figure 5.19 and Figure 5.21 for 10% and 20% area respectively). The results of the 100-cell patch scenarios will be illustrated by a 'results band' on a hydrograph combining the five scenario results which is comprised of the highest and lowest flow values in every time step.

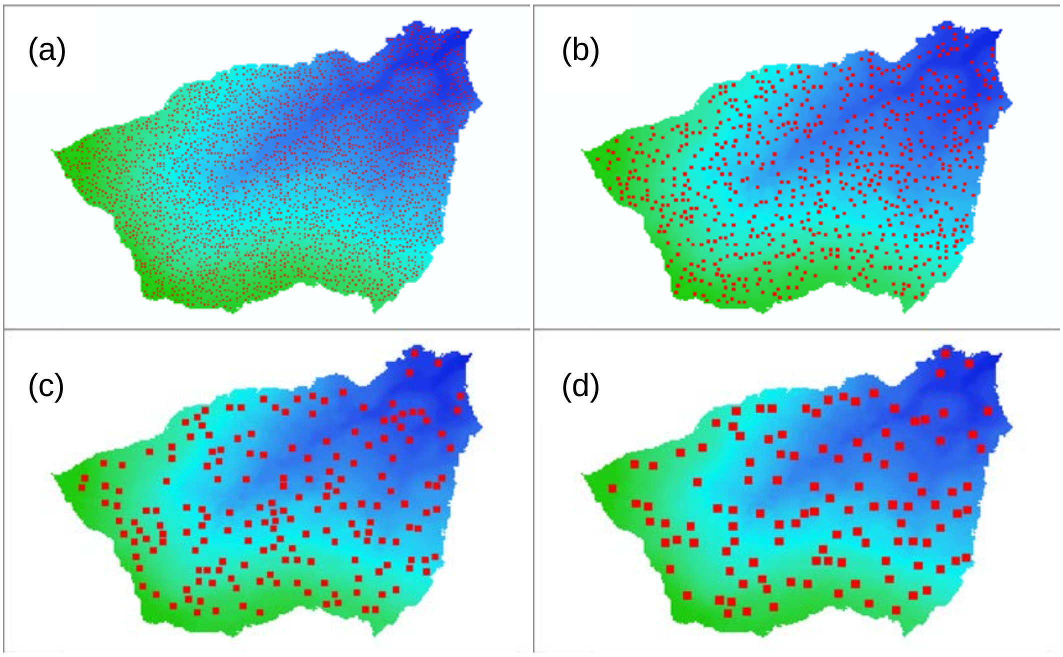


**Figure 5.18** Scenarios of random patches covering a total of 10% of the area of the catchment in each case; (a) 400m$^2$-patch scenario, (b) 1600m$^2$-patch scenario, (c) 6400m$^2$-patch scenario, (d) 10000m$^2$-patch scenario.

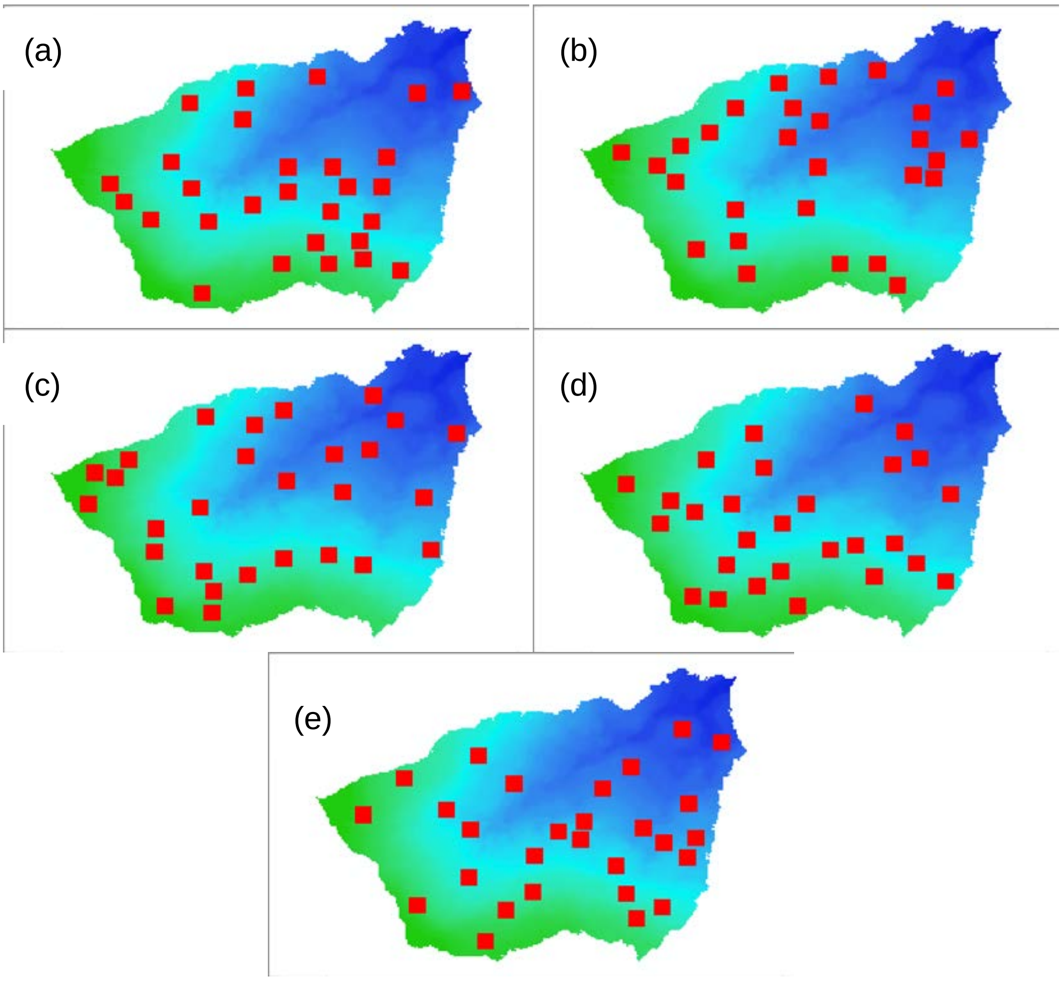


**Figure 5.19** Scenarios of random patches covering a total of 10% of the area of the catchment in each case for 40000m$^2$-patches.

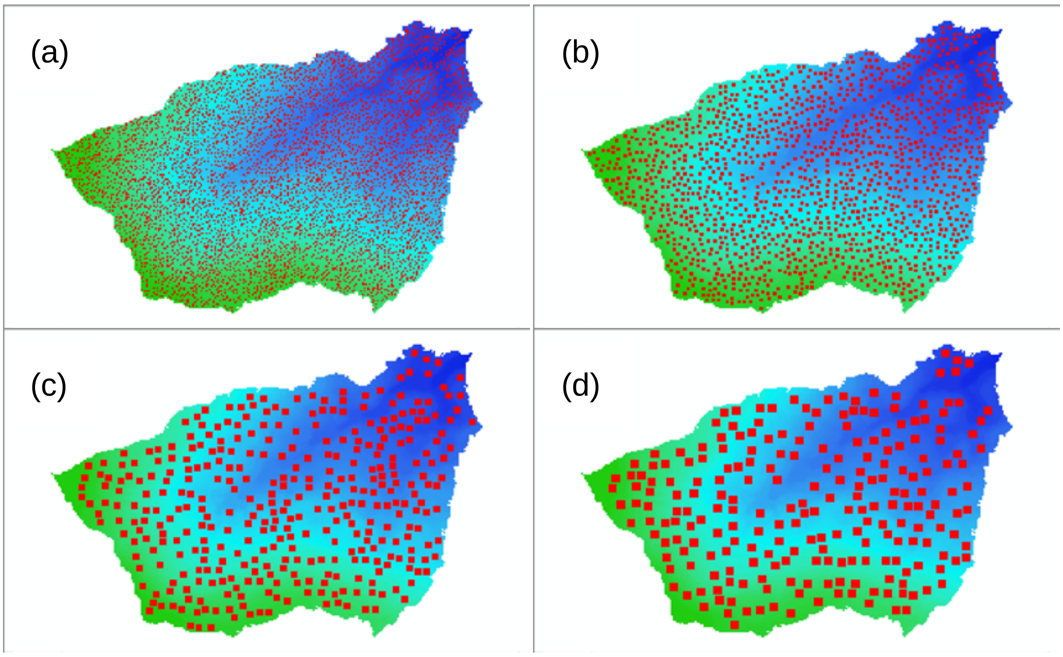


**Figure 5.20** Scenarios of random patches covering a total of 20% of the area of the catchment in each case; (a) 400m$^2$-patch scenario, (b) 1600m$^2$-patch scenario, (c) 6400m$^2$-patch scenario, (d) 10000m$^2$-patch scenario.

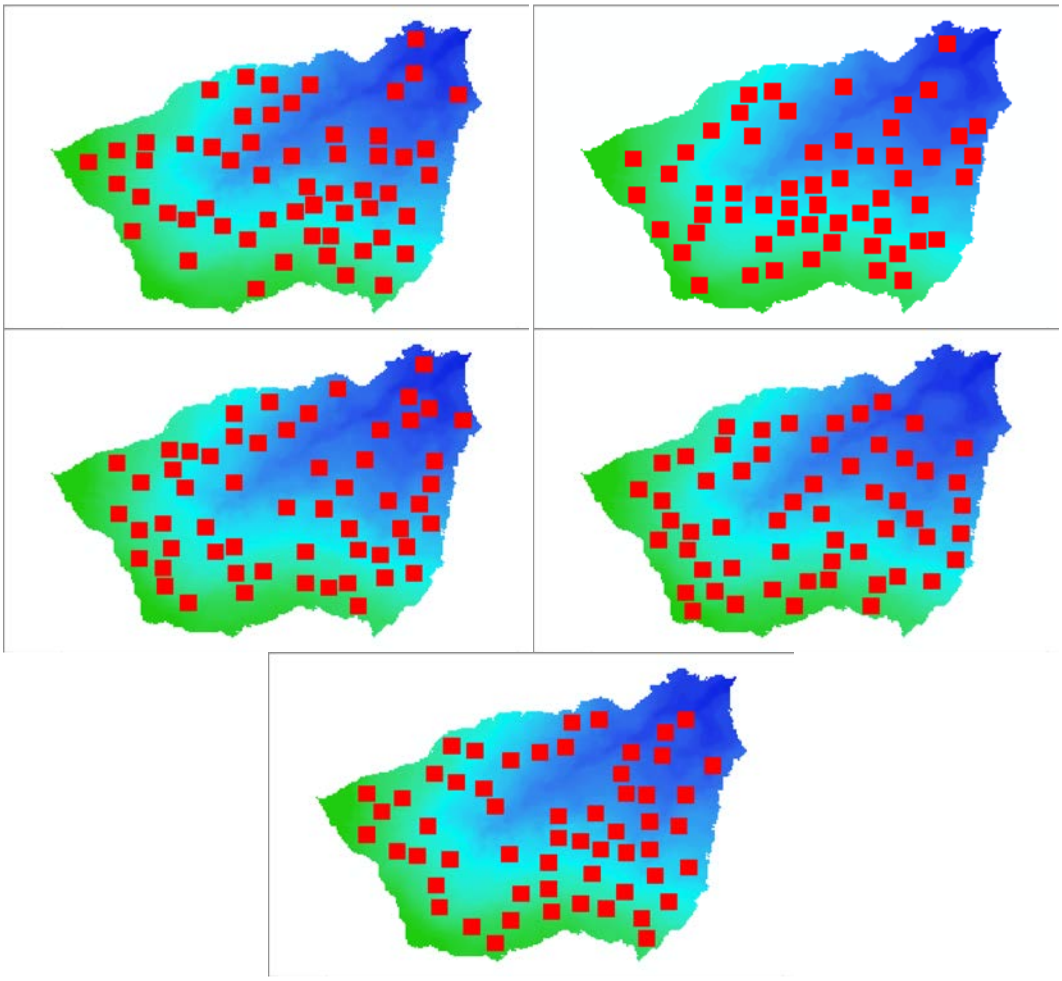

**Figure 5.21** Scenarios of random patches covering a total of 20% of the area of the catchment in each case for 40000m$^2$-patches.

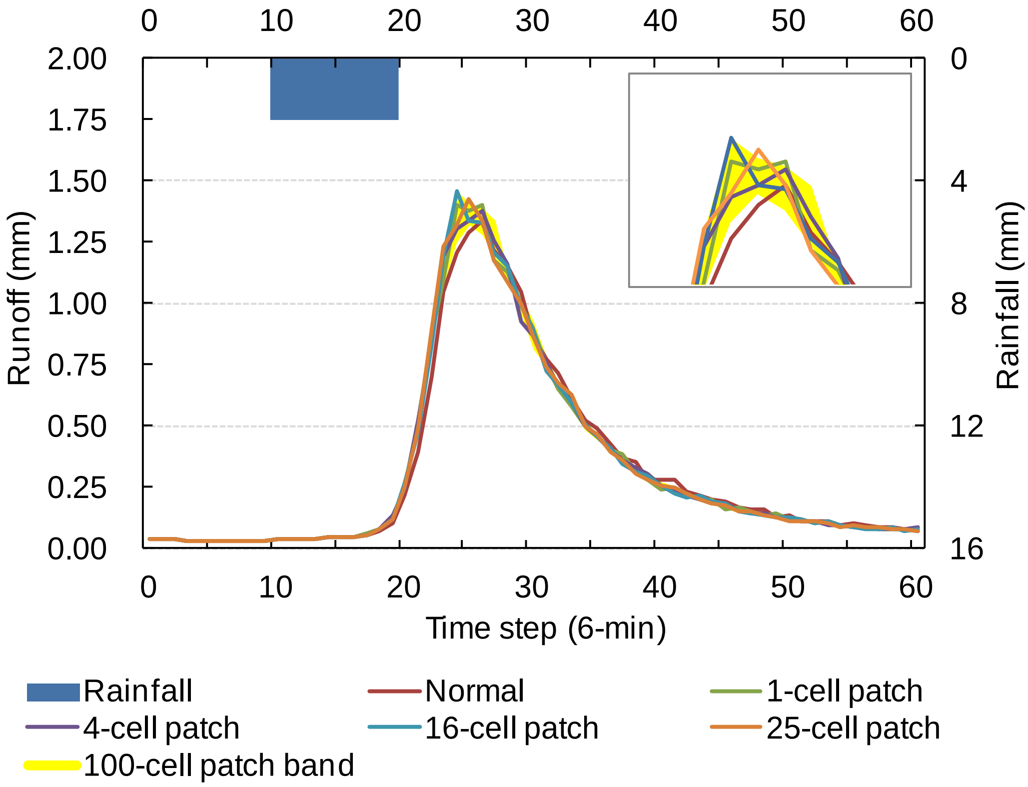


**Figure 5.22** Hydrographs of 10% area bare peat patch scenarios.

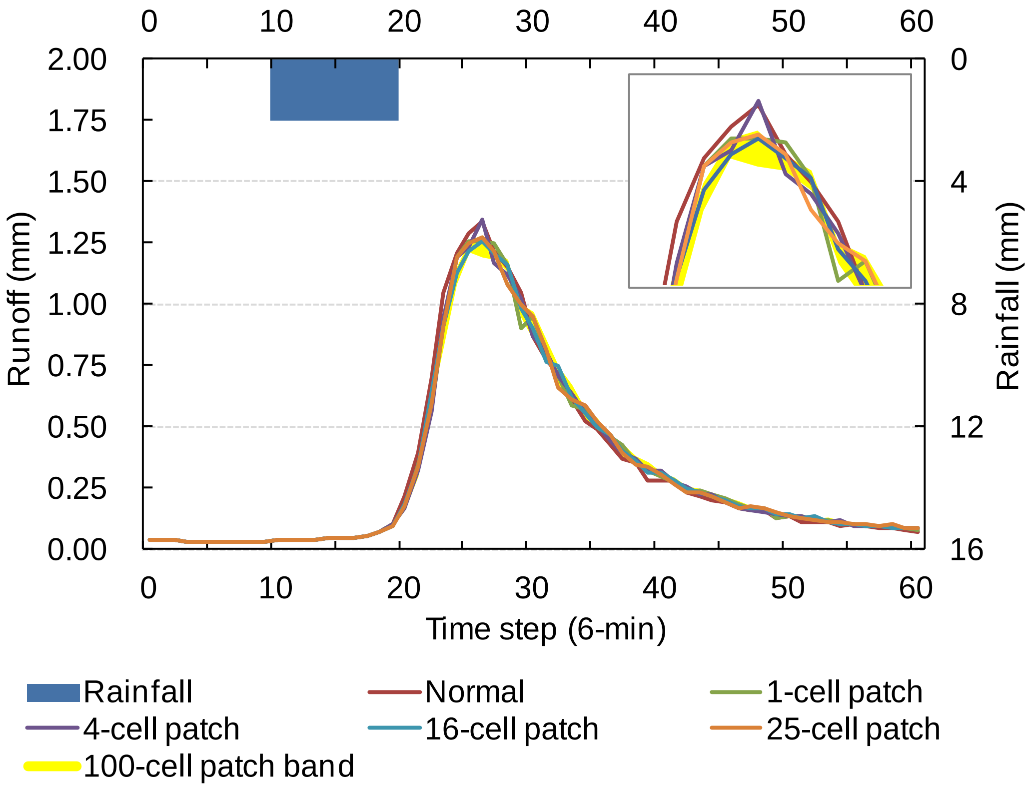


**Figure 5.23** Hydrographs of 10% area *Sphagnum* patch scenarios.

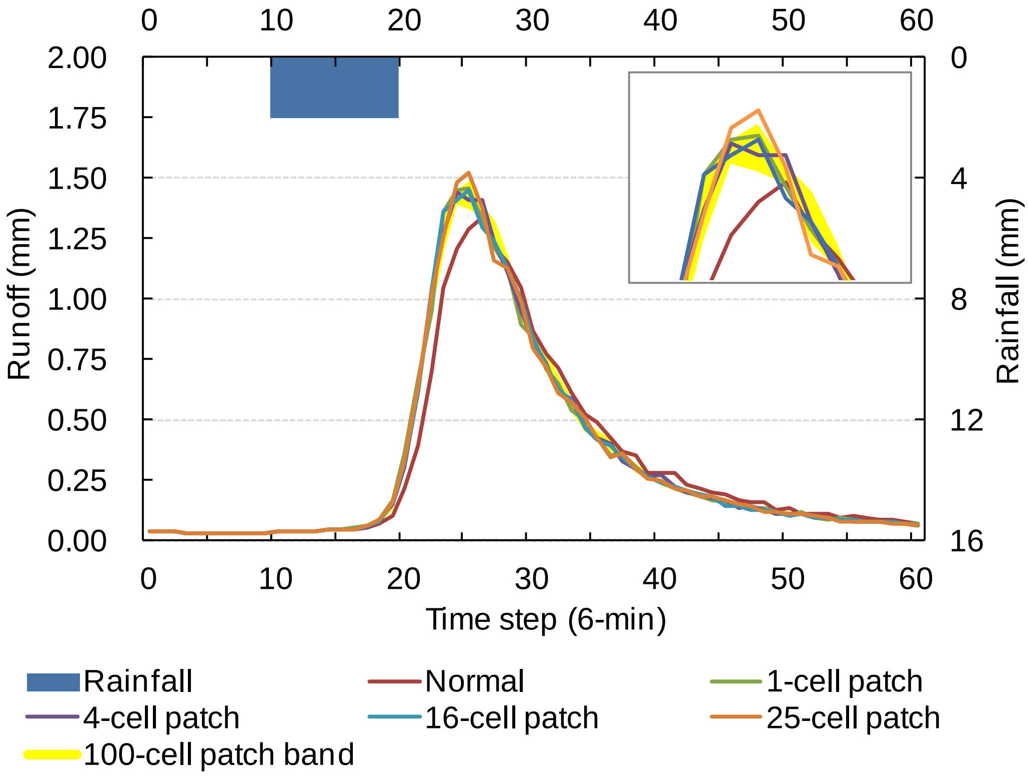


**Figure 5.24** Hydrographs of 20% area bare peat patch scenarios.

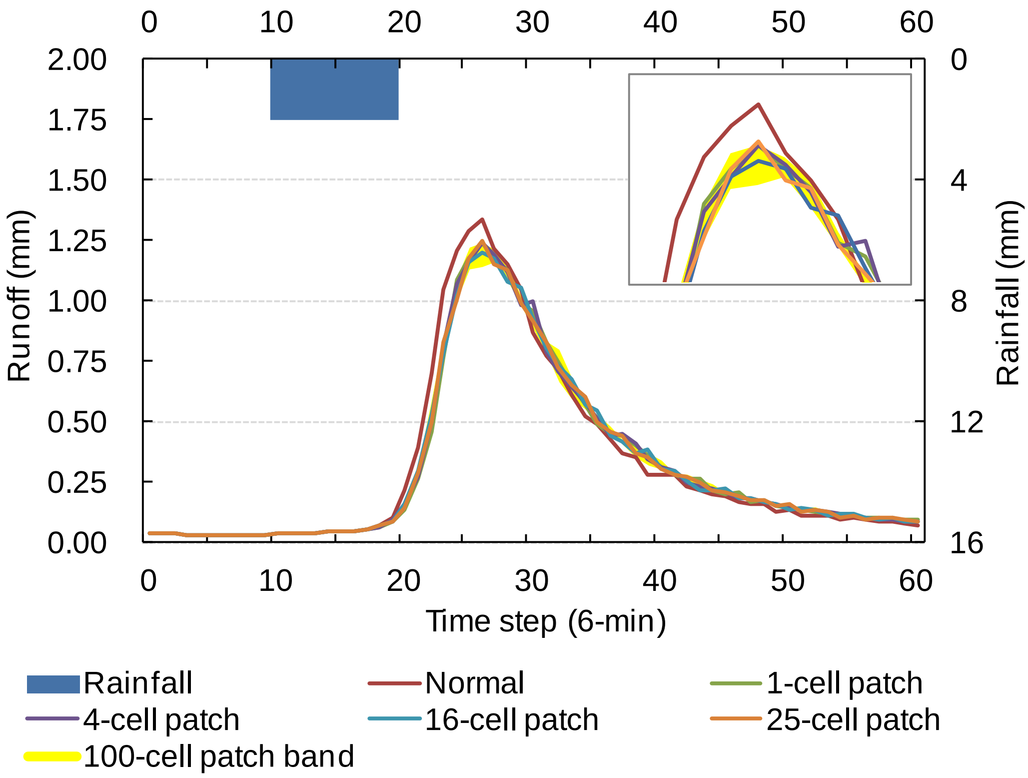


**Figure 5.25** Hydrographs of 20% area *Sphagnum* patch scenarios.

From the hydrographs, all bare peat patch scenarios produce higher and earlier peaks than that of the normal scenario without patches (see Figure

5.22 and Figure 5.24 for the bare peat scenarios). The peak flow from bare patch scenarios is higher than the normal one by around 10%, and the peak time of the bare peat scenarios are earlier than normal by 1 or 2 time steps. The *Sphagnum* patch scenarios generate later and lower peaks than the normal one (see Figure 5.23 and Figure 5.25).

Different patch sizes do not seem to result in differences in hydrographs, so patch size (less than 40000m$^2$) does not clearly impact outlet peak flow. For the small size bare peat patch scenario, widely spread little patches integrate across the hillslope and impact the original integrity and the synchronism of the whole catchment, so they smoothly change overland flow velocity all over the hillslope and impact river flow. In large patch scenarios, even though a large patch breaks land cover over a bigger area and may, in the case of bare peat, increase local overland flow velocity sharply, it is just an in-situ influence rather than a catchment scale one. The downstream area from the large patches with normal vegetation can mitigate the impacts at catchment outlet. However, from the results of the simulation, there is no noticeable impact of patch size on stream flow, which does not comply with hypothesis (2). Hence, it seems that there is no predominant side in these two mechanisms.

This may be helpful for understanding land management impacts, especially for rotational burning which is a widely used method in upland peatland catchments in the UK. Land owners employ it to keep a mosaic of vegetation from recently burnt (almost bare) surfaces to mature vegetation surfaces suitable for grouse (details of patch burning were described in chapter 2). Therefore, the total patch burning area or bare peat area in a peatland catchment is important for stream flow regardless of the size of burning or bare peat patch (although we have not investigated patches larger than 40000m$^2$).

## 5.5 Patch-slope scenarios

Overland flow movement is significantly affected by the surface slope which is a key factor for overland flow velocity. This section aims to probe the influence of land cover change in different slope patches on stream flow. Considering hypothesis (3), a set of patch scenarios in which patches are located on steep slope cells or on gentle slope cells, is introduced to reveal the impact of slope on river flow.

From the last section, patch size does not appear to contribute notable impact on river flow in the random patch scenario. Thus, one-cell size patches are employed in the slope scenario for convenience due to its elementary size and the fact that there is no variation of the slope within a patch.

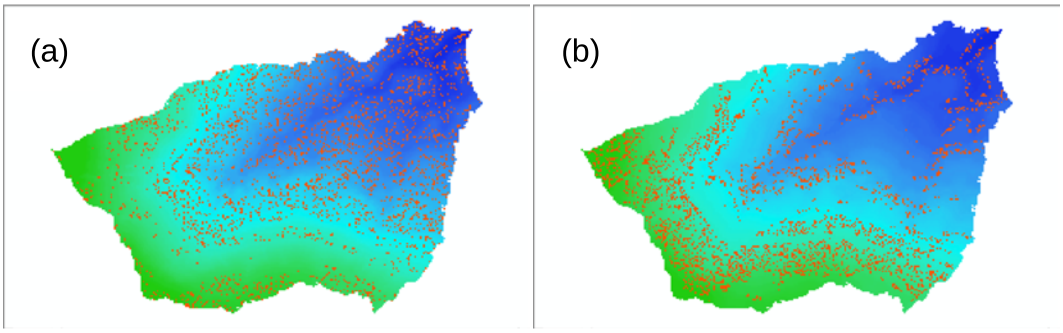


**Figure 5.26** Scenarios of 10% area random patches on slopes greater than 10% (a), and on slopes less than 10% (b). Orange is land cover change area.

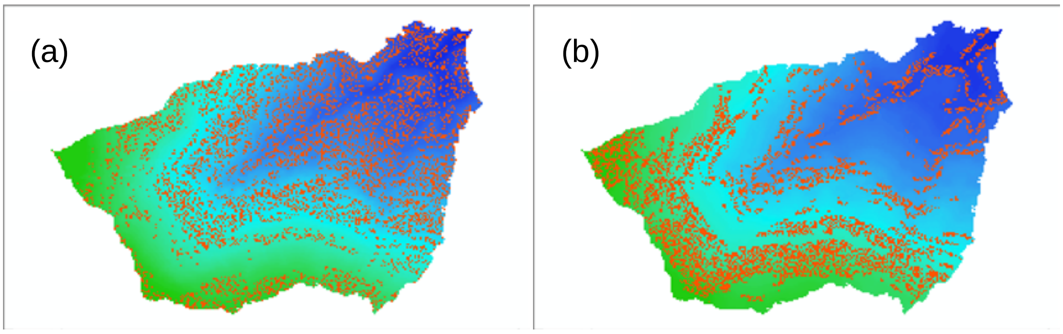


**Figure 5.27** Scenarios of 20% area random patches on slopes greater than 10% (a), and on slopes less than 10% (b). Orange is land cover change area.

The results show that the bare peat gentle slope patch scenarios create a higher and earlier peak than the steep slope ones (see Figure 5.28 and Figure 5.29), and more so for the 20% bare peat group. Lower and later peaks are given by gentle slope patch scenarios compared to steep slope patch scenarios in the *Sphagnum* scenario groups (see Figure 5.30 and Figure 5.31). Gentle slope patches have more influence on river flow than steep slope patches. This result is inconsistent with hypothesis (3).

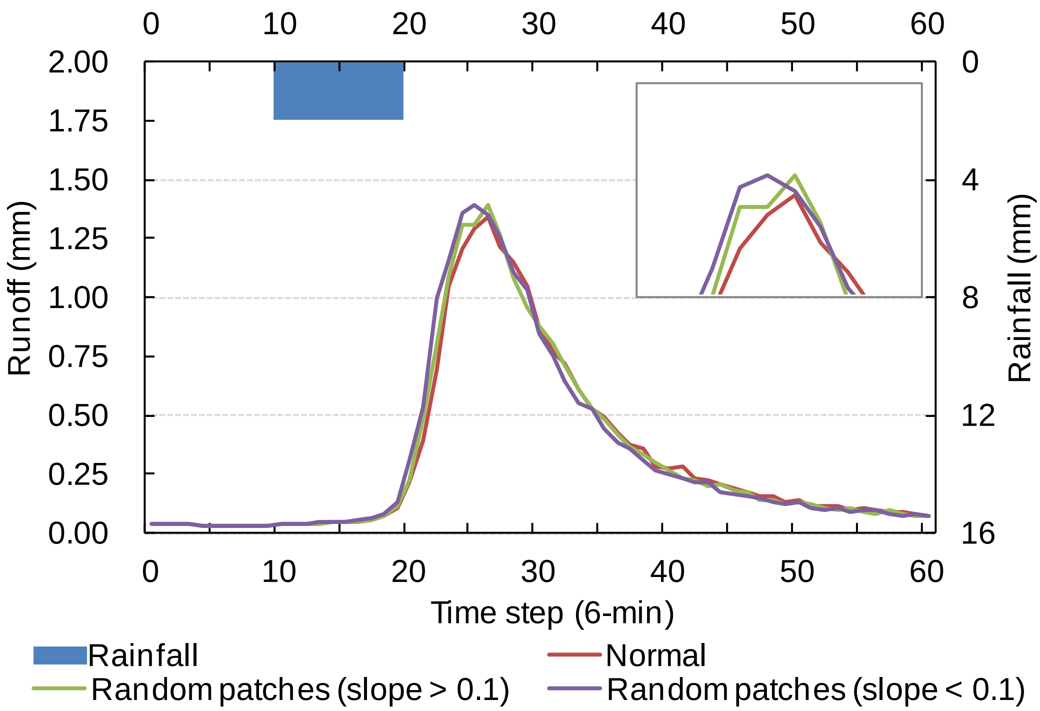


**Figure 5.28** Hydrographs of scenarios with 10% area bare peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

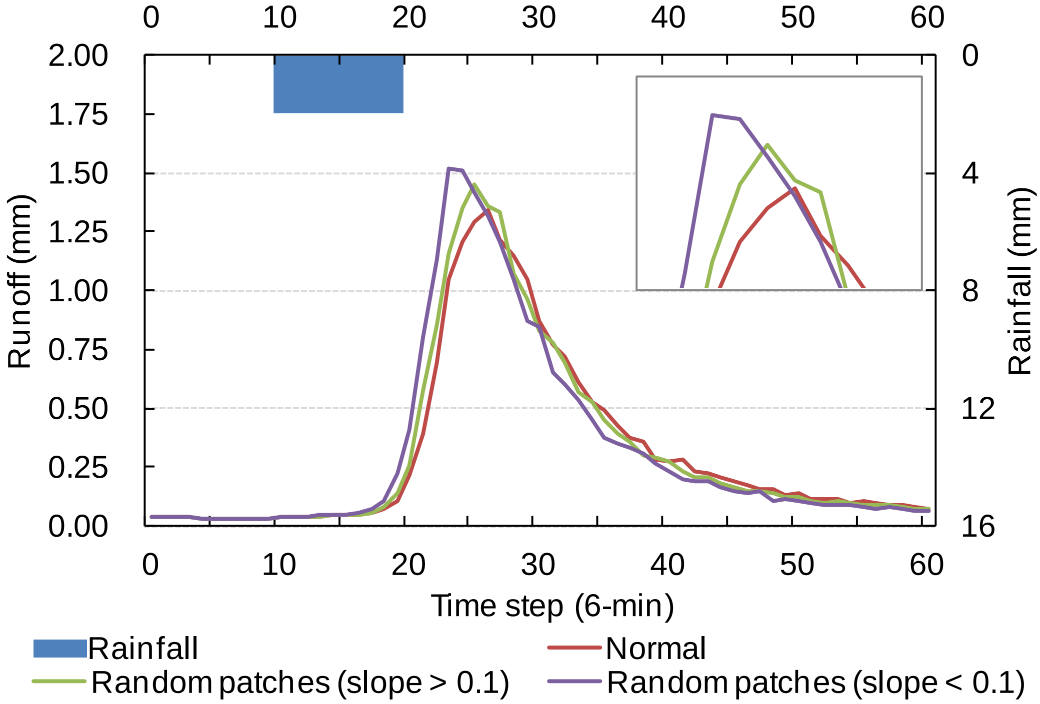


**Figure 5.29** Hydrographs of scenarios with 20% area bare peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

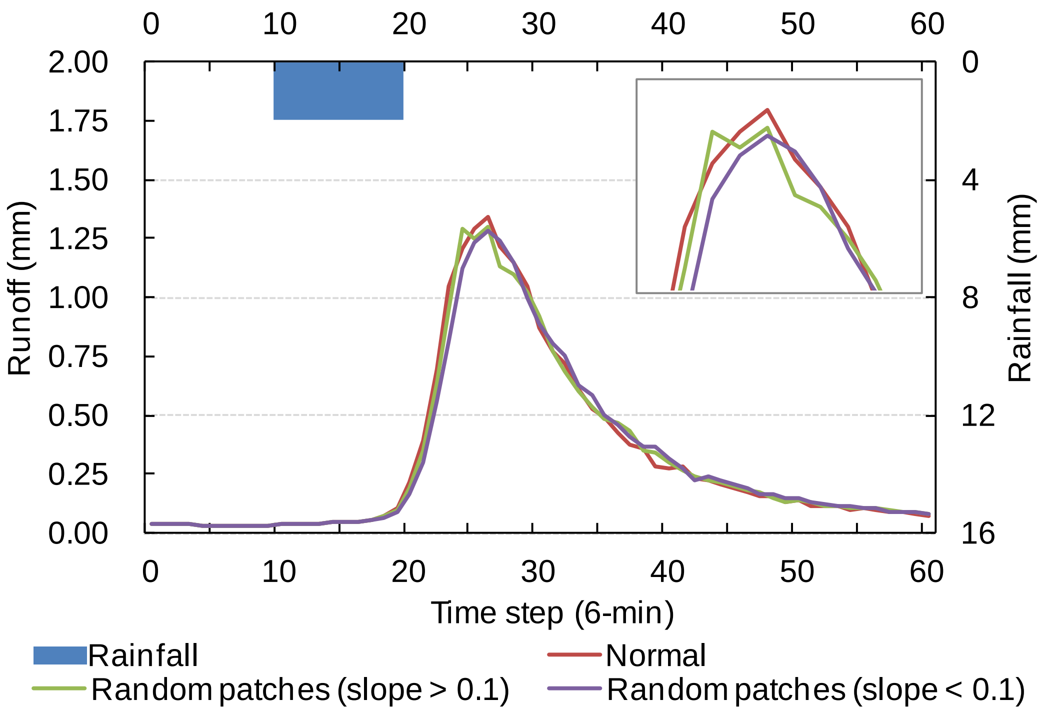


**Figure 5.30** Hydrographs of scenarios with 10% *Sphagnum* peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

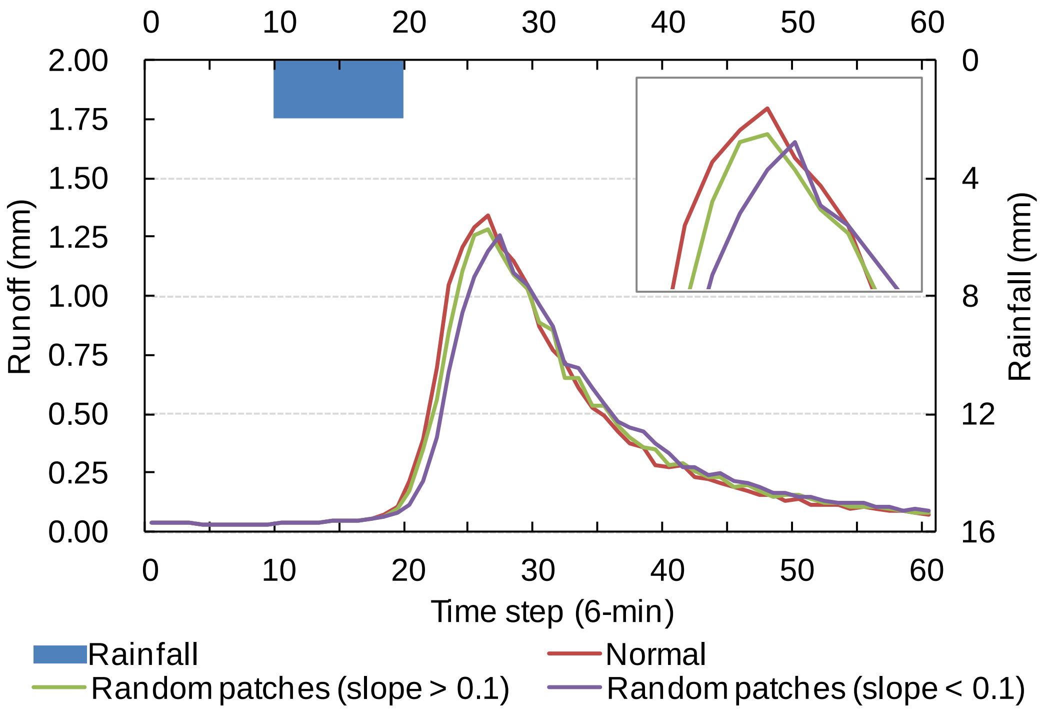


**Figure 5.31** Hydrographs of scenarios with 20% *Sphagnum* peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

A greater amount of gentle slope cells (slope < 10%) tend to be located around riparian buffer strip areas which are considered, from the buffer strip section 5.3, to have more impact on overland flow movement and consequently on river flow than other areas in the catchment. Many steep slope cells (slope > 10%) are coincident with hillslope zones near headwaters and far away from the river channel where land cover change may generate less influence on stream flow than that in a riparian area. This distribution feature of the slope is subject to topographic characteristics of the catchment and the patch effects will be worth exploring in other catchments with different topographic conditions (see Chapter 6).

We now compare patch slope scenarios and random patch scenarios (discussed in section 5.4), for a 20% area cover (see Figure 5.32, Figure 5.33, Figure 5.34, and Figure 5.35). These results show that the random 1-cell patch scenario, which could be considered as a scenario with patches spread between gentle and steep slopes (probably half-half, due to the random patch determination), has an intermediate hydrograph impact between the gentle slope and steep slope scenario. For the 20% bare peat area scenario, the gentle slope patch scenario peak is much higher and earlier than the two others. However, for 20% *Sphagnum* area scenarios, it the peak is slightly lower than the two others even though the peak time is later. It could be inferred that land cover change in the gentle slope area is more effective in river flow impact than that in the steep slope area in a high overland flow velocity situation (i.e. more bare peat).

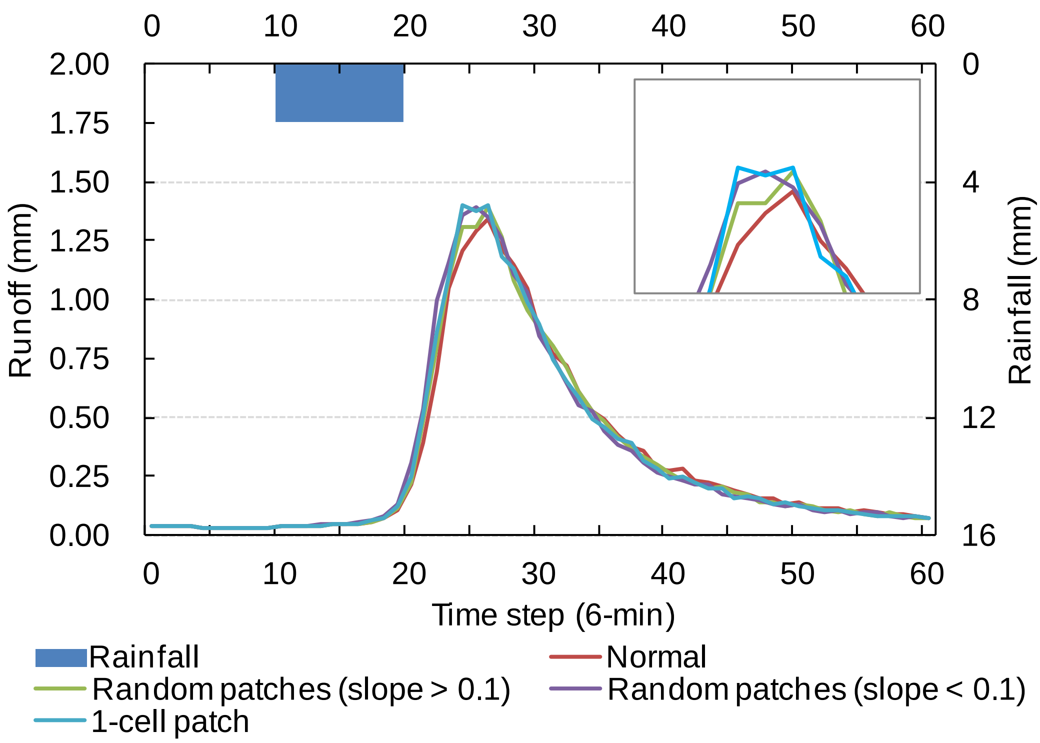


**Figure 5.32** Hydrographs of 10% bare peat steep slope random patch scenario, gentle slope random patch scenario, and random patch scenario with no slope distinction.

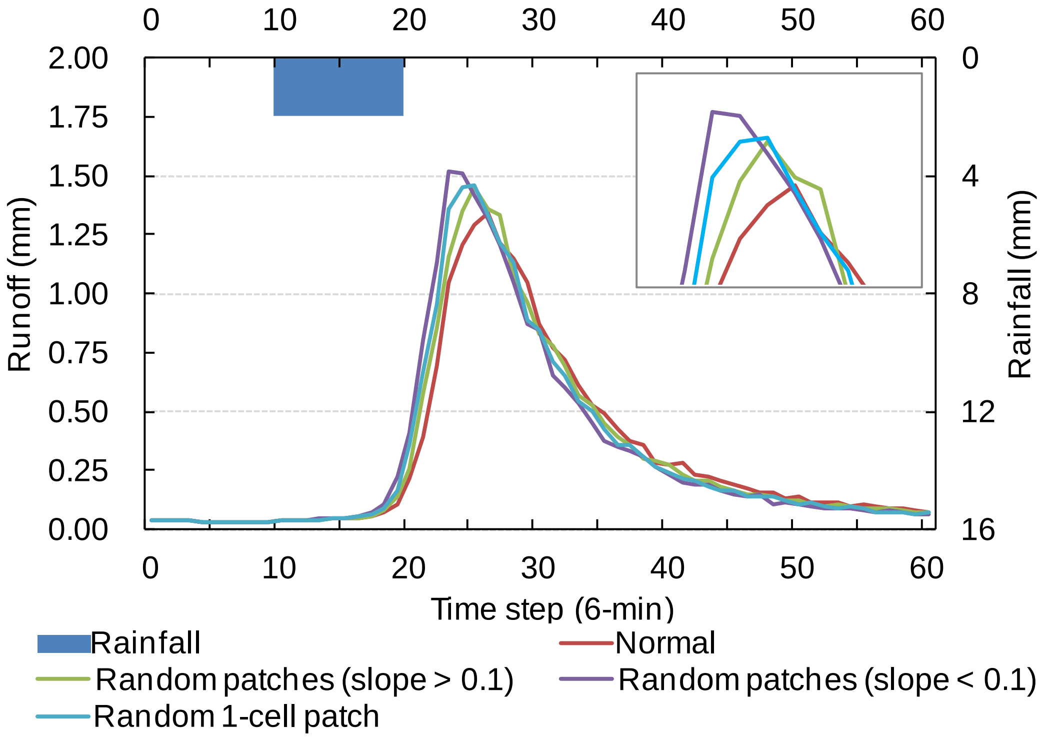


**Figure 5.33** Hydrographs of 20% bare peat steep slope random patch scenario, gentle slope random patch scenario, and random patch scenario with no slope distinction.

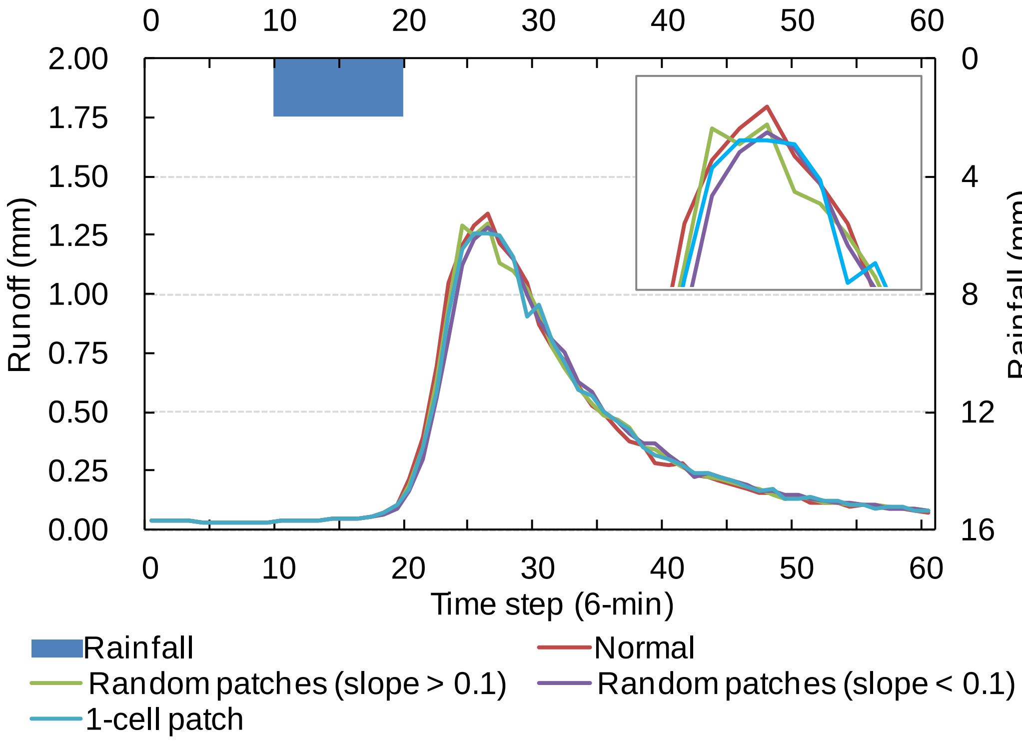


**Figure 5.34** Hydrographs of 10% *Sphagnum* steep slope random patch scenario, gentle slope random patch scenario, and random patch scenario with no slope distinction.

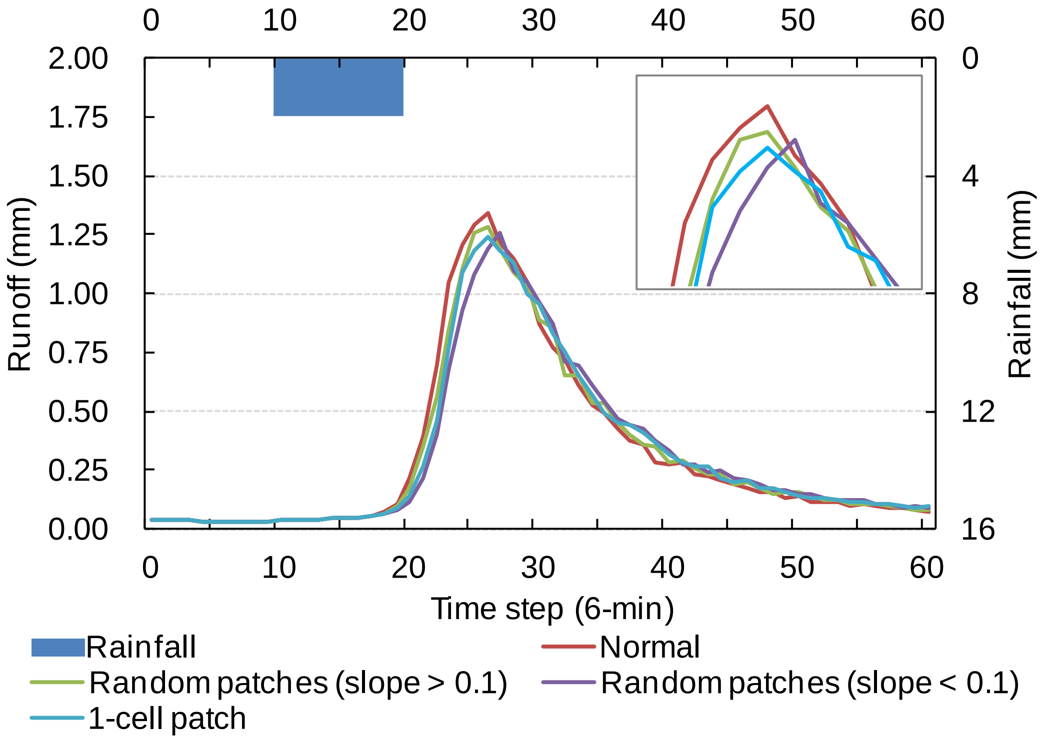


**Figure 5.35** Hydrographs of 20% *Sphagnum* steep slope random patch scenario, gentle slope random patch scenario, and random patch scenario with no slope distinction.

Both downslope-focused scenarios, the gentle slope patch scenario and the 3000-cell riparian buffer strip scenario, are compared in Figure 5.36 and Figure 5.37. Bare peat (see Figure 5.36), for the gentle slope patch scenario and for the scattered bare peat patches where those patches occur near the river channel, may both increase overland flow velocity and maintain a moderate synchronization of overland flow concentration. The 3000-cell riparian bare peat buffer strip raises the velocity of overland flow in a block area close to river channels, so it produces an earlier rising limb in the hydrograph. Yet, in the meantime, it may also break the synchronization of overland flow concentration for the whole area near the river channel. Hence, this may be why the gentle slope bare peat patch scenario gives a higher peak but later rising limb in the hydrograph than those of the riparian bare peat buffer strip scenario.

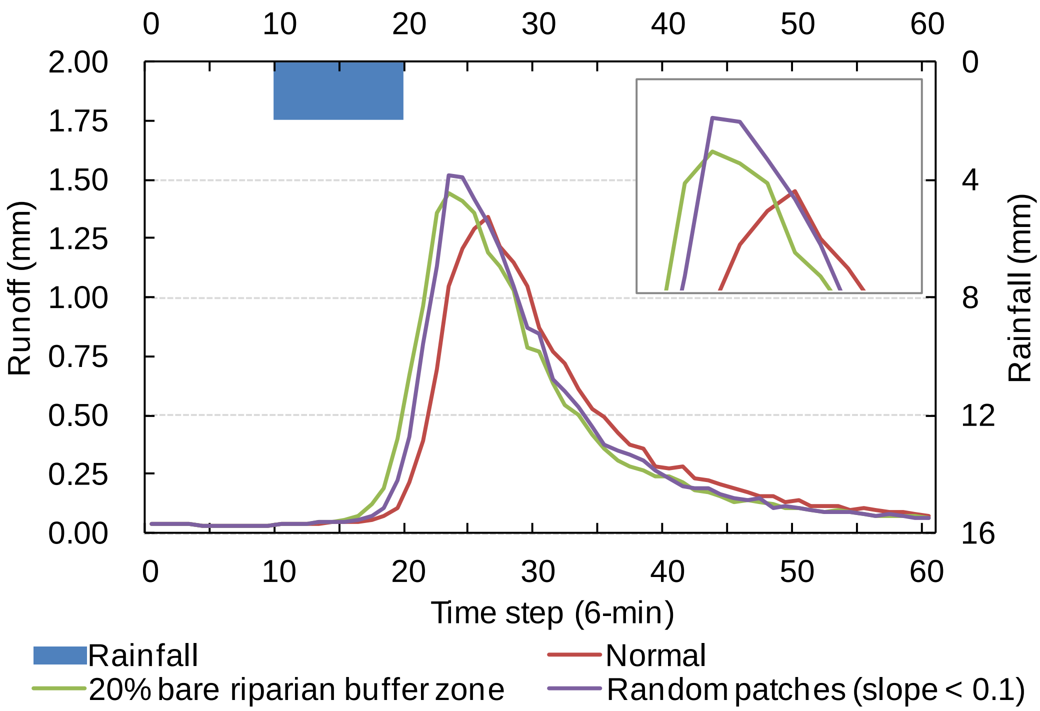


**Figure 5.36** Hydrographs of 20% bare peat gentle slope random patch scenario and 20% bare peat riparian buffer strip scenario.

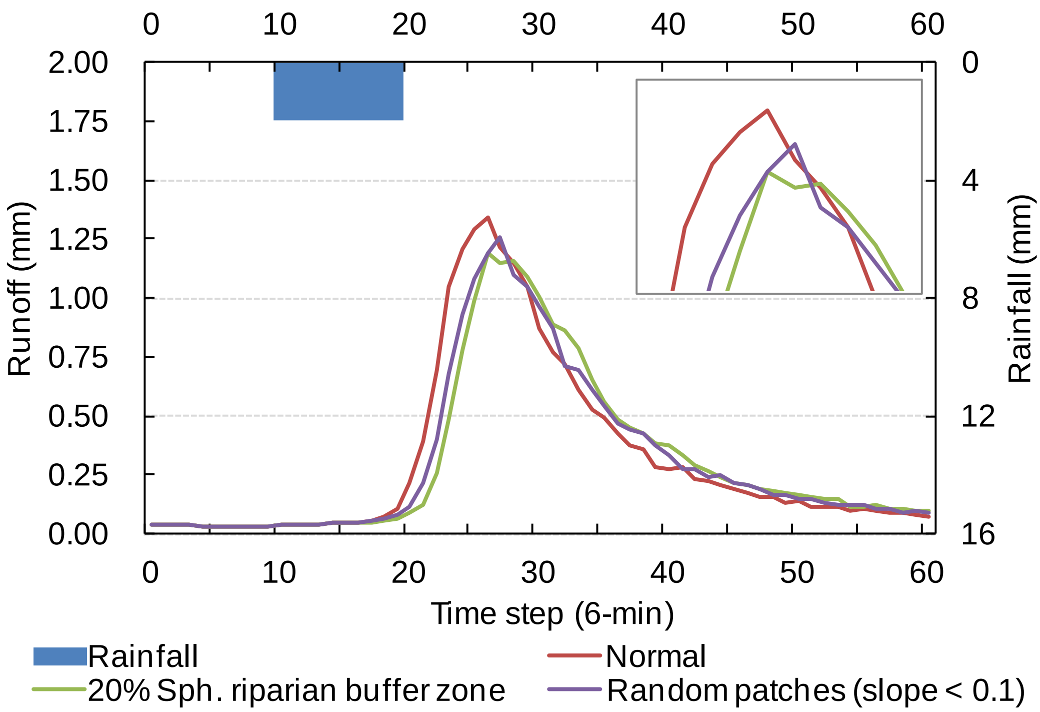


**Figure 5.37** Hydrographs of 20% *Sphagnum* low slope random patch scenario and 20% *Sphagnum* riparian buffer strip scenario.

For the *Sphagnum* scenario comparison (see Figure 5.37), there is a potential concomitant mechanism to the bare peat scenarios. The gentle slope *Sphagnum* patch scenario keeps a more moderate synchronization of overland flow concentration than the *Sphagnum* riparian buffer strip scenario, so it still creates a higher peak than the *Sphagnum* riparian buffer strip despite the reduced and delayed flow peak produced by both of them.

In summary, the above section suggests that, from the perspective of land management and flood risk, it is more crucial to protect gentle slope areas from vegetation deterioration than for steep slope areas in a peatland catchment.

## 5.6 Summary

The scenario results of this chapter shows that, for all hypotheses introduced at the start of the chapter, they are not fully supported by the outcomes of the simulation. The buffer strip surrounding the upstream and downstream channel has a larger influence on stream flow than that of just bordering the downstream channel, contrary to hypothesis (1). For hypothesis (2), patch size does not generate a noticeable effect on river flow for both denser patches and sparser patches. In contradiction with hypothesis (3), land cover change for gentle slope areas has bigger impact on river flow. However, other aspects of the hypotheses were shown to hold for the Trout Beck case study. Therefore, the three hypotheses can be modified to three principles as follows.

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

Principle (2): The size of the land cover change patch does not have noticeable effect on river flow for patch sizes no more than 40000$m^2$.

Principle (3): Bare peat on a gentle slope area gives a faster flow response and higher peak value at the catchment outlet, while high density vegetation or re-vegetation on a gentle slope area has larger positive impact on peak river flow delay when compared with the same practices on steeper slopes.

As an example, we now consider the case of what might happen if we re-vegetate the real areas of bare peat that exist in the Trout Beck catchment. It should be noted that starting in 2013 local managers have been investing in revegetation of bare peat in the area and so this application has additional relevance. Bare and eroding peat maps were produced in 2012 by the North

Pennines AONB Partnership (Figure 5.38). These data indicate that 9.7% of Trout Beck is occupied by bare peat.

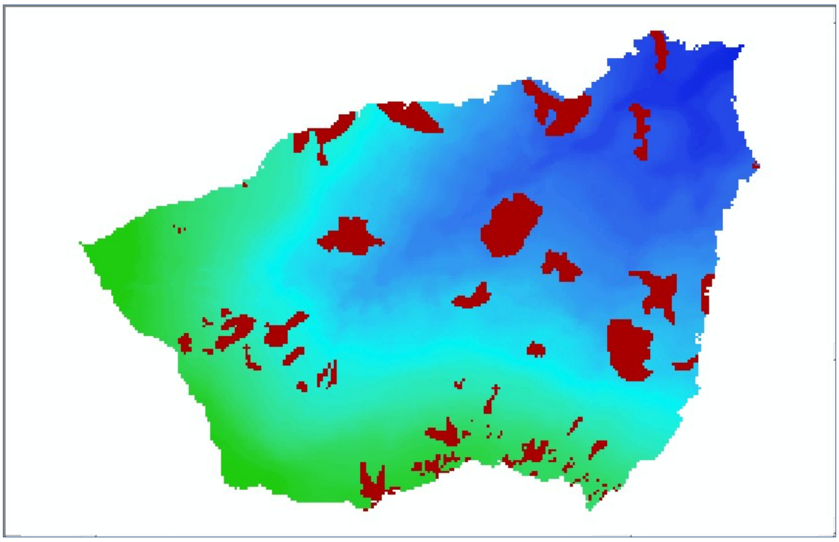

**Figure 5.38** Distribution of bare peat in the Trout Beck catchment in 2012 based on data provided by the North Pennines AONB Partnership.

Model runs representing re-vegetation of the bare peat patches shown in Figure 5.38 with *Eriophorum* and *Sphagnum* were conducted to assess the possible future flow impacts. A 20mm 1-hr rainfall event is used and Figure 5.39 shows that the re-vegetation project would delay the flow peak and decrease the peak flow by 6% if *Eriophorum* successfully grew on the patches. If *Sphagnum* is planted to fill the bare patches, the decrease of the peak flow can extend to 8%.

Linking this example to principle (3), this revegetation plan should be effective and economic as the mean slope of all bare patches is 6.5% which is lower than the mean slope of the catchment (9.1%). It can be expected that most of the benefit is coming from the bare peat revegetation on the gentle slope patches. From principle (2), there is no need to be concerned about which patches have the priority to be restored because the patch size does not impact river flow. Principle (1) seems to not apply to this case due to the fact that the bare peat patches have different relative positions to the channel network (see Figure 5.40)

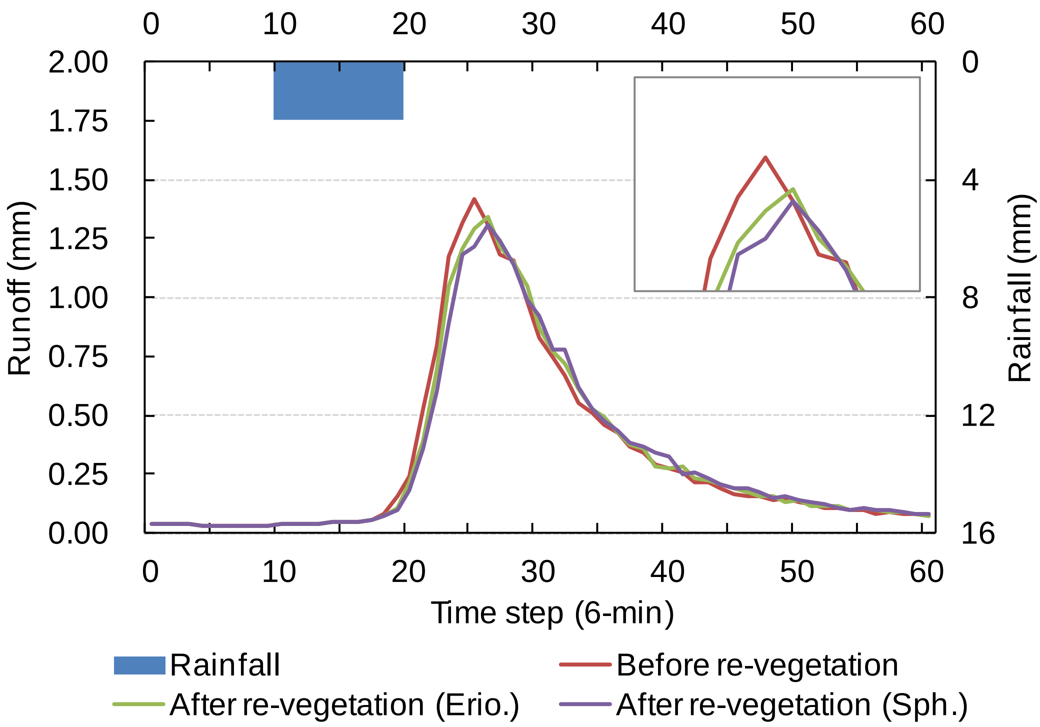


**Figure 5.39** Hydrographs of scenarios for Trout Beck bare peat restoration before and after re-vegetation work (*Eriophorum* and *Sphagnum*).

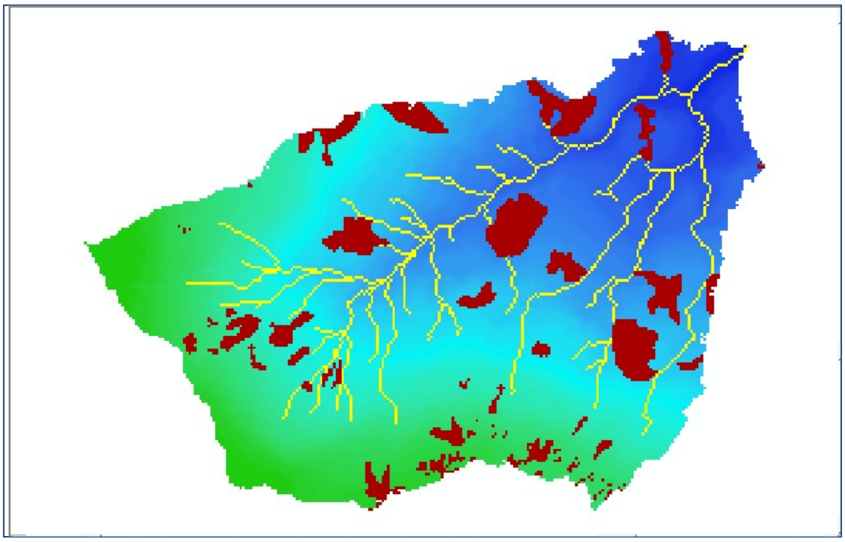

**Figure 5.40** Distribution of bare peat and river channels (250-cell accumulative area threshold) in the Trout Beck catchment.

For each scenario group, two representative scenarios with similar spatial configuration respectively, from 10% and 20% area sets, are picked up due to their largest impacts in each group, i.e. the 250-cell riparian buffer strip scenario for the buffer strip scenario group, the 1-cell random patch scenario for the random patch scenario group, and the gentle-slope patch scenario for the slope-patch scenario group. They are compared in Figure 5.38 and

Figure 5.39 to illustrate their impacts on river flow at the catchment outlet. There are two primary features of impact on the hydrograph that we have so far examined: peak volume increase (or reduction, shown in Figure 5.38) and peak time hastening (or delay, shown in Figure 5.39). It is not easy to evaluate the scenario impacts by only one feature and so combining the results, Figure 5.40 summarises the peak flow impact of the three groups of scenarios. Land cover change in the buffer strip surrounding the upstream and downstream channel network (i.e. 250-cell buffer strip scenario in section 5.3.3) seems to have the largest impact on river flow of all land cover scenarios in this chapter. Land cover change in the gentle slope patch scenario is more effective than that in the random-picked patch scenario at altering river flow peaks.

For peak increase, the scenarios of 20% area of land cover change have a much bigger impact than those of 10% land cover change areas, but most of the 20% scenarios do not double the effect of the 10% scenarios in spite of doubled area covered by land cover change. One possible implication of this is that for peatland re-vegetation work, more effort in a single sub-catchment may decrease the benefit per cost unit in a re-vegetation project compared with a more diffuse effort across a wider area.

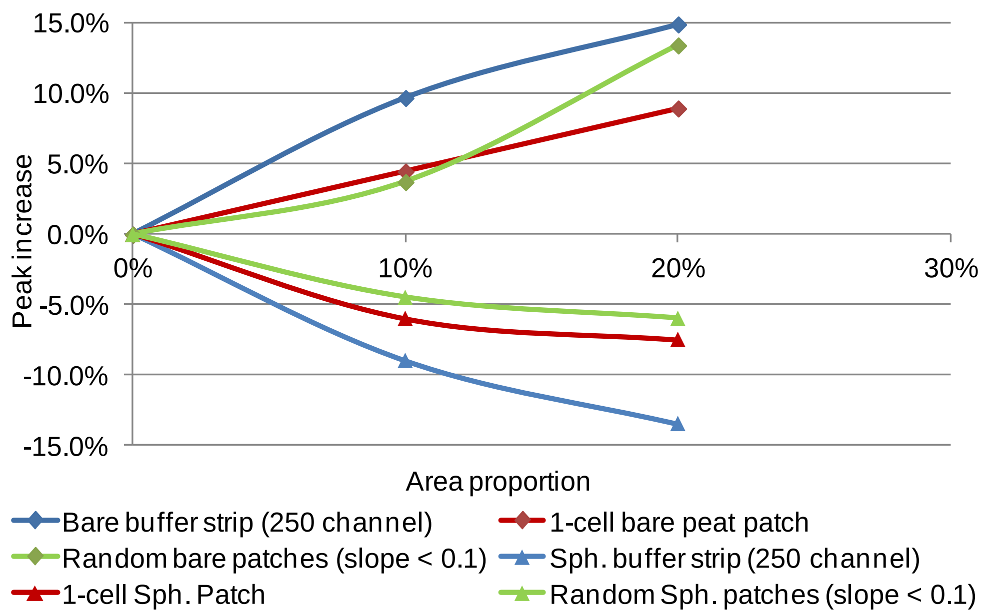


**Figure 5.41** Scenario comparison of impact on peak flow increase compared to the 'normal'.

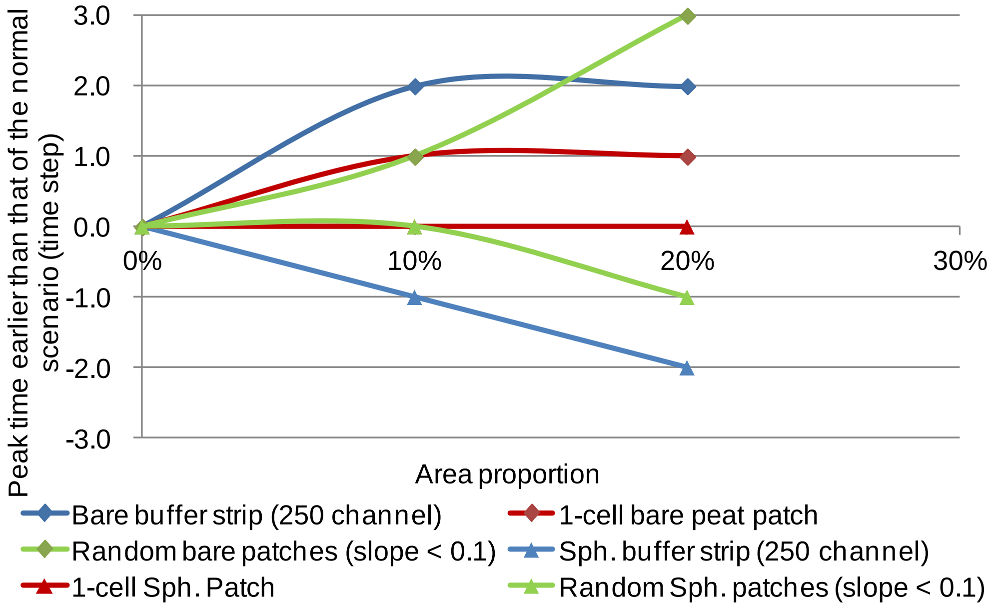


**Figure 5.42** Scenario comparison of impact on peak time compared to the 'normal'.

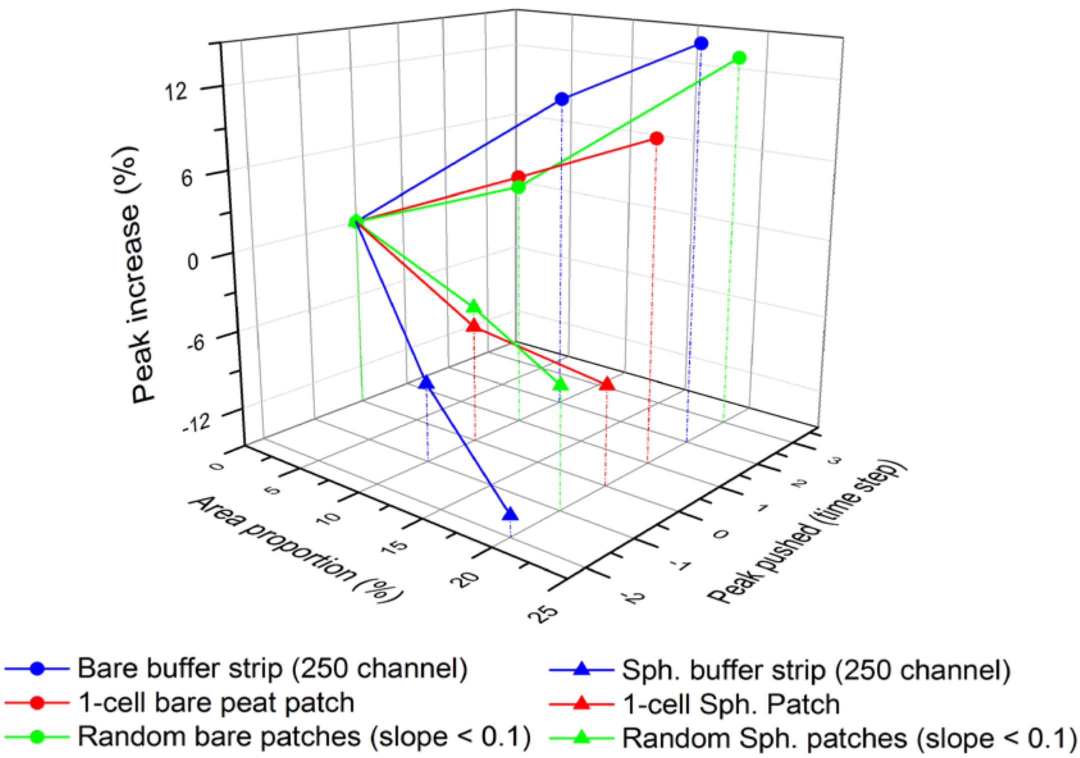


**Figure 5.43** Scenario comparison of the combined impacts on peak flow.

The results of the scenario simulations in this chapter are useful guides for land management, and the three principles could lead to helpful suggestions for practical land use management. However, there may be catchment-specific reasons for the findings above and so the findings from Trout Beck will now be checked and extended for two other headwater peatland catchments in the next chapter. The work will demonstrate that the model can be used at other sites and will also provide more confidence in the results and their application for land managers.

# Chapter 6
# Model application and land-cover scenario tests for new catchments

## 6.1 Introduction

In chapter 4, the distributed TOPMODEL was applied and tested in the catchment of Trout Beck. Three hypotheses of land cover change impacts on river flow have been modified to produce three land cover impact principles based on the results of a series of experimental scenario modelling runs and analyses in chapter 5.

In this chapter, another two UK upland peat catchments, the Wye catchment, Plynlimon, and the East Dart Catchment, Bellever, for which data are available, are employed to further test the distributed TOPMODEL and the three land cover principles. The Wye catchment, with a similar area of the Trout Beck catchment (11.4 $km^2$ vs. 10.6 $km^2$), is much steeper than the Trout Beck catchment and the mean slope of the Wye catchment is about twice of the Trout Beck catchment (20.0% vs. 9.1%). For the East Dart catchment, it has more than twice the area compared to the Trout Beck catchment (11.4 $km^2$ vs. 21.5 $km^2$) but similar mean slope (9.4% vs. 9.1%). Land cover scenario modelling in the two sites will verify whether the three modified principles still hold for these two upland peat catchments with different slopes and areas. Another reason for choosing these two catchments is because there was reliable streamflow and precipitation data from these headwaters, good topographic data, a substantial peat cover, a lack of major forestry areas or other major disturbances in the headwaters. Simulation runs were conducted for key land cover scenario groups; the buffer strip scenario group, the random patch scenario group and the slope-patch scenario group. A 0.1 hr time step was used in both catchments to match that used in Trout Beck so that differences in peak flow timing and size could be reliably compared between catchments.

Section 6.2 will present the model test and land cover scenario study undertaken in the Wye catchment while section 6.3 deals with the East Dart. A summary of the findings from these two catchments will be combined in section 6.4. Around 200 model runs were conducted to complete the work presented in this chapter.

## 6.2 Model runs for the Wye catchment, Plynlimon

Plynlimon is located in the Cambrian Mountains of mid-Wales, which is 100 km north of Cardiff and 25 km from Aberystwyth, (see Figure 6.1). The catchments of Plynlimon comprise the headwaters of the River Severn and River Wye. Most of the upper Severn catchment is forested with conifer plantations. However, grassland dominates the Wye catchment which is 43% covered by blanket peat and valley mires (Marc and Robinson, 2007). Because of good data availability and appropriate land cover at the site the Wye catchment was selected as a case study site for the model test and scenario experiments.

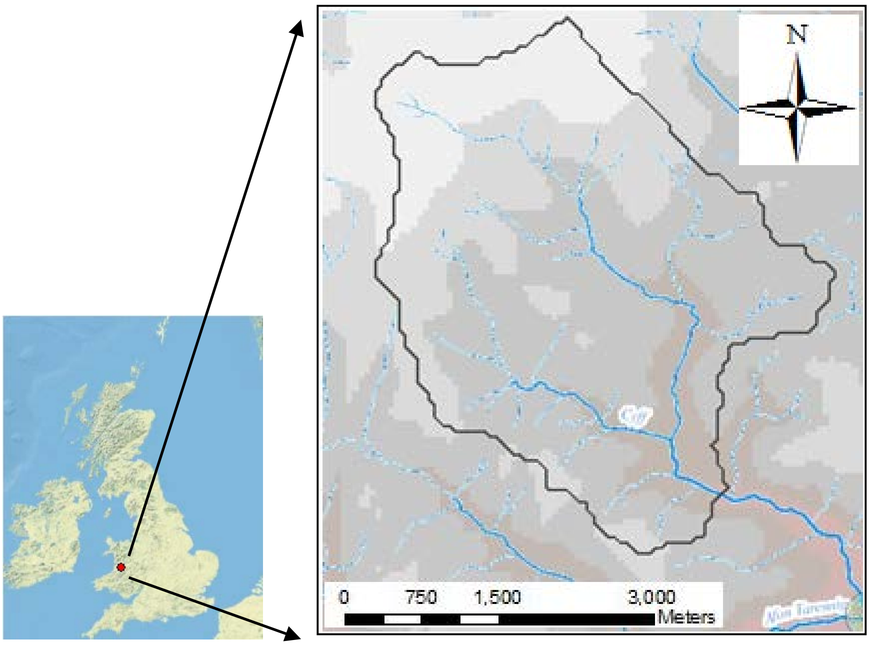


**Figure 6.1** Maps showing the location and the boundary of the Wye catchment, Plynlimon.

The elevation of the Wye catchment ranges from 350 m to 650 m AOD, overlying weather resistant Silurian slates and shales (CEH, 2013). It has a very wet climate with an annual precipitation of more than 2599 mm (1972-2004) (Marc and Robinson, 2007). The mean slope of the catchment is about 20%. Hourly river flow data is available from 1969 to the current year.

### 6.2.1 Model calibration and validation in Wye catchment

Due to the huge number of model runs and the amount of time consumed by them, it is difficult to employ the method of GLUE (generalized likelihood uncertainty estimation) (Beven and Binley, 1992) for every study site. Thus, a simplified routine of model testing has been utilized for the two study sites in this chapter as follows.

First, 20 testing runs of the model were operated through the calibration period to identify a well-performing set of parameters. The parameters were adjusted to give good correspondence (high efficiency of resulting hydrograph) of simulated flow with the observed data in this optimizing process. The model performance of each parameter set was determined by the Nash-Sutcliffe efficiency for the observed river discharge. A good parameter set (e.g. its efficiency over 0.80) was then picked to run the model in the validation process. The Nash-Sutcliffe efficiency of the simulated result in the validation period was obtained through the comparison between the simulated and the observed river flow. The linear regression between the observed and simulated river flow was also applied, with the coefficient of determination ($r^2$) analysed to assess the model applications in both the calibration and validation periods.

This routing is firstly applied to the case study of the Wye catchment. In order to avoid confusion due to the impact of snow and its melt on the catchment hydrology in winter, the rainfall events for the calibration and validation periods in the Wye catchment case study were picked from the summer half year. Two weeks with plentiful rainfall in August and July 2004 were picked as the periods for calibration and validation. The observed hourly river flow data used in this section is from the flow gauge on the River Wye at Cefn Brwyn, the catchment outlet shown in Figure 6.1.

The calibration period is the week commencing 22 August 2004, including 168 time steps (hours). After the parameter optimization, a good parameter set was selected as $m$ = 16 mm, $K$ = 100 m hr$^{-1}$, $k_v$ = 80 ($m$ is active depth for subsurface flow; $K$ hydraulic conductivity of soil; and $k_v$ is velocity parameter of overland flow. ), and the model performance with this set is shown in Figure 6.2 (the simulation efficiency is 0.88). The slope of the regression line between the observed and simulated river flow is 0.89 ($r^2$ = 0.88, see Figure 6.3). For convenience, the unit of river flow is changed to depth of runoff and ease of comparison in the plots that have been produced.

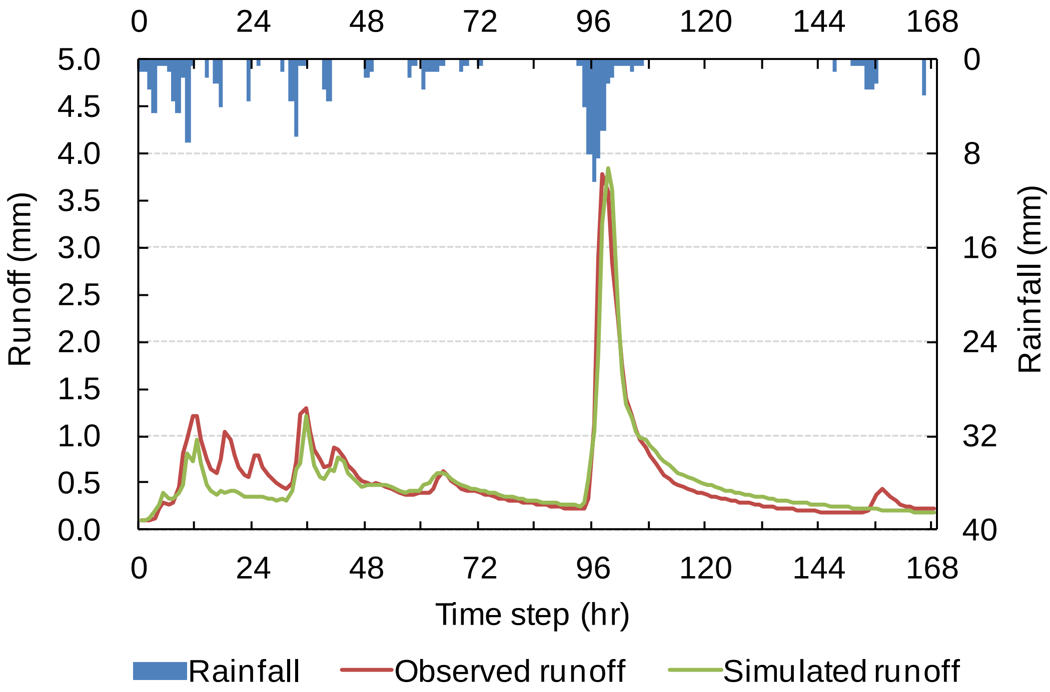


**Figure 6.2** Time series of observed and simulated runoff in the calibration period for Wye catchment.

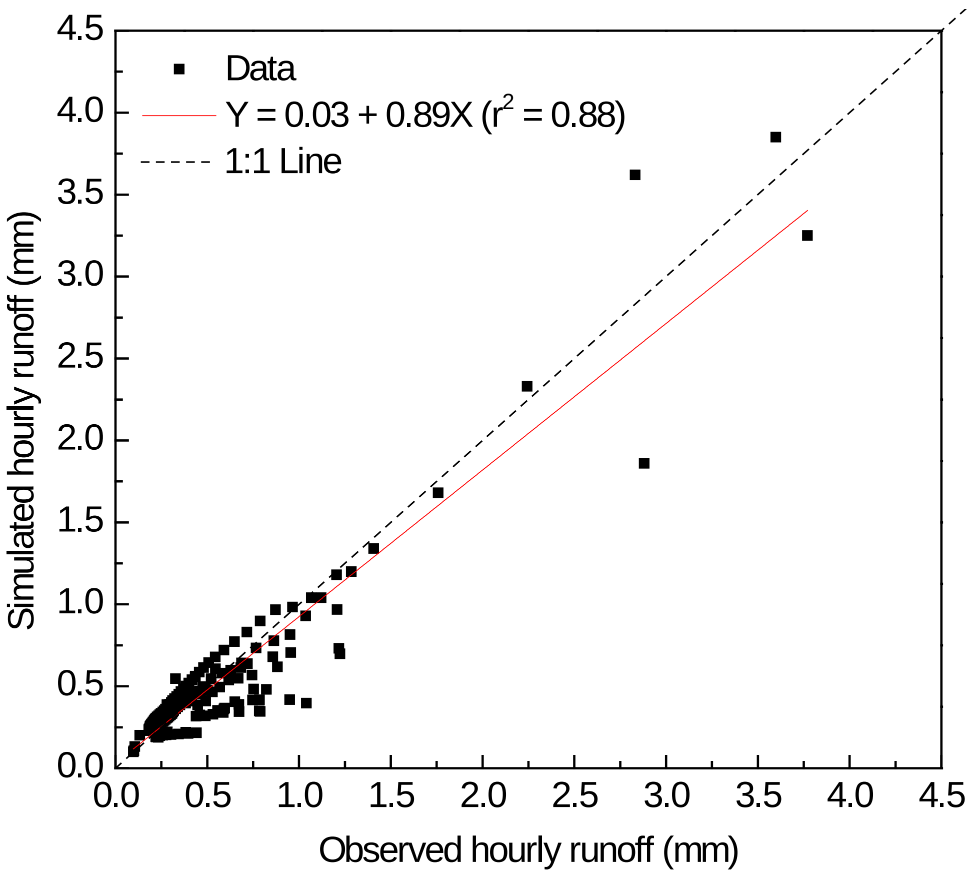


**Figure 6.3** Scattergram of observed and simulated hourly runoff during the calibration period of the Wye catchment.

The model validation was conducted using the observed river flow data in the one-week period commencing 14th Aug 2004. The identical parameter set optimized in the calibration period was employed to model the river flow through the validation period.

The observed and simulated hydrographs are shown in Figure 6.4. The efficiency of the modelling result reaches 0.88, and the observed and simulated flow regression line is displayed in Figure 6.5. The slope of the line is 0.94 with $r^2$ = 0.92.

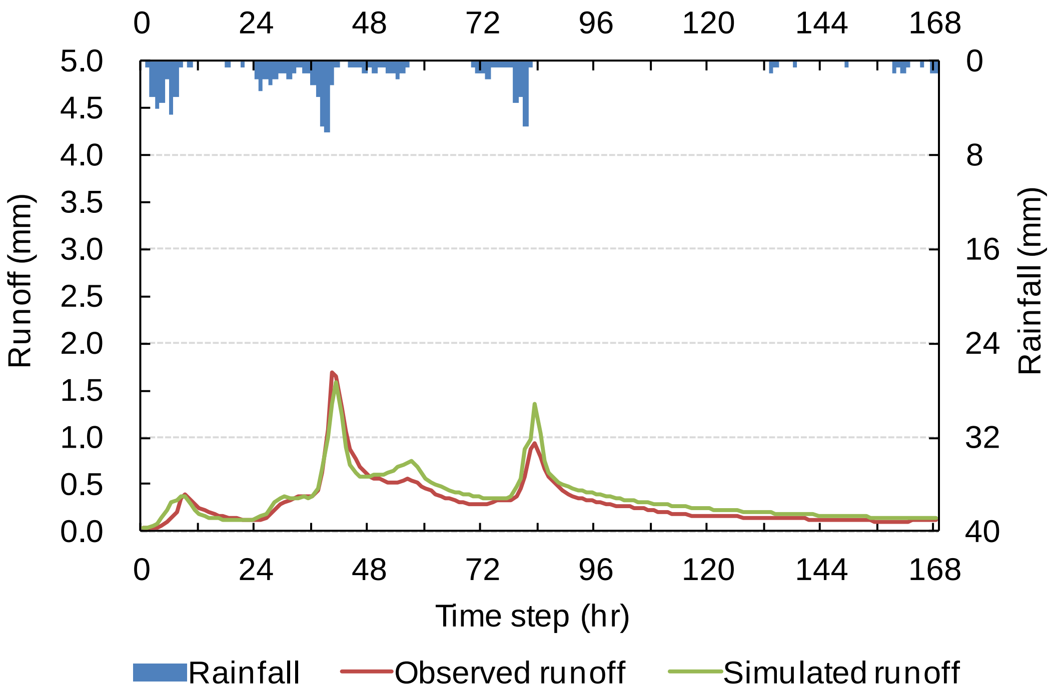


**Figure 6.4** Time series of observed and simulated runoff in the validation period for the Wye catchment.

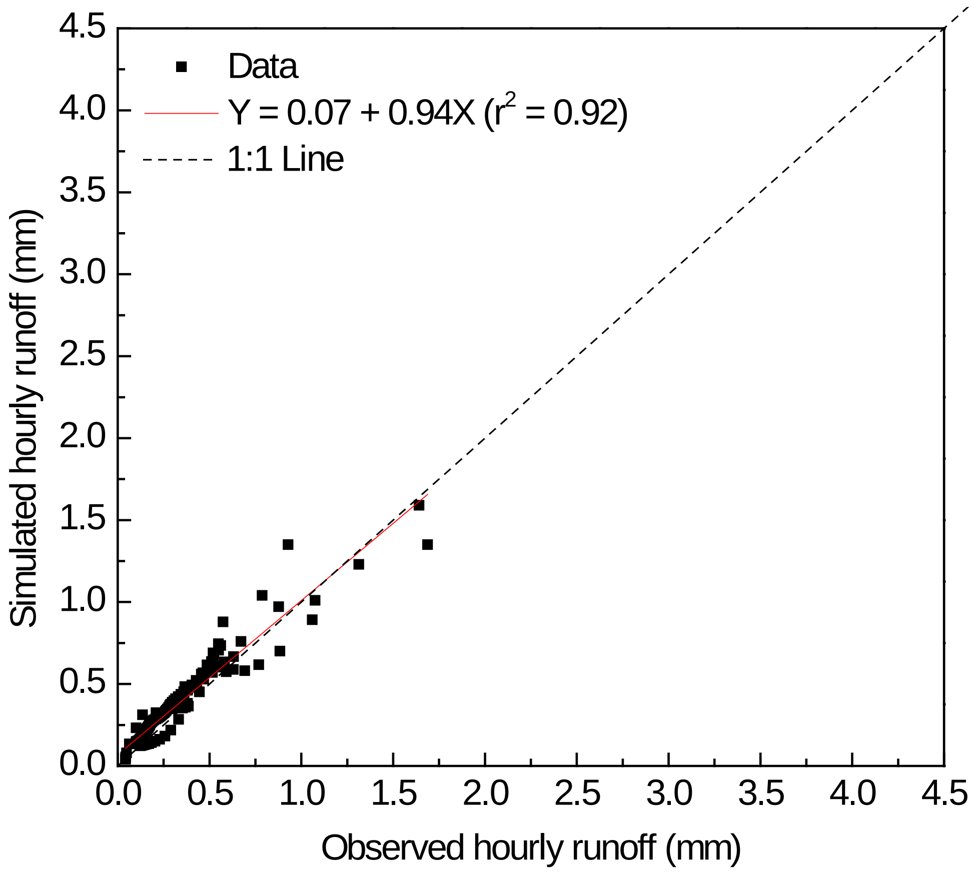


**Figure 6.5** Scattergram of observed and simulated hourly runoff during the validation period of the Wye catchment.

Overall, the Nash-Suttcliffe simulation efficiencies of the calibration and validation periods are both over 0.85. The slopes of the regression lines between the observed and simulated river flow for both the calibration and validation periods are 0.89 and 0.94 respectively. The coefficient of determination ($r^2$) for the linear regressions is around 0.90 for the two periods. This result implies that the model performed well with the optimized parameter set in Wye catchment in summer storm events.

The area proportion covered by peat in Wye catchment is 43%, which is much lower than that in the Trout Beck catchment (90%). That may be the reason why the model parameter *m* value in Wye catchment is much larger than that in the catchment of Trout Beck. The *m* value in peatlands is normally smaller than for other types of soil due to the difference in soil properties such as specific yield (Beven, 1997).

### 6.2.2 Scenario outcomes in the Wye catchment

Land cover scenario groups similar to those in the catchment of Trout Beck were formulated to verify the three principles of land cover change impact obtained from the scenario study in the Trout Beck catchment in the last chapter. In all scenarios, the input situations and the scenario patterns of each group are kept parallel with those used in Trout Beck in which the three test principles have originally been derived. This method aims to retain the validity of the scenario study in an alternative catchment to test the land cover change impact principles. The 1-hour 20 mm storm event with uniform rainfall rate is still employed as per the Trout Beck scenarios, and the parameters in the scenario formulation process remain the same too. The scenarios are divided into three groups, i.e. the buffer strip scenario group, the random patch scenario group, and the slope-patch scenario group. These scenario groups and their matching principles will be discussed respectively in this section.

The complex land cover status in the catchment is simplified resulting in a uniform *Eriophorum*-covered scenario which is treated as a 'normal' condition and applied, for the purpose of the experiment, as a standard to evaluate the modelling results of other land cover scenarios in this chapter. Other land cover change scenarios are created by changing part of the *Eriophorum* land cover to other types of vegetation cover, as was done in the Trout Beck catchment.

#### 6.2.2.1 Buffer strip scenarios

The buffer strip scenario group has been used primarily to examine the land cover change principle (1).

The first scenario set is concerning the position of the buffer strip, shown as Figure 6.6 (for 10% area) and Figure 6.7 (for 20% area).

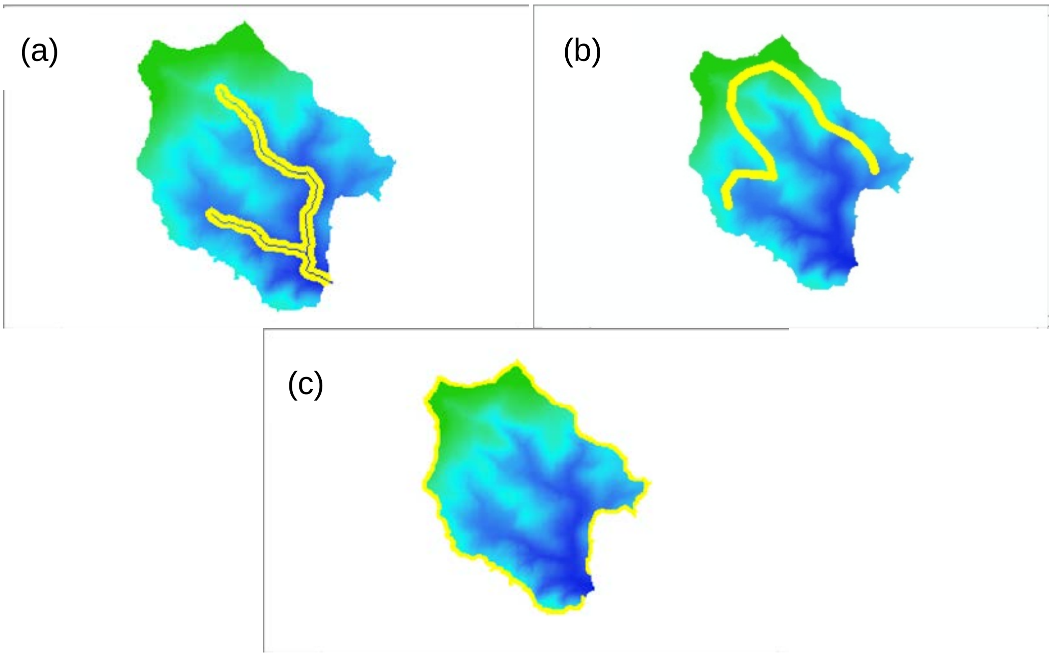


**Figure 6.6** Scenarios of buffer strips with a 10% area in different positions on the hillslope: (a) riparian buffer strip, (b) mid-hillslope buffer strip, (c) headwater buffer strip.

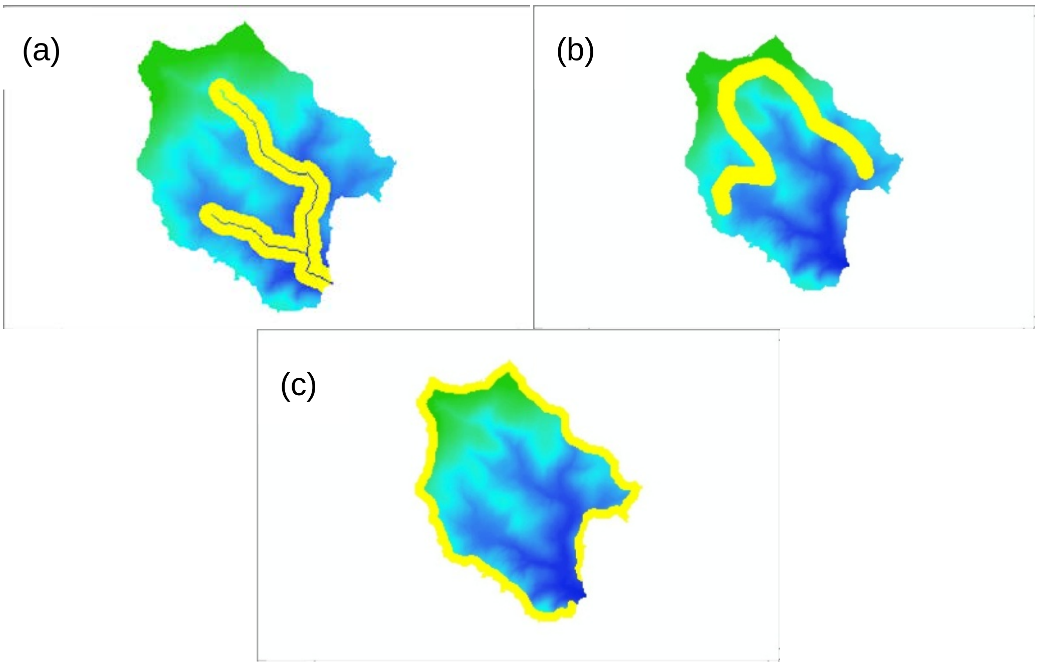


**Figure 6.7** Scenarios of buffer strips with a 20% area in different positions on the hillslope: (a) riparian buffer strip, (b) mid-hillslope buffer strip, (c) headwater buffer strip.

For bare peat scenarios, all of them produce higher and earlier peaks than the normal peak. The differences between 10% area scenarios are not clear (see Figure 6.8); while 20% area scenarios indicate that the riparian buffer strip has a larger impact on river flow than the other two and the mid-hillslope buffer strip scenario has a bigger influence than the headwater buffer strip one (see Figure 6.9). In both the 10% and 20% scenarios, the orders of rising limbs of peaks are the same as the riparian buffer strip, the mid-hillslope buffer strip, and lastly the headwater buffer strip, which reflects the order of impact on river discharge. In *Sphagnum* scenarios, most scenarios have lower and later peaks than the normal one. The orders of rising limbs of peaks are converse to the order in the bare peat scenarios, as illustrated by Figure 6.10 and Figure 6.11. Overall, the result of buffer strip position scenarios matches the first part of principle (1), i.e. the larger buffer strip closer to the river channel has more impact on river flow.

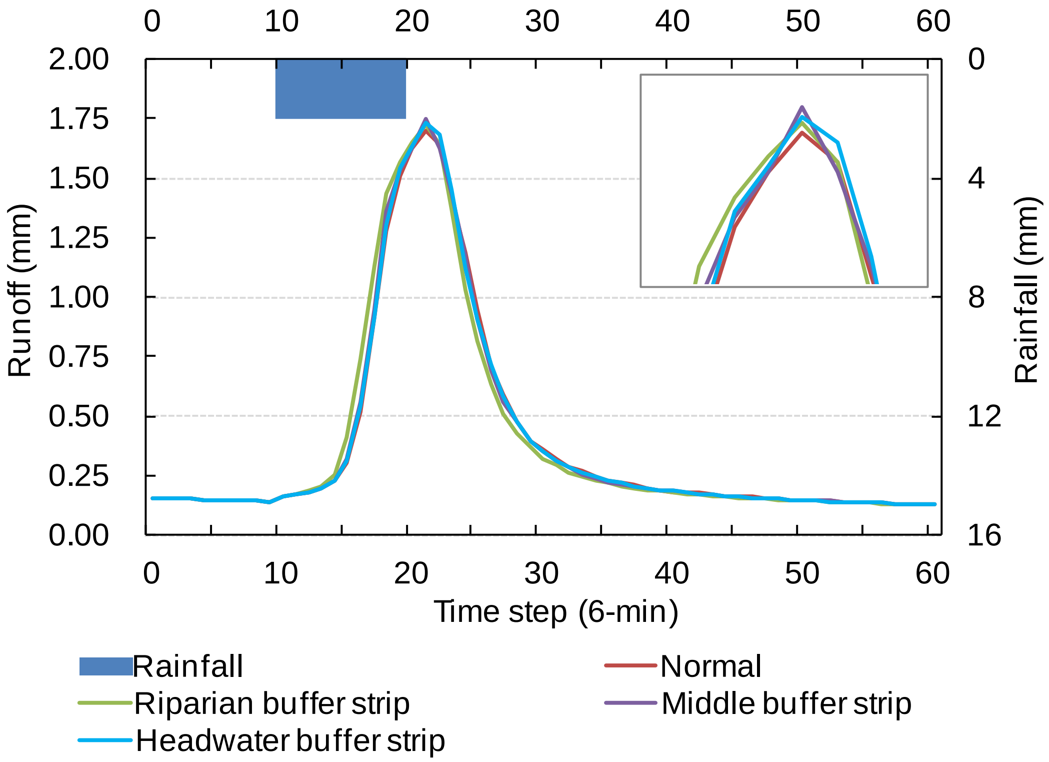


**Figure 6.8** Hydrographs of 10% area bare peat buffer strip scenarios in different positions.

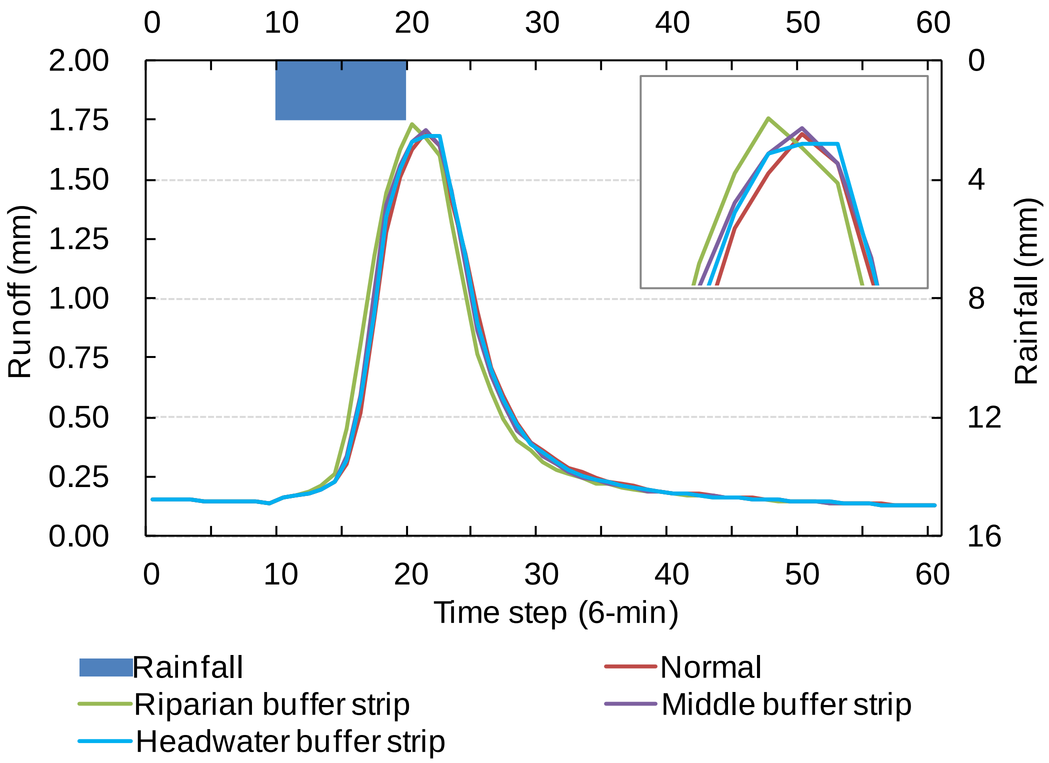


**Figure 6.9** Hydrographs of 20% area bare peat buffer strip scenarios in different positions.

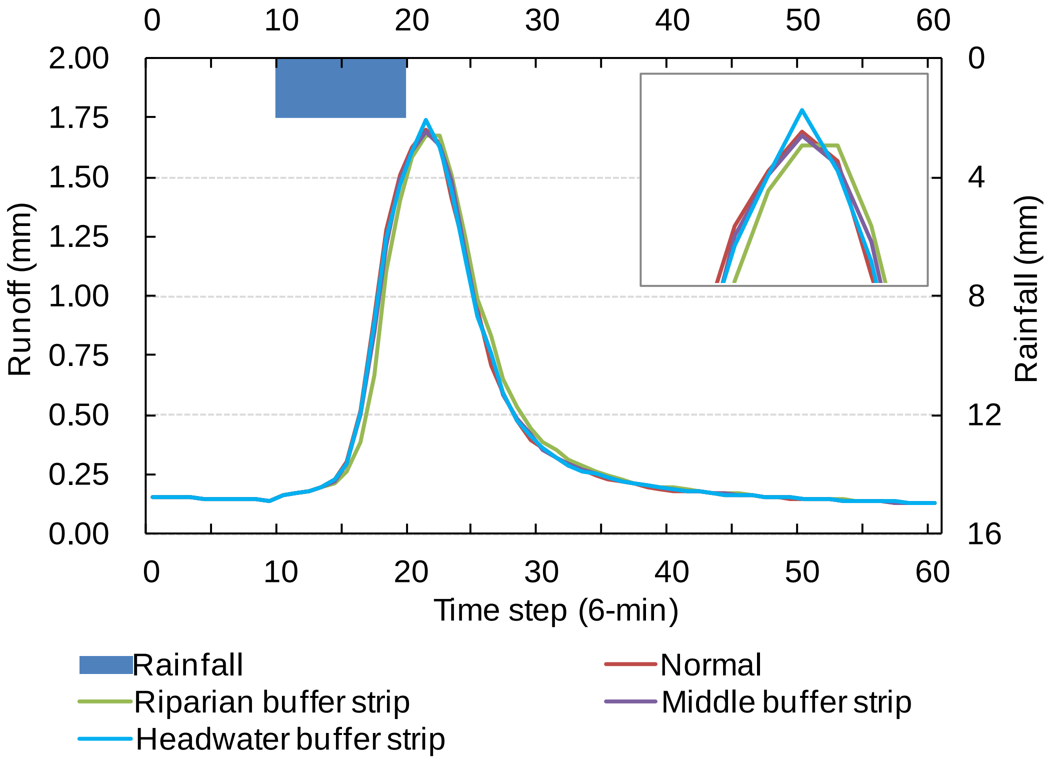


**Figure 6.10** Hydrographs of the 10% area *Sphagnum* buffer strip scenarios in different positions.

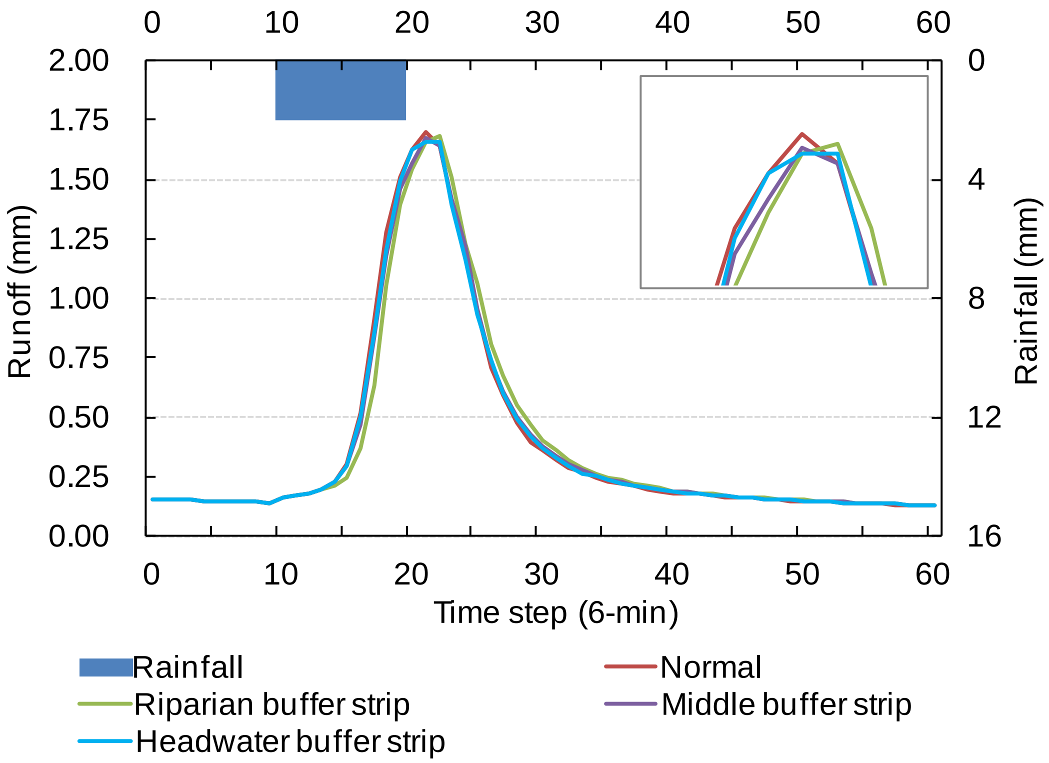


**Figure 6.11** Hydrographs of the 20% area *Sphagnum* buffer strip scenarios in different positions.

Riparian buffer strip scenarios, based on stream channel networks of varying branches, are formulated to investigate the second part of principle (1) in the Wye catchment. Two sets of riparian buffer strip scenarios for the 10% area and 20% area land cover change, in which riparian buffer strips are surrounding different stream channel networks, are formulated in the Wye catchment to investigate the last part of principle (1). The channel networks are based on different thresholds of upslope accumulative areas, which are identical to those in the Trout Beck catchment scenarios, in order to hold the consistency of scenario study. Figure 6.12 and Figure 6.13 present the 10% area buffer strip scenario set and the 20% area buffer strip scenario set respectively.

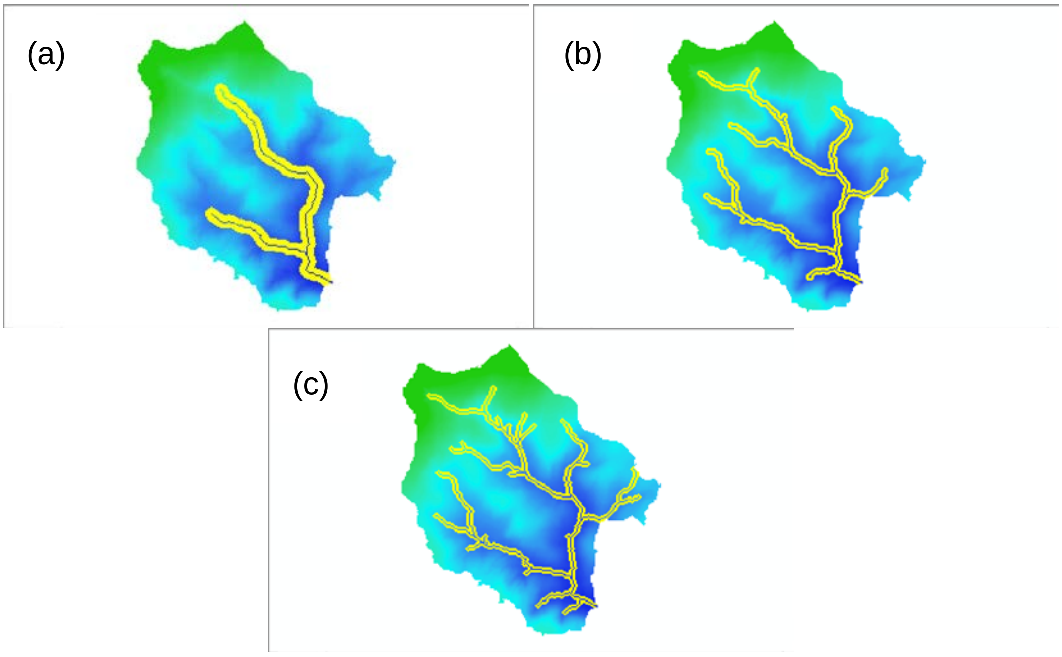


**Figure 6.12** Scenarios of 10% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions; (a) 3000-cell accumulative area, (b) 500-cell accumulative area, (c) 250-cell accumulative area.

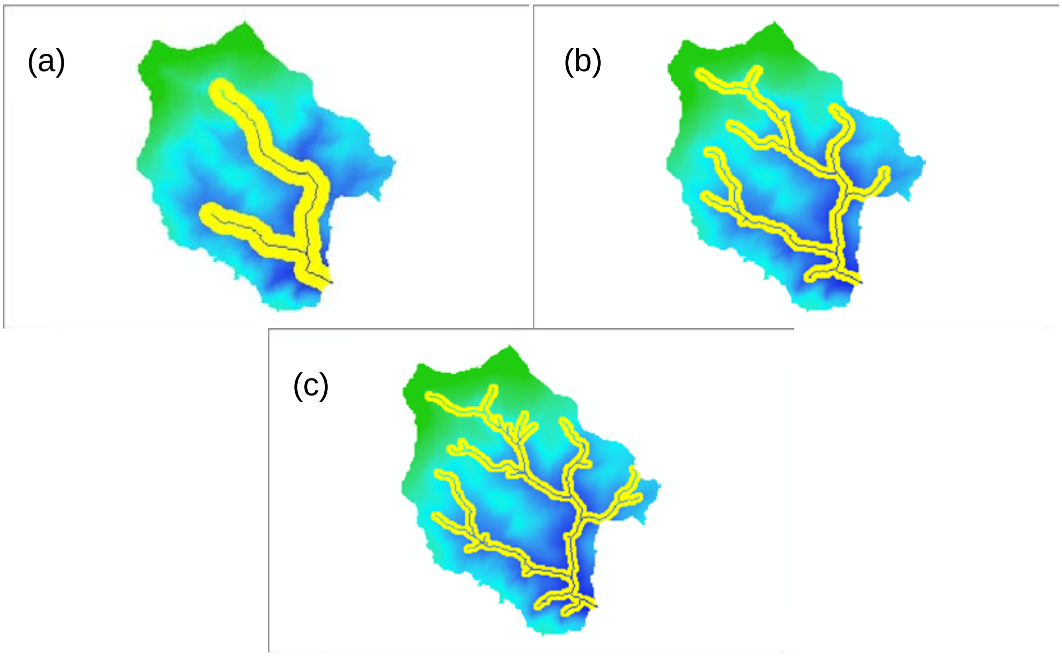


**Figure 6.13** Scenarios of 20% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions; (a) 3000-cell accumulative area, (b) 500-cell accumulative area, (c) 250-cell accumulative area.

From the results of the bare peat scenarios (see Figure 6.14 and Figure 6.15), the 250-cell riparian bare peat buffer strip gives a higher peak than the other two but the differences (less than 2%) are not as noticeable as those in the same scenarios used at Trout Beck in Chapter 4. The 500-cell and 3000-cell riparian bare peat buffer strips do not have evident distinctions between their simulation results in both sets. For the group of *Sphagnum* scenarios (see Figure 6.16 and Figure 6.17), all of the *Sphagnum* buffer strips have similar impacts on river flow, and their hydrographs almost overlap during peak time for both 10% and 20% area scenario groups.

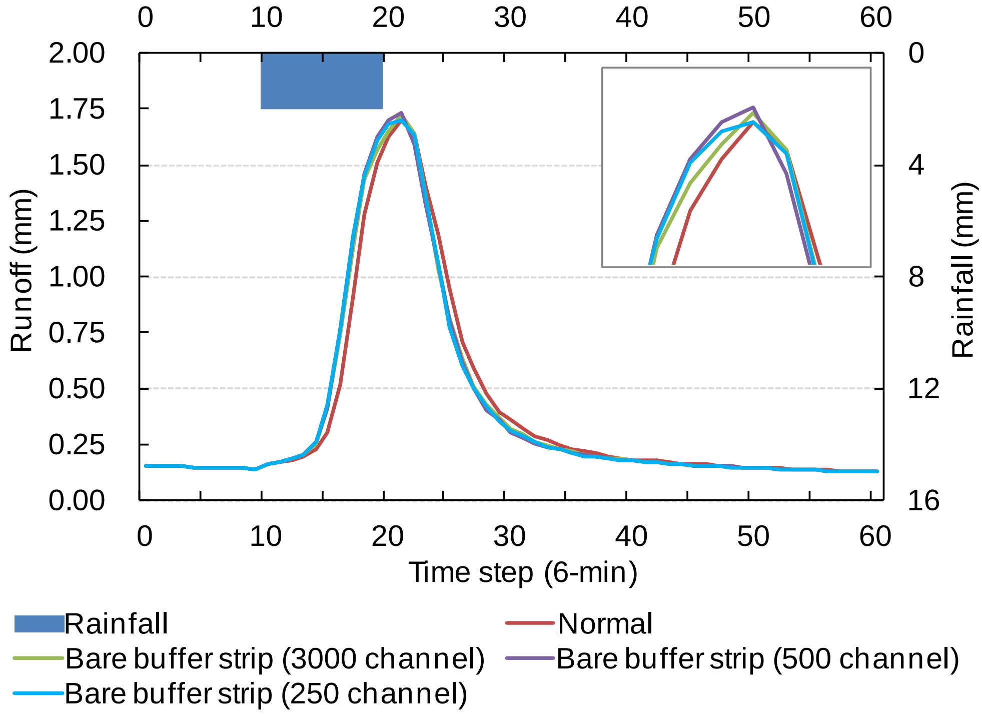


**Figure 6.14** Hydrographs of 10% area riparian bare buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

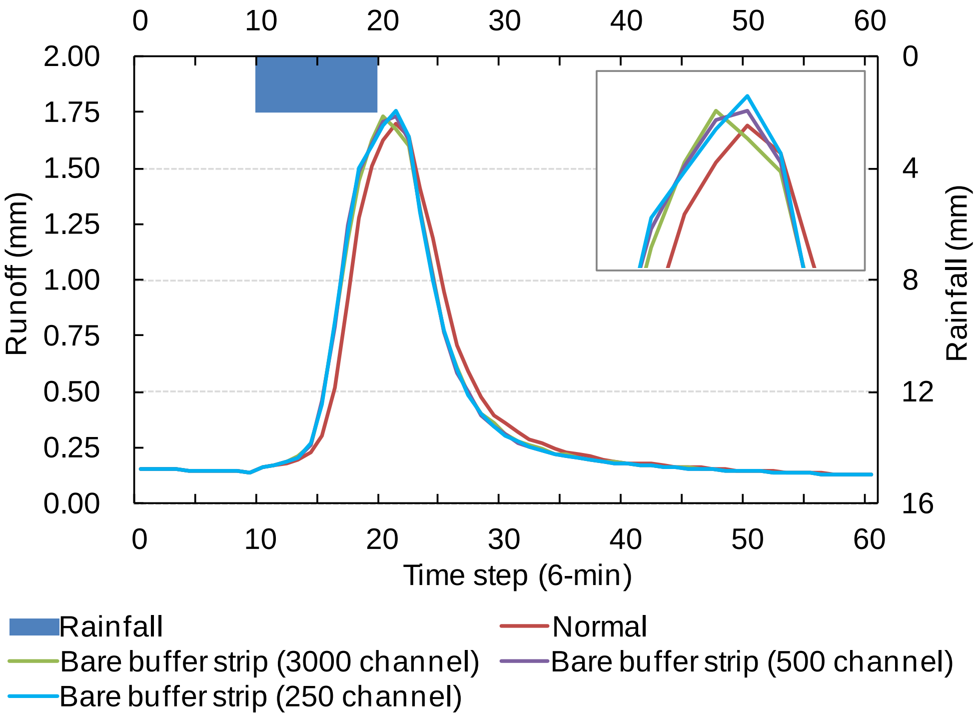


**Figure 6.15** Hydrographs of 20% area riparian bare buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

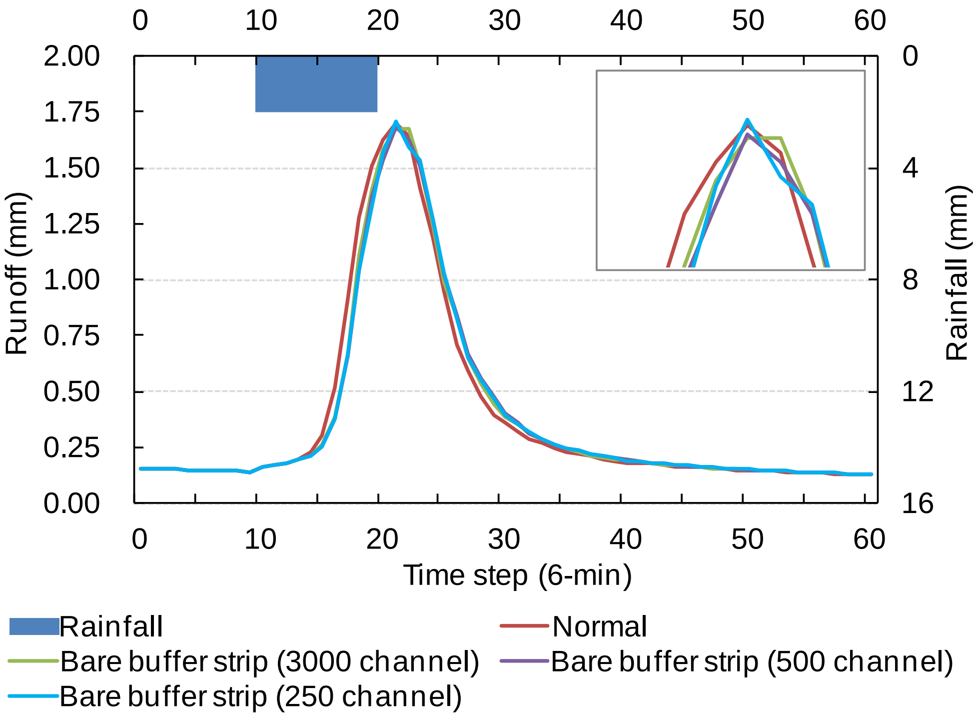


**Figure 6.16** Hydrographs of 10% area riparian *Sphagnum* buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

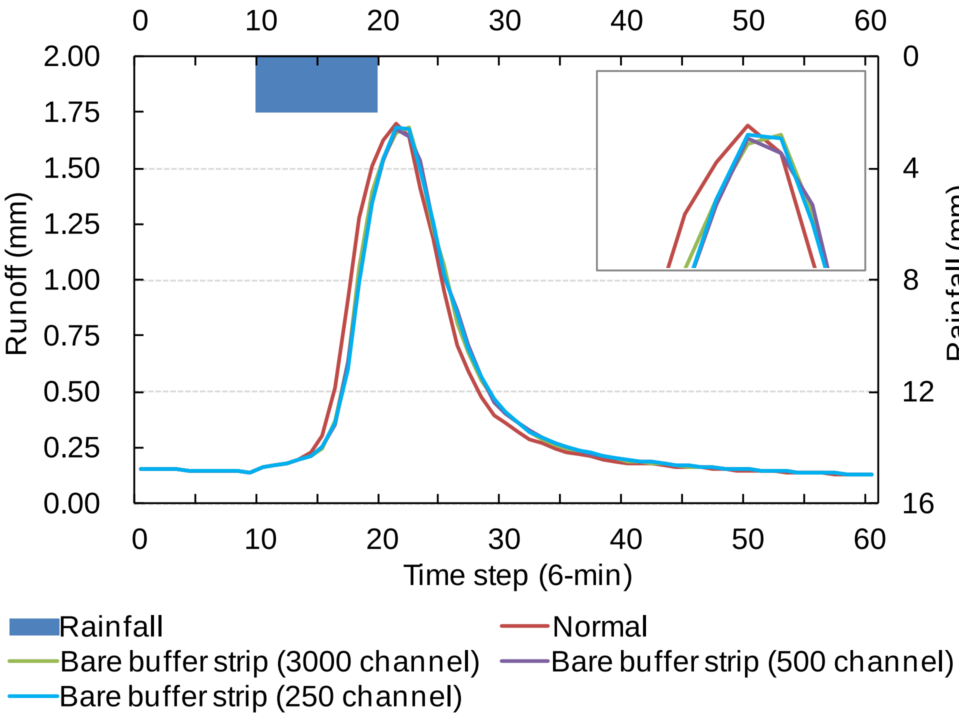


**Figure 6.17** Hydrographs of 20% area riparian *Sphagnum* buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

Overall, the differences between the buffer strip scenarios and the normal scenario are mostly inconspicuous and much lower than those differences found for Trout Beck. For principle (1), a wider bare peat buffer strip nearer to the river channels gives a higher peak and reduced delay to peak, and, conversely, a wider buffer strip with higher density vegetation (e.g. *Sphagnum*) leads to a lower peak and postpones the peak. The buffer strip scenario result of the Wye in this section mainly supports this part of principle (1). However, the narrow buffer strip surrounding upstream and downstream channels just have a slightly greater effect than a wide buffer strip along the main channel in the bare peat land cover case, and they do not produce different hydrographs for the case of *Sphagnum* land cover change.

### 6.2.2.2 Random patch scenarios

For principle (2), a series of random patch land cover change scenarios was produced. The land cover change patches in each scenario are picked in the catchment based on the 2-dimention uniform distribution, in which the method was used in the random patch scenario group of the Trout Beck catchment in chapter 5. The scenarios of different patch sizes are shown in

Figure 6.18 for 10% area patch scenarios and Figure 6.19 for 20% area patch scenarios.

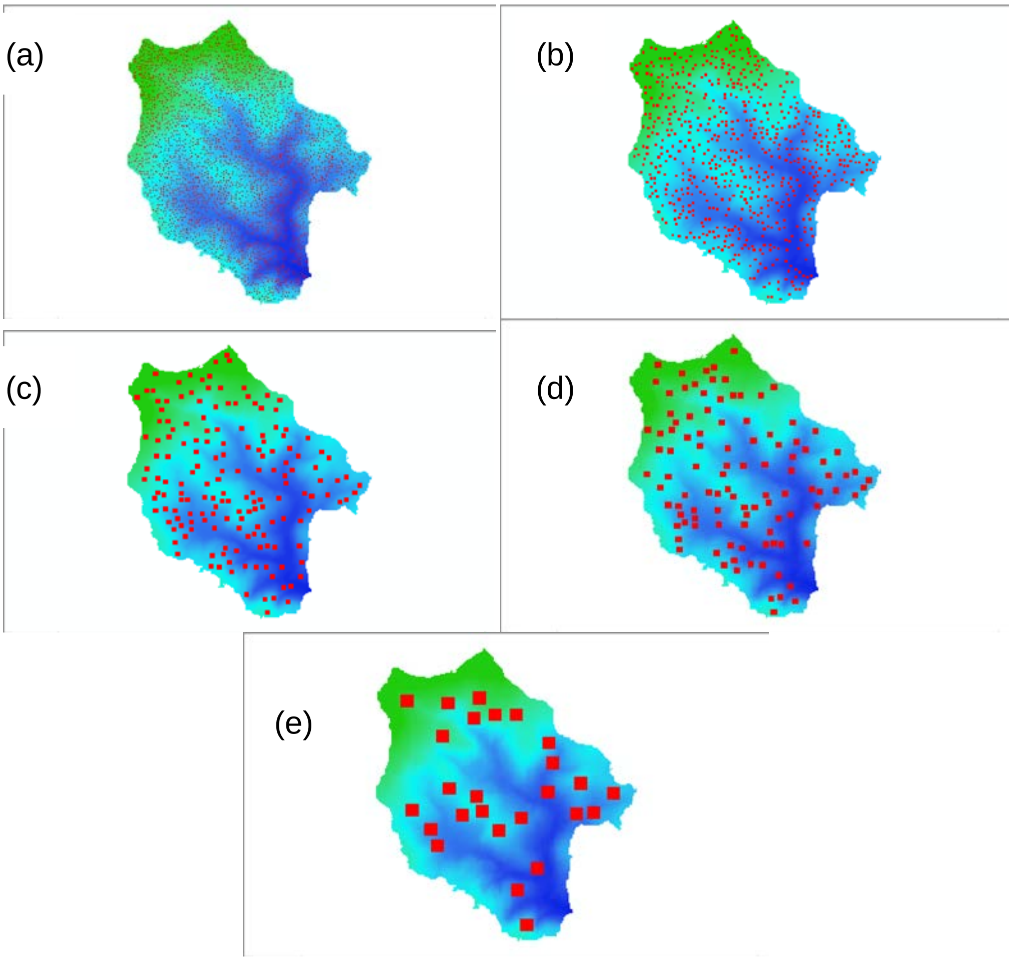


**Figure 6.18** Scenarios of random patches covering a total of 10% of the area of the catchment in each case; (a) 400m$^2$-patch scenario, (b) 1600m$^2$-patch scenario, (c) 6400m$^2$-patch scenario, (d) 10000m$^2$-patch scenario, (e) 40000m$^2$-patch scenario.

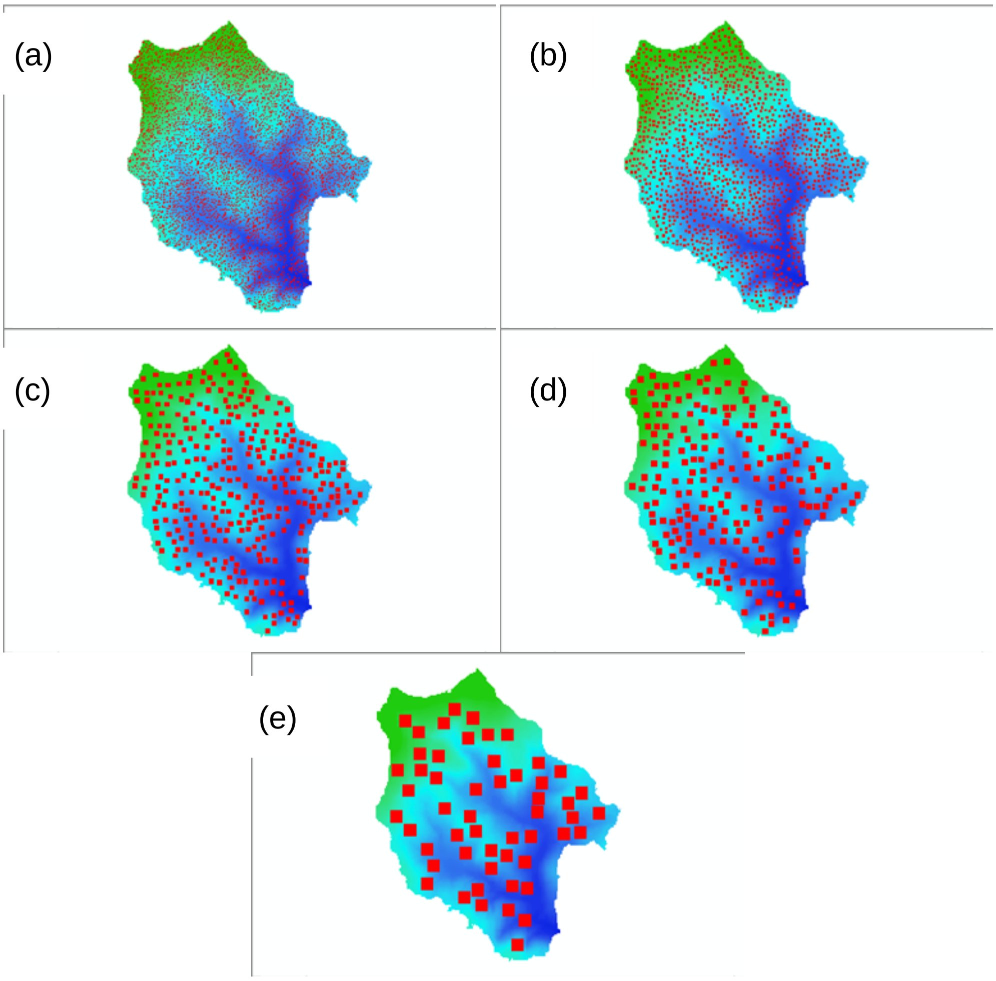


**Figure 6.19** Scenarios of random patches covering a total of 20% of the area of the catchment in each case; (a) 400m$^2$-patch scenario, (b) 1600m$^2$-patch scenario, (c) 6400m$^2$-patch scenario, (d) 10000m$^2$-patch scenario, (e) 40000m$^2$-patch scenario.

For the scenario groups of 10% area land cover change, there are small differences between scenario hydrographs and the normal hydrograph. The flow peaks of the 10% bare peat scenarios are about 1% higher than the normal peak (Figure 6.20), while the differences between the 10% *Sphagnum* scenarios and the normal flow peak are less than 1% (see Figure 6.22).

The 20% bare peat scenario peaks are higher than the normal peak by 3% (Figure 6.21), and they have more effect than the 10% bare peat scenarios on river flow due to more bare peat area. However, for 20% *Sphagnum* cover scenarios (Figure 6.23), the hydrograph peaks produced are only lower than those in the 10% *Sphagnum* scenarios by 1%.

By and large, in the same group of scenarios, there is no notable difference between the hydrographs of the scenarios with differing patch sizes, which is consistent with principle (2). The difference between 10% and 20% area land cover change for each land cover type is not as remarkable as that found in the scenarios for the Trout Beck catchment.

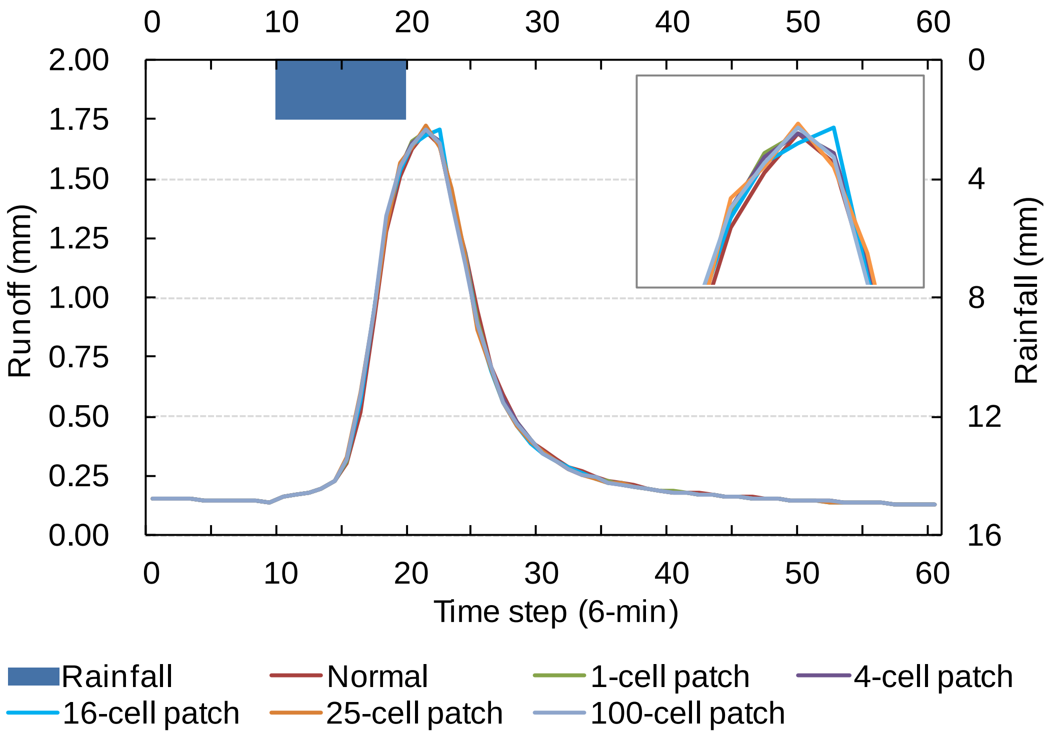


**Figure 6.20** Hydrographs of 10% area bare peat patch scenarios.

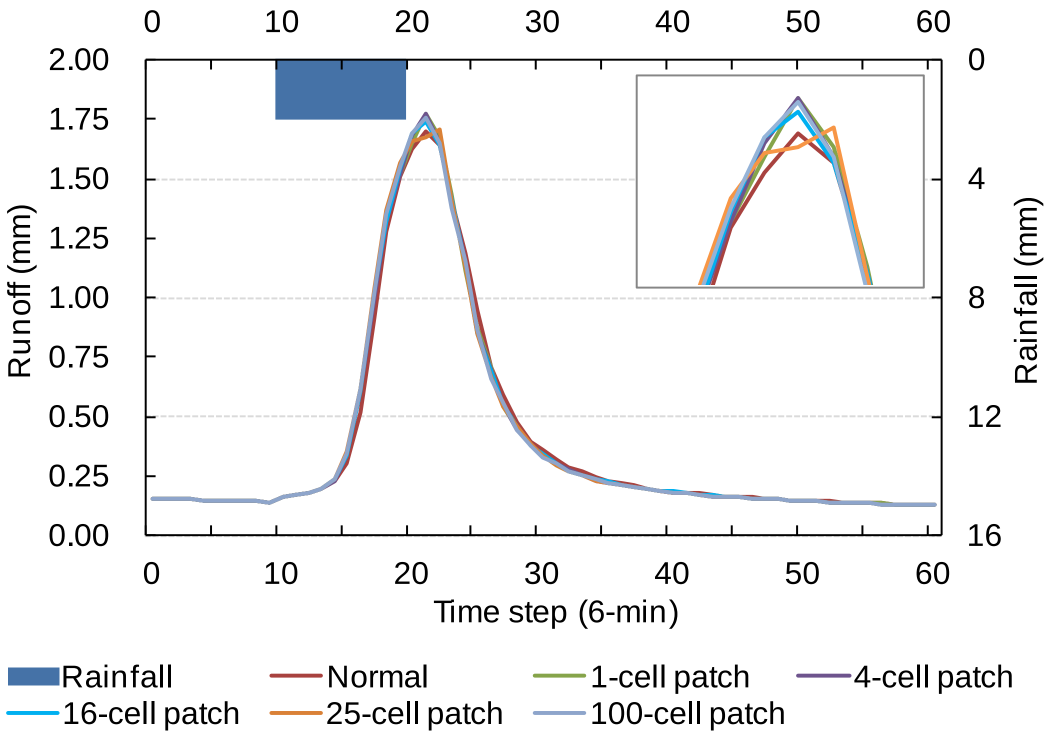


**Figure 6.21** Hydrographs of 20% area bare peat patch scenarios.

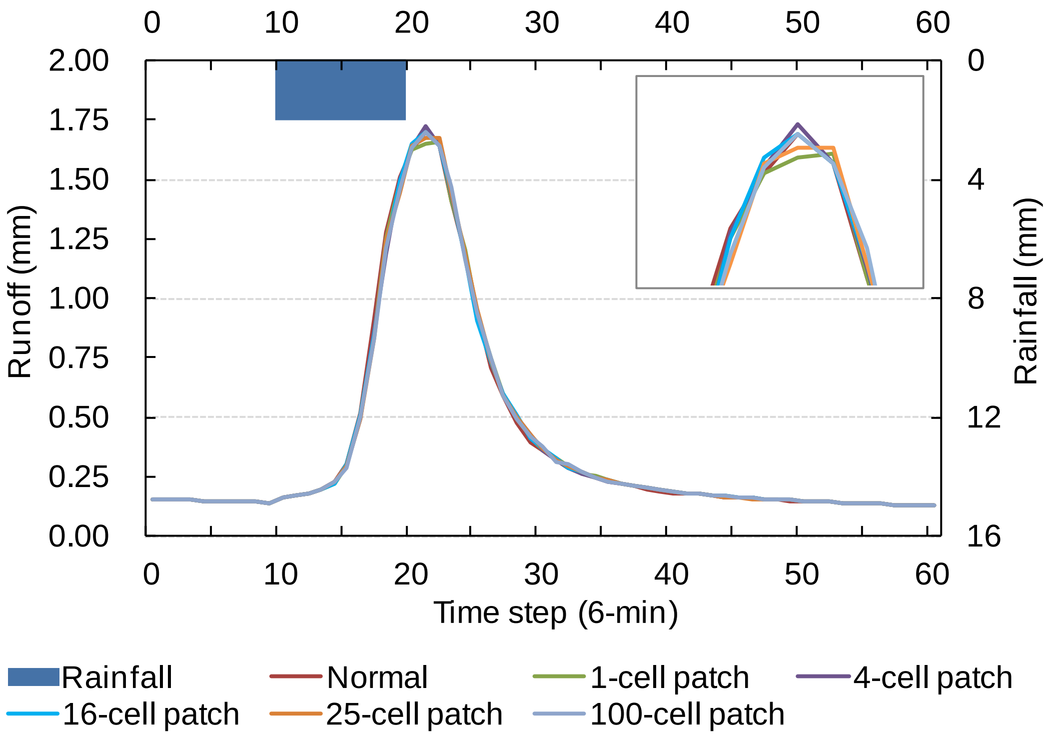


**Figure 6.22** Hydrographs of 10% area *Sphagnum* patch scenarios

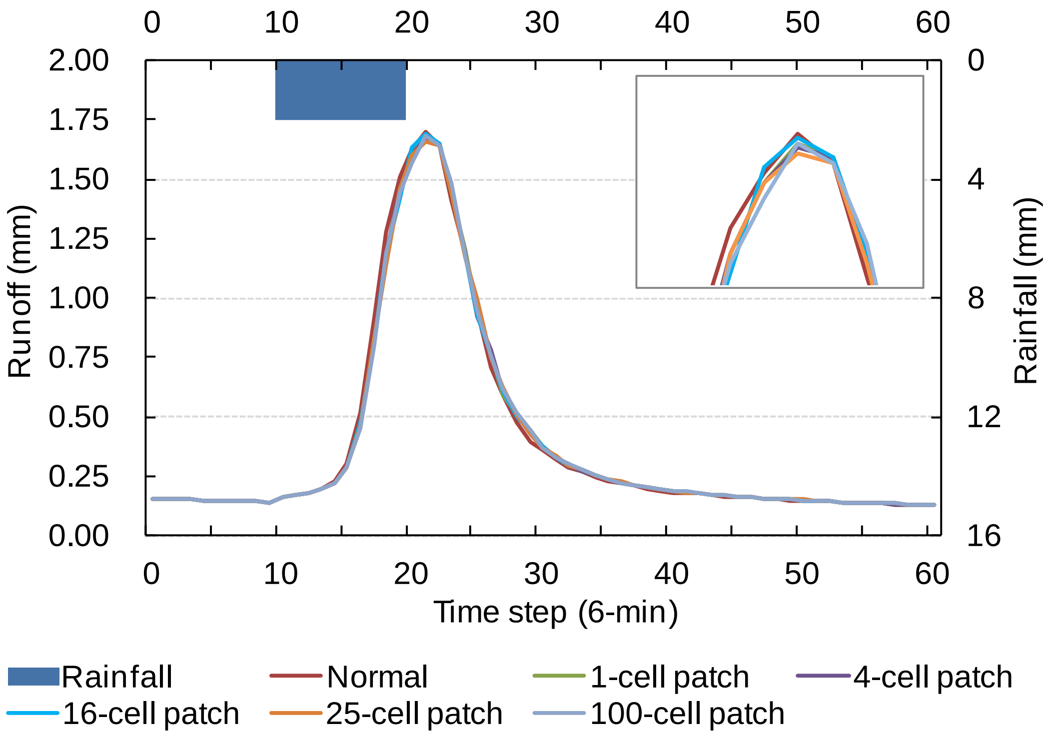


**Figure 6.23** Hydrographs of 20% area *Sphagnum* patch scenarios.

### 6.2.2.3 Slope-patch scenarios

Slope-patch scenarios are investigated in the Wye catchment to evaluate land cover change impact principle (3). Steep and gentle slope patch scenarios are still involved in this scenario study.

The Wye catchment is very steep and the mean slope of it reaches probably 20% for 20m×20m cells (the slope map is shown as Figure 6.24). As a consequence of this, much more than half of the grid cells are located on slope steeper than 10% which was used as the threshold of the slope in the slope-patch scenarios in the catchment of Trout Beck. However, in order to retain the consistency of the study on the slope-patch scenario in different catchments, the threshold 10% is still employed to distinguish steep patches and gentle patches. Two sets of slope-patch scenarios are produced, as shown in Figure 6.25 and Figure 6.26 for the 10% and 20% land cover change area scenario groups respectively.

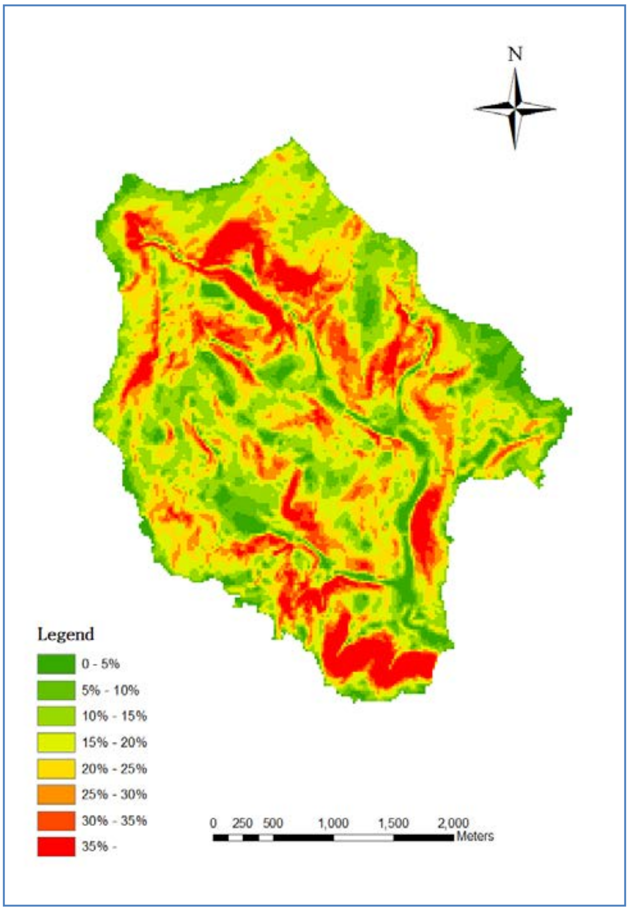


**Figure 6.24** The slope map of the Wye catchment.

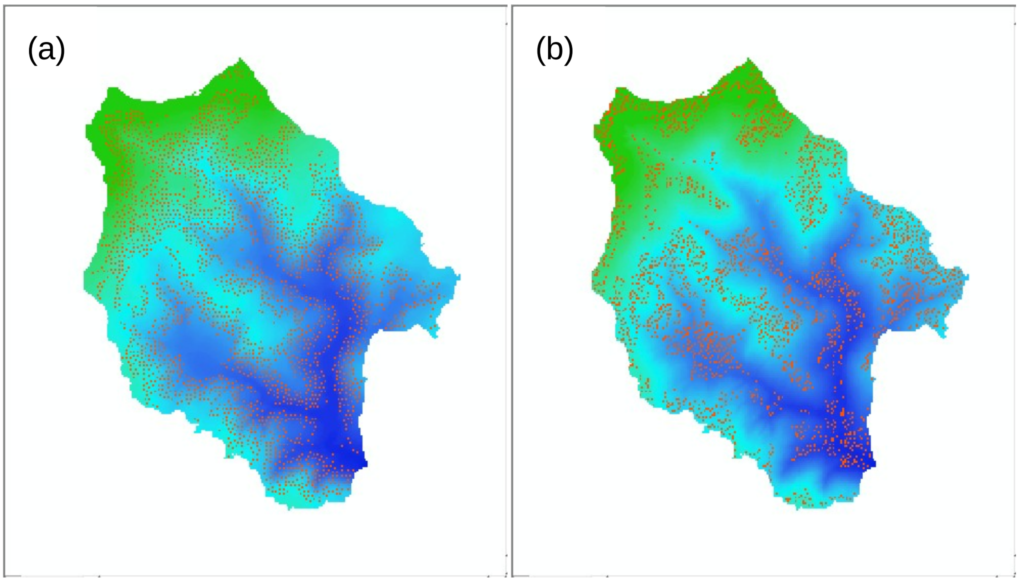


**Figure 6.25** Scenarios of 10% area random patches on slopes greater than 10% (a), and on slopes less than 10% (b).

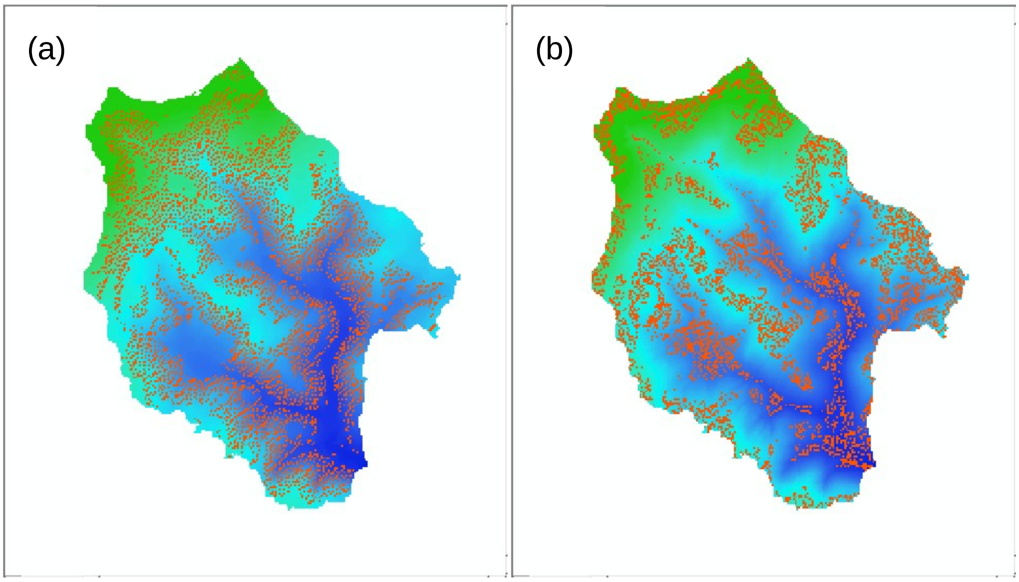


**Figure 6.26** Scenarios of 20% area random patches on slopes greater than 10% (a), and on slopes less than 10% (b).

For the entire slope-patch scenario simulation results, bare peat patch scenarios give higher and earlier peaks than the normal scenario, and conversely *Sphagnum* patch scenarios create lower and later peaks than the normal one. The two gentle slope patch scenarios, with bare peat land cover change, generate marginally earlier peaks than their matching steep slope patch scenarios. For the 20% area bare peat scenarios, a slightly higher peak of gentle slope patch scenario is given than that of steep slope scenario (Figure 6.27 and Figure 6.28).

For both of the groups of *Sphagnum* patch scenarios, the gentle slope patch scenarios result in later peaks than the steep slope patch scenarios; whilst their peak flow values are very close (see Figure 6.29 and Figure 6.30).

Land cover change for gentle slope patches has more impact on river flow compared to the same land cover change on steep slope patches, even though the difference is smaller than that found for the slope-patch scenarios in Trout Beck (Chapter 5). This conclusion is in line with land cover principle (3).

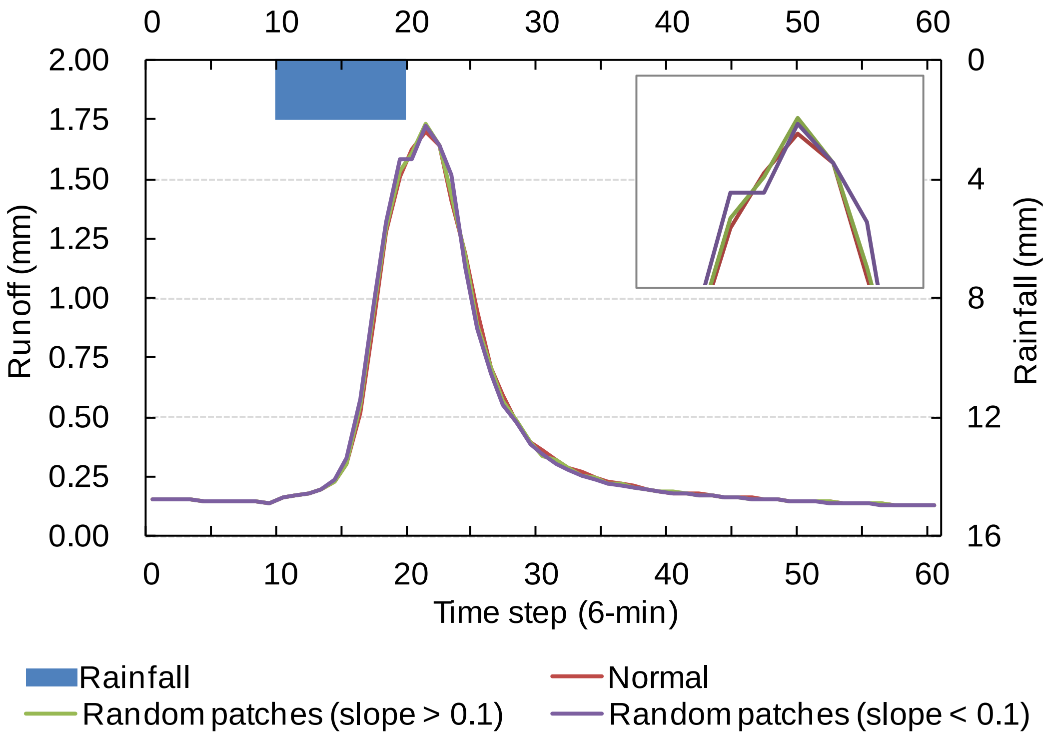


**Figure 6.27** Simulation hydrographs of scenarios with 10% area bare peat patches on steep slope (> 0.1) and gentle slope (< 0.1).

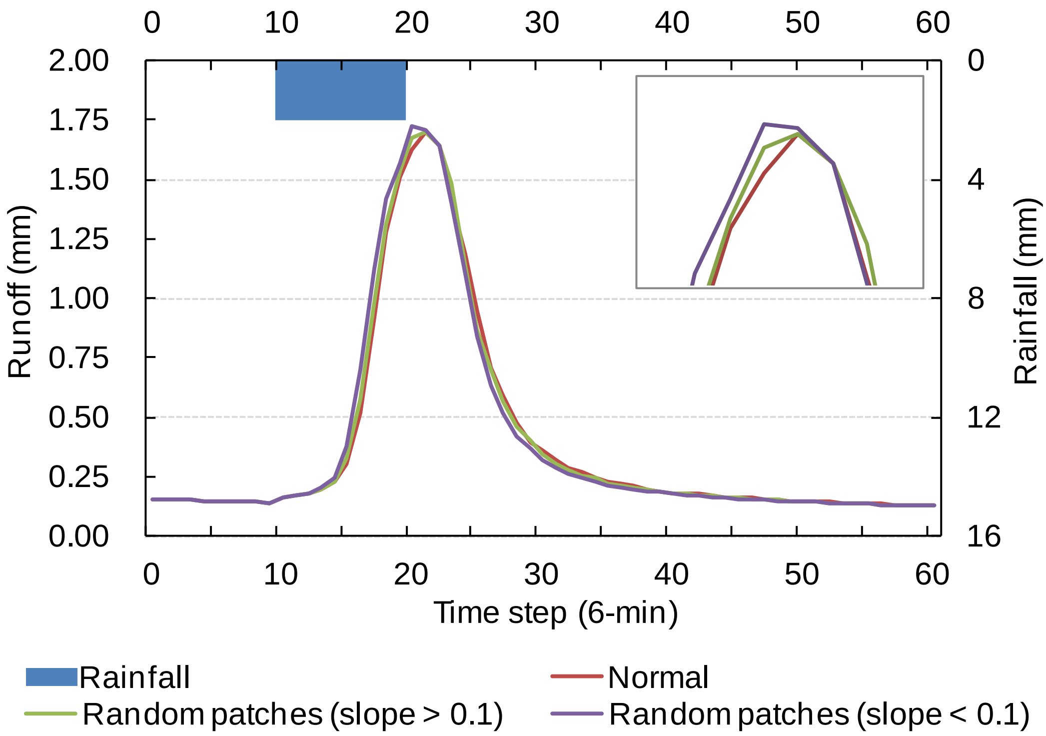


**Figure 6.28** Simulation hydrographs of scenarios with 20% area bare peat patches on steep slope (> 0.1) and gentle slope (< 0.1).

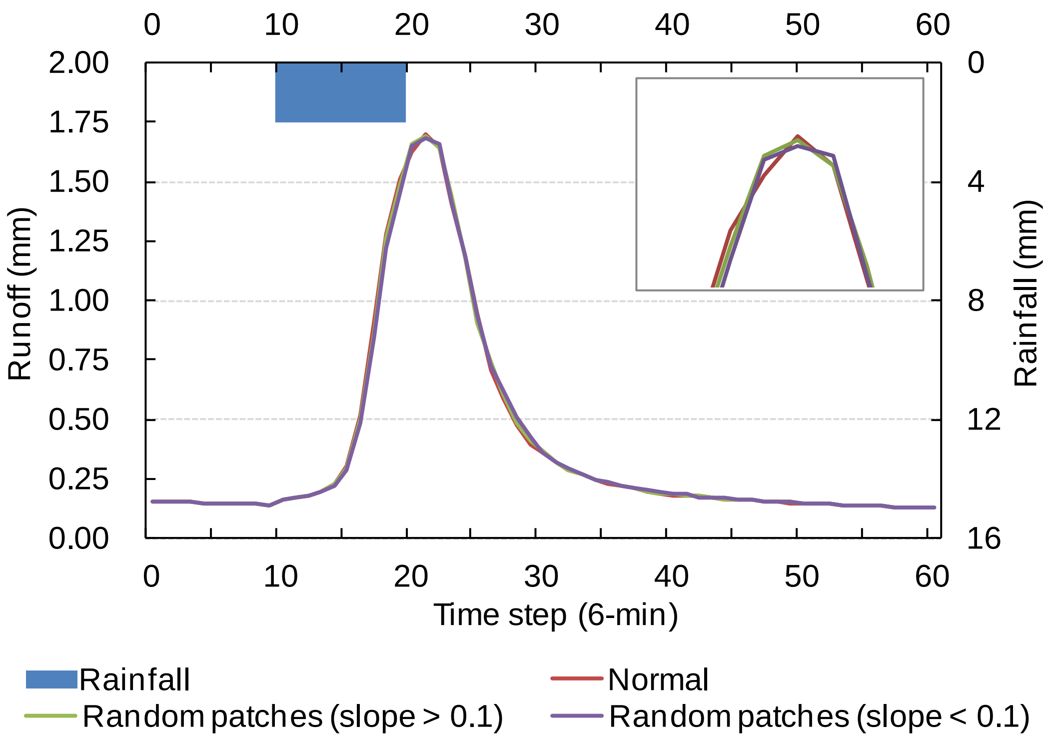


**Figure 6.29** Simulation hydrographs of scenarios with 10% area *Sphagnum* patches on steep slope (> 0.1) and gentle slope (< 0.1).

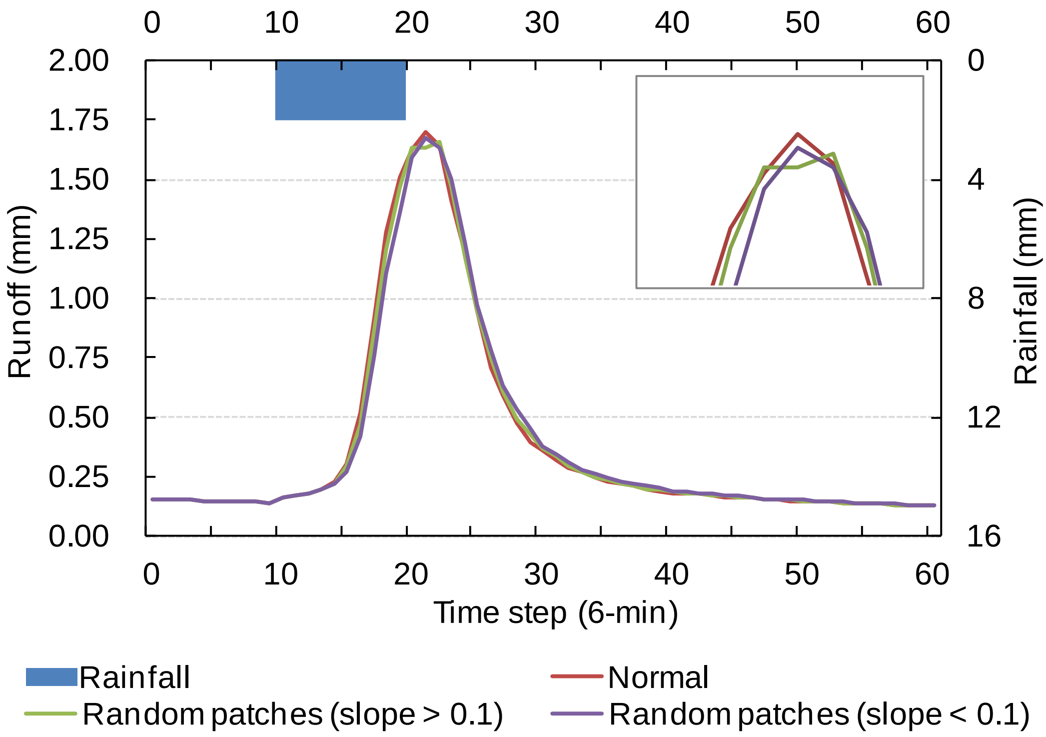


**Figure 6.30** Simulation hydrographs of scenarios with 20% area *Sphagnum* patches on steep slope (> 0.1) and gentle slope (< 0.1).

### 6.2.3 Summary of the scenario study in the Wye catchment

The three land cover change impact principles were checked through the three representative scenario group model runs. The basic point of each principle is supported by the modelling results of each matching scenario group. However, the magnitude of differences in areal weighted discharge peaks (Figure 6.31) was reduced compared with findings from Trout Beck. Most scenarios influenced flow peaks by less than 5% in flow rate compared to the peak of the normal scenario, and only the gentle slope patch scenario with 20% bare peat resulted in a change of peak flow timing by more than one time step (6 minutes). However, it should be noted that the peak of the normal scenario in the Wye catchment is much earlier and higher than that of the normal scenario for Trout Beck. Their rainfall inputs are the same for both of the normal scenarios, and the difference of river flow at the start cannot account for such a large differences in peak flow. Furthermore, the groundwater deficit of the Wye catchment is larger than that of Trout Beck, so the runoff concentration in storms should be theoretically more attenuated in the Wye catchment.

The implication of these scenario results seems to be that some factors decrease or mitigate the impact of land cover change in the Wye catchment which has a similar area (around 11 $km^2$) to the Trout Beck catchment. Comparing the two peat catchments, the most prominent difference of the two catchments is the slope. The mean slope of cells (for 20 m × 20 m DEM data) in the Wye catchment is 20.0%, which is much higher than that of 9.1% in the Trout Beck catchment. The slope plays a vital role for overland flow movement which actually dominates the generating process of river flow peak in peat catchments. Thus, it is conceivable that the steep mean slope decrease the difference of the river flow responses to land cover change in the Wye catchment. A steep slope means overland flow has higher velocity and less time in the process of transport on the hillslope, so the faster and higher peaks which are narrowed by the process, are generated in all scenarios in the steep catchment. Thus, this mechanism narrows the difference between the land cover scenarios and makes it harder, in this expeditious flow response situation, to track the internal impact caused by land cover change on flow peaks.

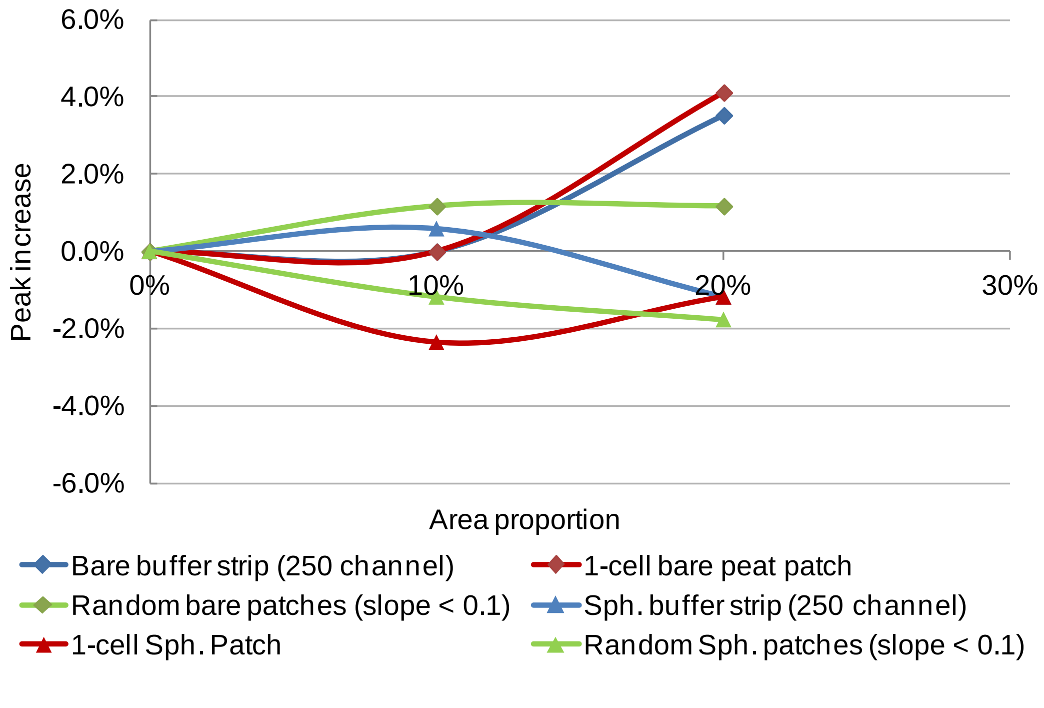


**Figure 6.31** Scenario comparison of impact on peak flow increase compared to the ‘normal’ scenario in the Wye catchment.

## 6.3 Model runs for the East Dart catchment, Bellever

The upland peat catchment of the East Dart lies on the east part of the Dartmoor National Park in southwest England, draining an area of 21.5 $km^2$.

It is very wet with a mean annual rainfall of 2088 mm (1961-1990) (CEH, 2012). The catchment ranges in elevation from 309 m AOD at the outlet to 601 m AOD at the top. The location and the map are shown in Figure 6.32.

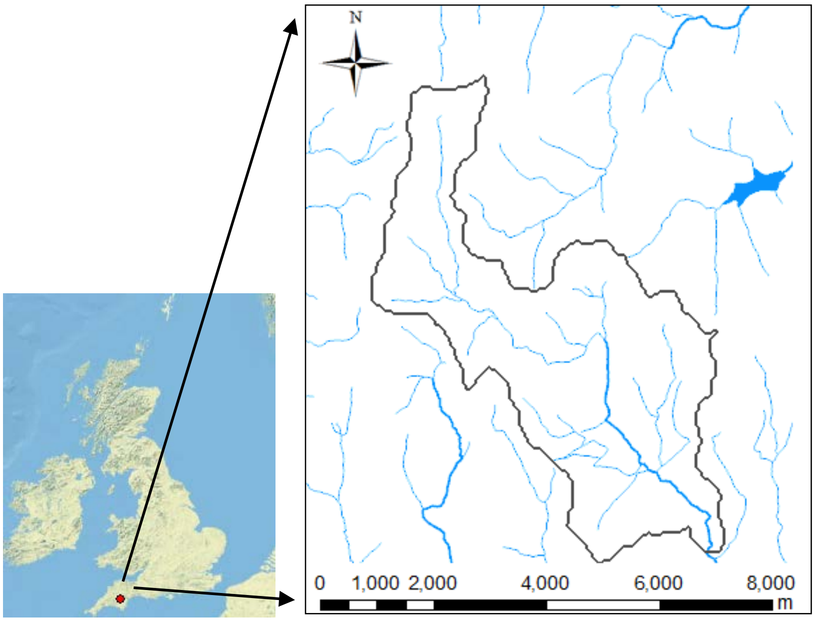


**Figure 6.32** Maps showing the location and the boundary of the East Dart catchment, Bellever.

In the East Dart catchment, 47% of the area is covered by peatland and there is low grade agriculture and woodland in the downstream area (9% area of the catchment). The catchment is mainly underlain by Dartmoor Granite. The mean slope of the catchment is 9.4% using 20 m × 20 m DEM data which is similar to the mean slope in the Trout Beck catchment.

### 6.3.1 Model calibration and validation in the East Dart catchment

For the model test in the East Dart catchment, the method and routine for model calibration and validation introduced in section 6.2.1 was utilized. Test conditions were retained to keep consistency across the three upland peat catchments. Two one-week periods in the summer of 2012 were picked for calibration and validation. Each period contains a big storm event, giving a valid magnitude of input rainfall to the model for testing.

The flow calibration was conducted for the one-week period commencing 22 September 2012. The parameter set, $m$=10 mm, $K$ =100 m hr$^{-1}$, $Kv$=30, with good modelling performance is gained through a series of test runs and simple parameter optimization.

Figure 6.33 illustrates the observed and simulated runoff during the calibration period. The Nash-Sutcliffe efficiency of the simulated result is 0.98. The scattergram of observed and simulated hourly river runoff and the linear regression is shown in Figure 6.34. The slope of the regression line is 0.99 which is very close to 1.0.

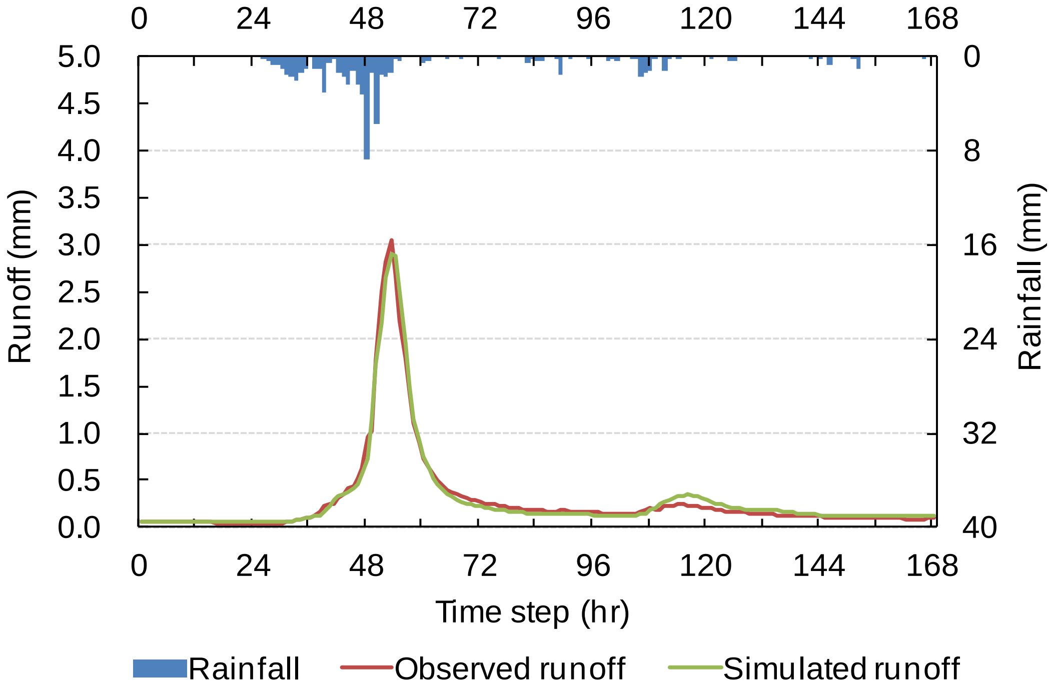


**Figure 6.33** Time series of observed and simulated runoff in the calibration period for the catchment of East Dart.

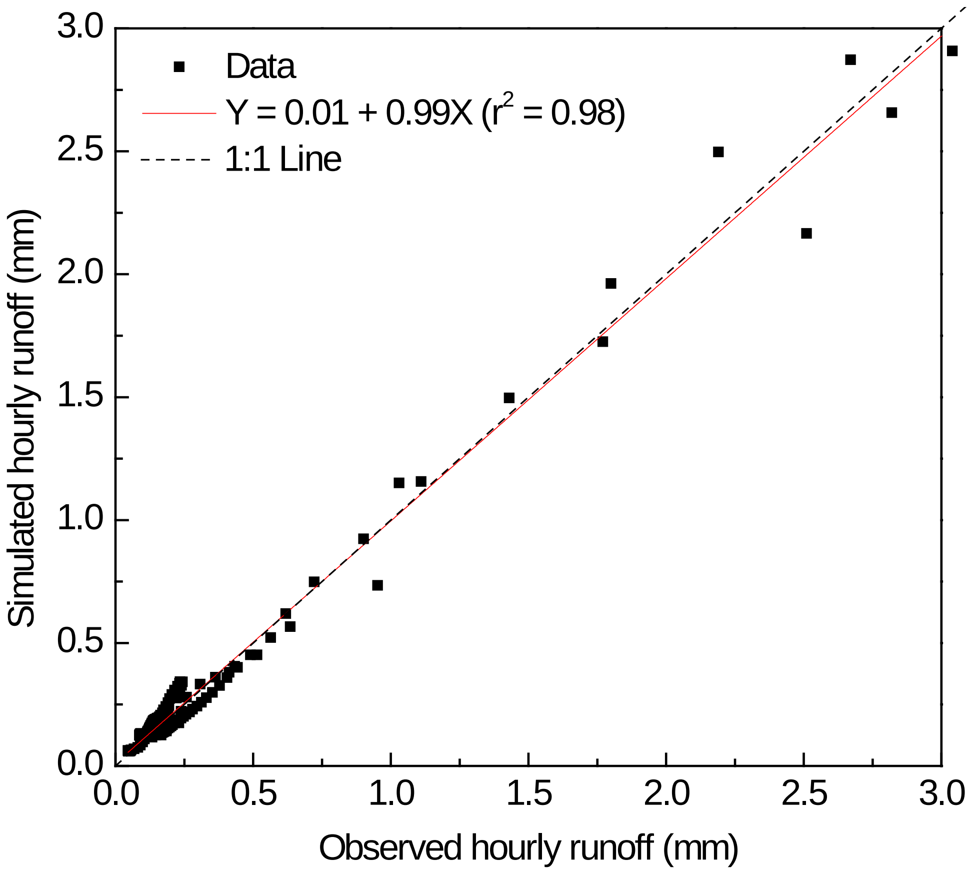


**Figure 6.34** Scattergram of observed and simulated hourly runoff during the calibration period of the East Dart catchment.

The parameter set optimized in the calibration period was employed in another one-week period commencing 12 August 2012 for the model validation. The Nash-Sutcliffe efficiency of the simulated result in the validation period reaches 0.87 (Figure 6.35). The slope of the regression lines between the observed and simulated runoff is 0.85, which marginally differs from 1.0 at 95 percent confidence level (Figure 6.36). The coefficient of determination ($r^2$) for the linear regression is 0.87.

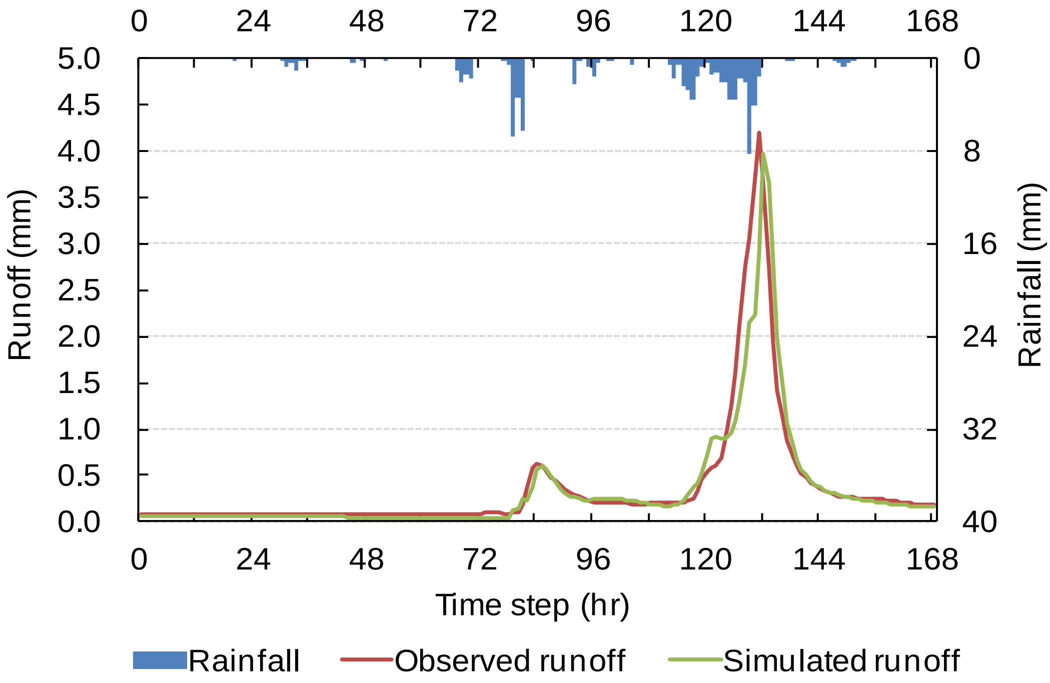


**Figure 6.35** Time series of observed and simulated runoff in the validation period for the East Dart catchment.

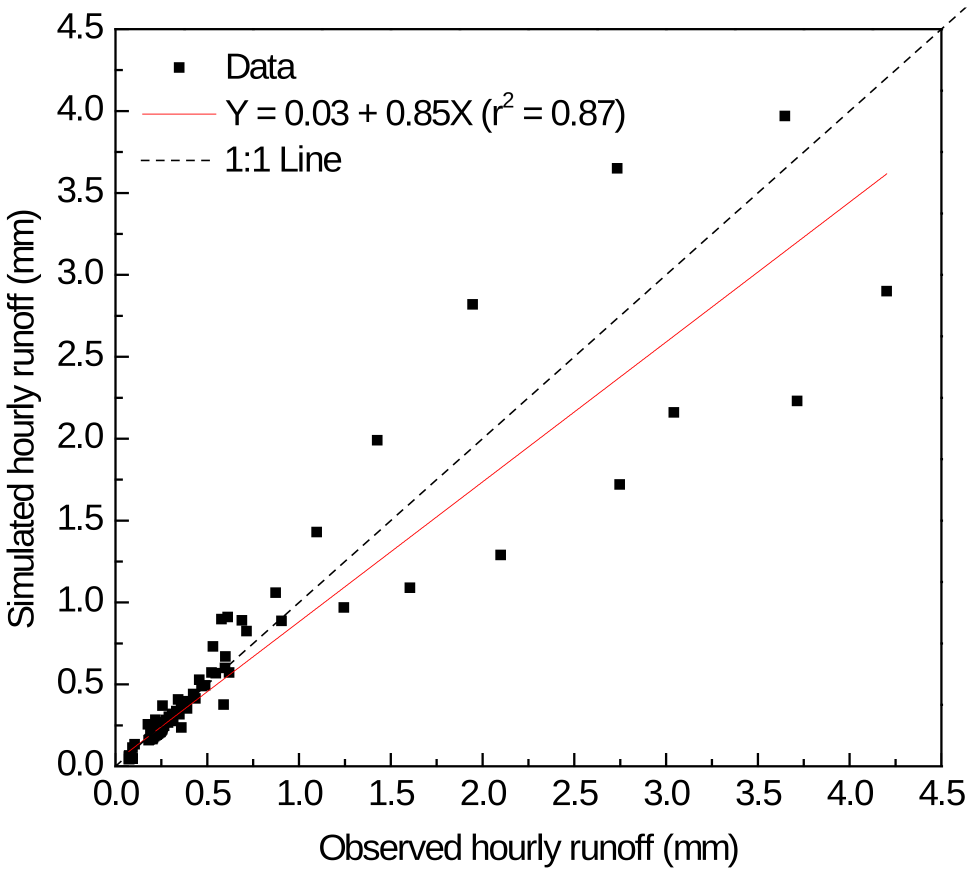


**Figure 6.36** Scattergram of observed and simulated hourly runoff during the validation period of the East Dart catchment.

The prediction of hourly runoff in the validation period, by and large, is satisfactory, but it is not as good as the performance in the calibration period. The reason for this may be the position of the rain gauge which is near the river flow gauge. This may lead to a loss of gauge representativeness for the whole catchment rainfall distribution, especially considering that the catchment system is quite long and narrow. This ‘loss’ can be magnified by spatially discrete summer thunder storms involved in this model test process.

In summary, the distributed TOPMODEL was tested in the East Dart catchment, and its performance was good both in the calibration and validation periods. The implication is that the model can be operated in the catchment to study the potential impacts of land cover change.

### 6.3.2 Scenario outcomes in the East Dart catchment

To check the three principles of land cover change impacts in the East Dart system  the land cover change scenario groups were created by which each scenario group retains the features of land cover patterns consistent with the previous land cover scenario groups used in Trout Beck and the Wye catchments. The groups of buffer strip scenarios, the random patch scenarios, and the slope-patch scenarios are presented respectively related to a discussion of the three principles which are being tested.

#### 6.3.2.1 Buffer Strip Scenarios

To check principle (1), buffer strip scenarios are studied. Due to the narrow shape of the East Dart catchment, it was not easy to build proper mid-hillslope scenarios. The patterns of the 10% area and 20% area riparian buffer strip scenario sets are displayed in Figure 6.38 and Figure 6.39. The accumulative area threshold of the river channel in each scenario is identical to those in Trout Beck and the Wye catchments.

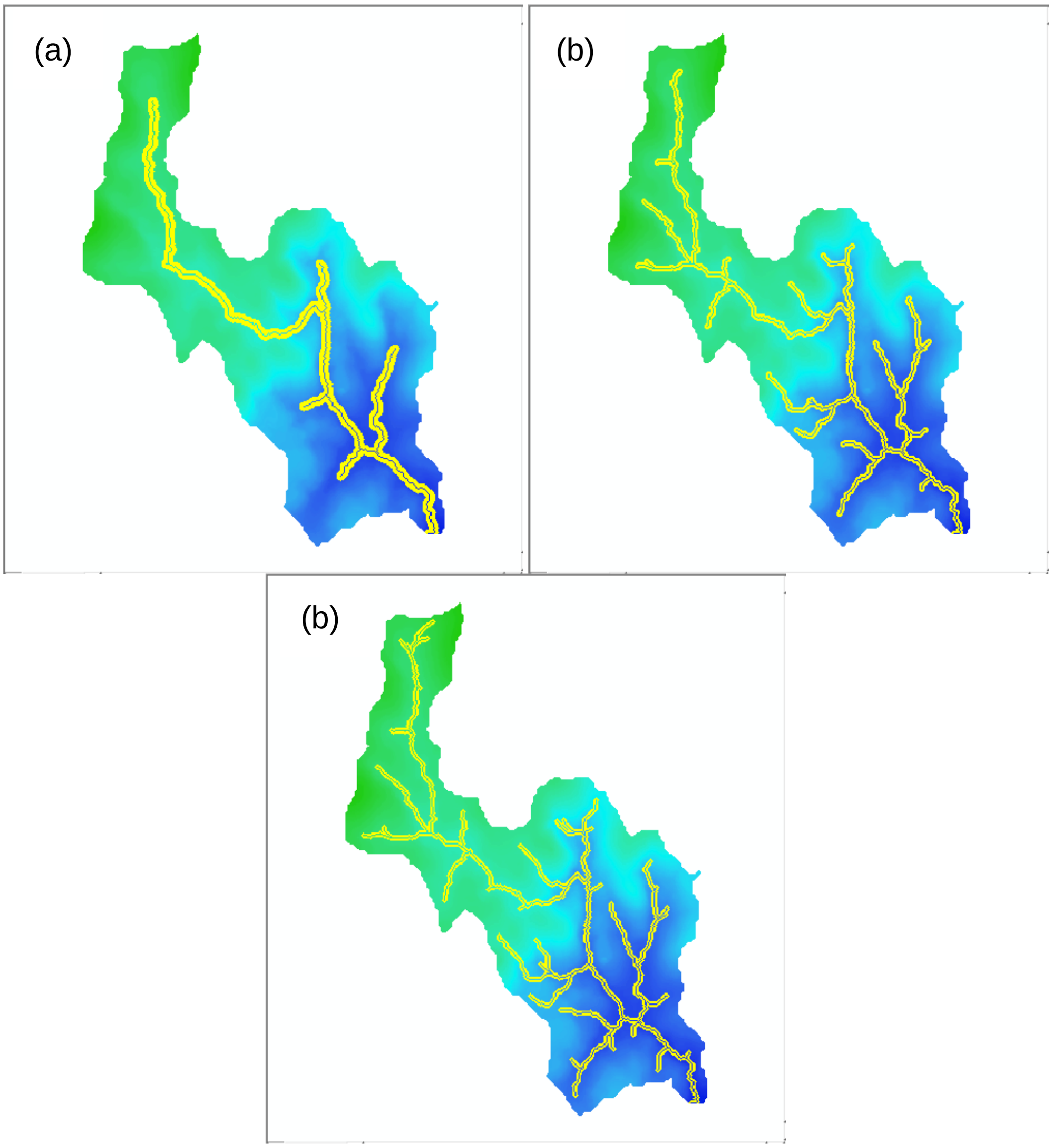


**Figure 6.37** Scenarios of 10% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions; (a) 3000-cell accumulative area, (b) 500-cell accumulative area, (c) 250-cell accumulative area.

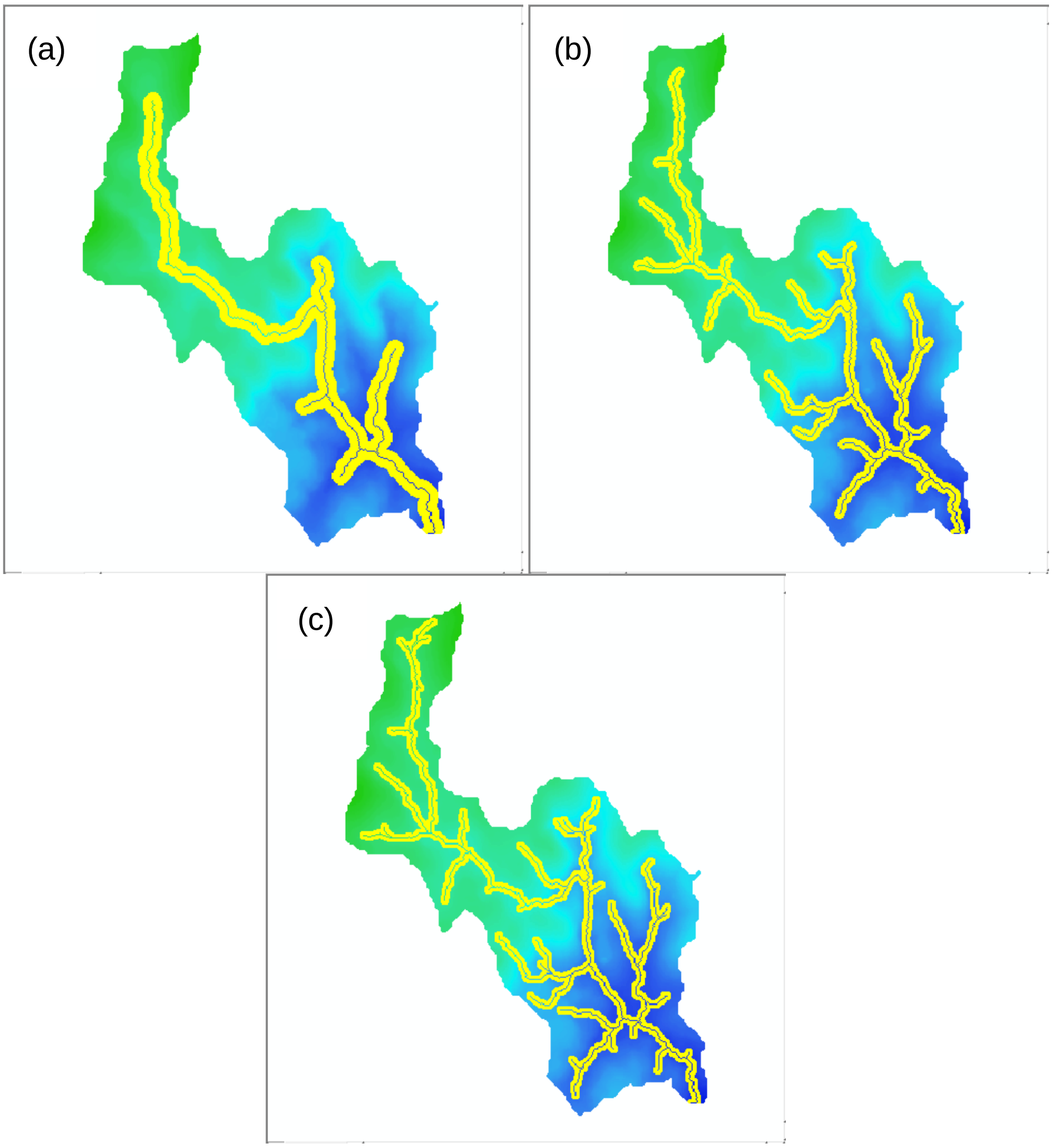


**Figure 6.38** Scenarios of 20% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions; (a) 3000-cell accumulative area, (b) 500-cell accumulative area, (c) 250-cell accumulative area.

All riparian bare peat buffer strip scenarios result in river flow peaks that are higher and three time steps earlier compared to the normal flow peak (see Figure 6.39 and Figure 6.40). The 250-cell and 500-cell channel bare peat buffer strips generate the flow peaks which are both 19% higher than the normal one, and both of their peaks are 6% higher than that of 3000-cell buffer strip.

The 3000-cell buffer strip scenario (10% buffer strip) produces a higher flood peak than the 20% area buffer strip, even though the 20% strip produces an earlier rising limb and a delayed falling limb of the peak. This could be related to the synchronization of overland flow concentration, as for the bare riparian buffer strip scenario group at Trout Beck (section 5.3.1; Figure 5.2).

This implies that a larger bare peat area, on some occasions, may give a different timing of hydrograph features instead of a higher flow peak. However, this does not change the principle that a narrower bare peat buffer strip surrounding upstream and downstream channels has a greater flow peak than a thicker buffer strip of the same-area which is just based around the downstream river network.

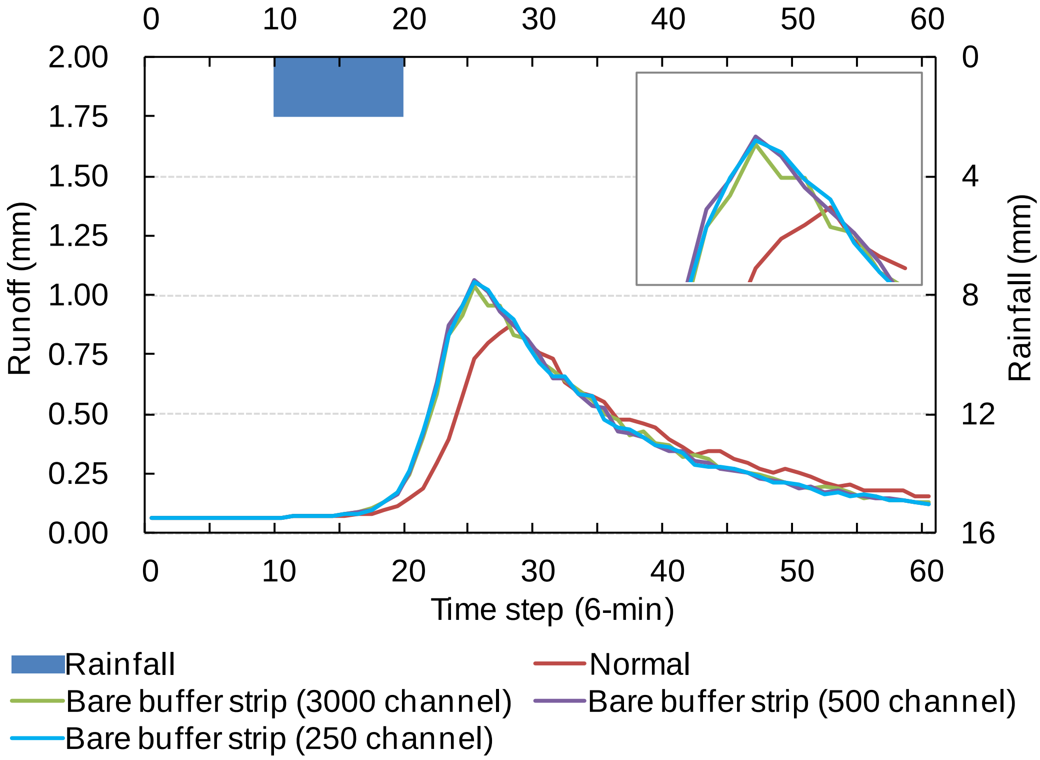


**Figure 6.39** Hydrographs of 10% area riparian bare peat buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

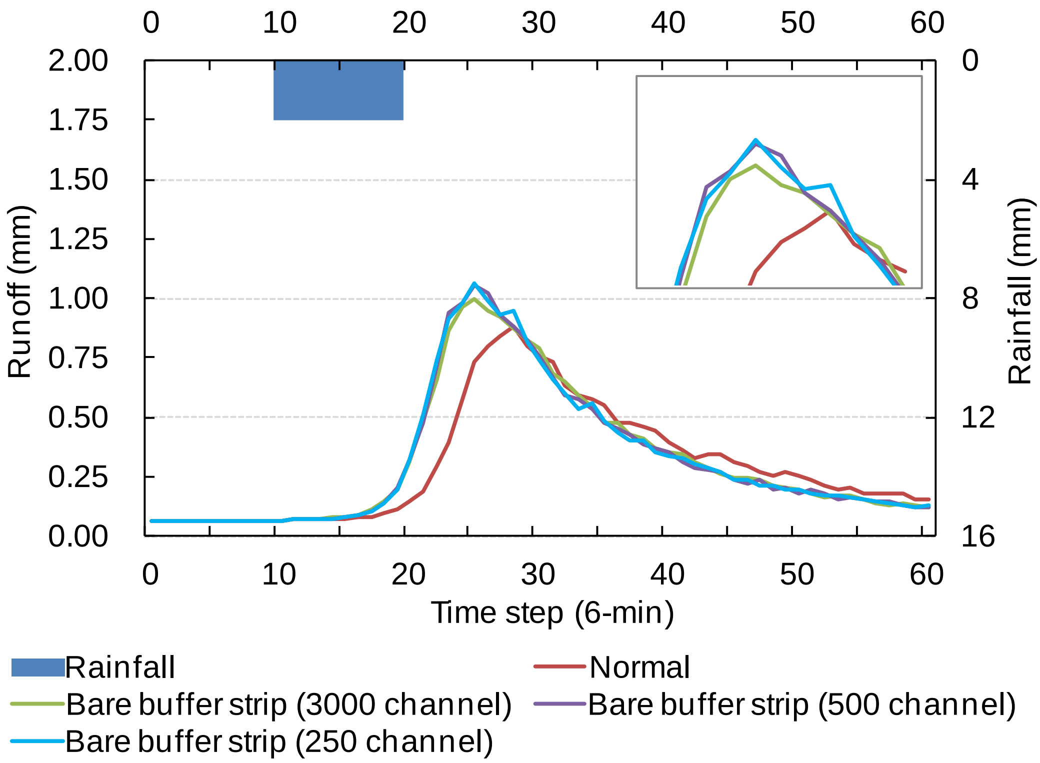


**Figure 6.40** Hydrographs of 20% area riparian bare peat buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

As identified in Figure 6.41 and Figure 6.42, *Sphagnum* buffer strips delay and decrease flow peak. For the 20% area scenarios, the flow peaks of *Sphagnum* buffer strip scenarios are lower than the normal one by nearly 20% and later than the normal one by 2 or 3 time steps. The 250-cell *Sphagnum* buffer strip scenario creates the lowest peak flow and the 3000-cell buffer strip scenario has the highest one. The differences between the three hydrographs of the *Sphagnum* buffer strip scenarios are more apparent in the 20% scenarios group compare to the 10% ones.

The simulation result of the riparian buffer strip scenario group is in line with principle (1). The 250-cell buffer strip scenarios produce the most effective impact on river flow in both of the scenario sets with 10% and 20% area, while the 3000-cell buffer strip scenarios have the lowest influence.

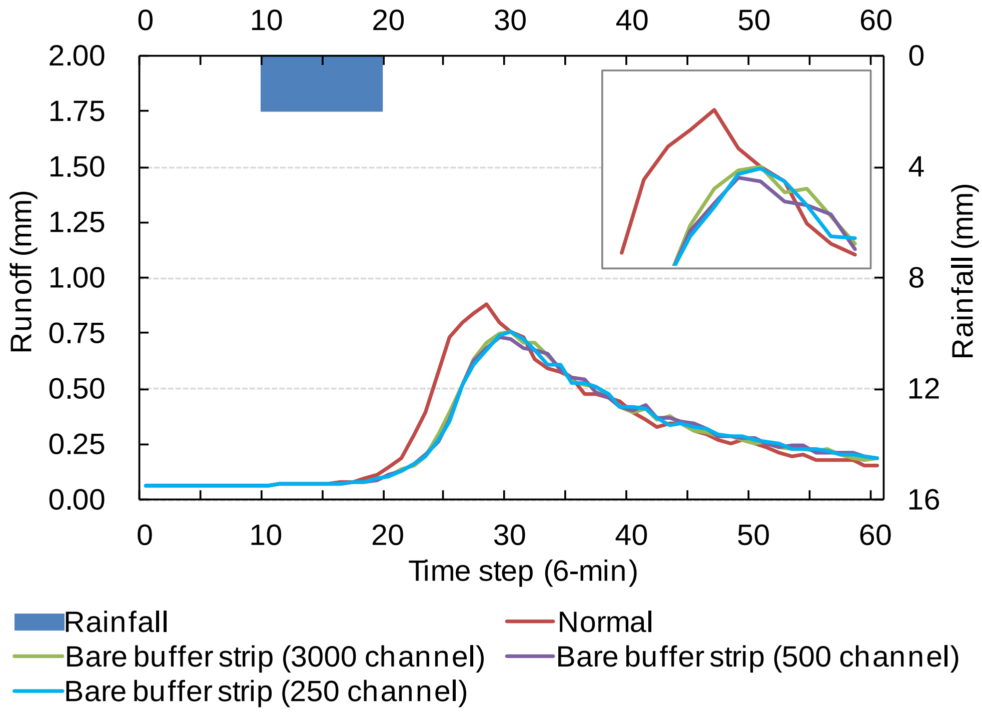


**Figure 6.41** Hydrographs of 10% area riparian *Sphagnum* buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$.

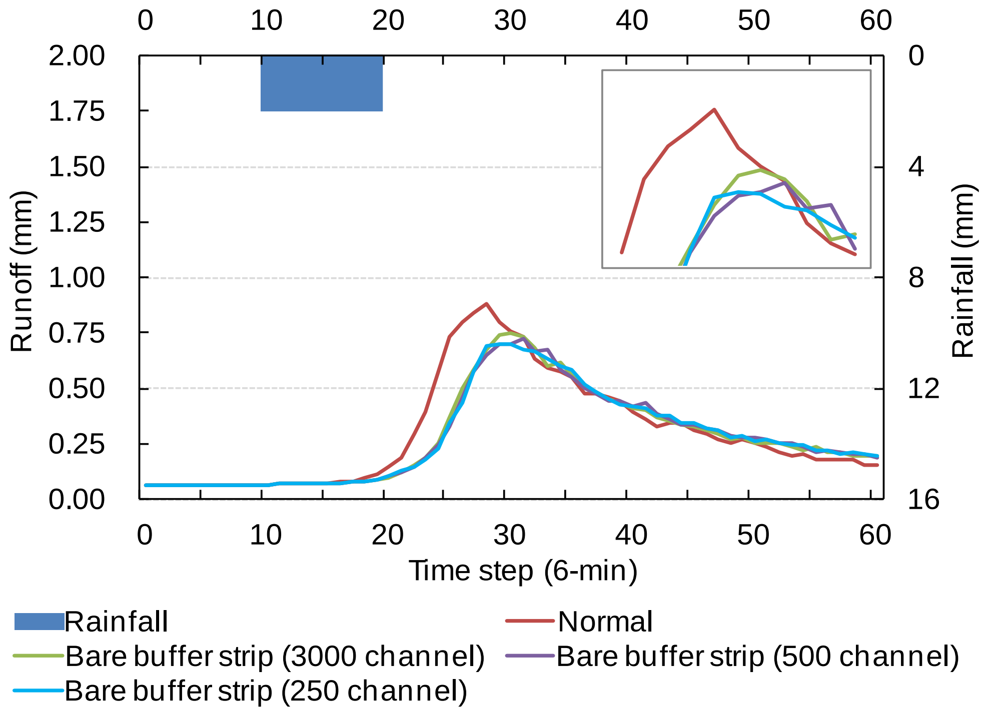


**Figure 6.42** Hydrographs of 20% area riparian *Sphagnum* buffer strips surrounding different river networks. The threshold of accumulative upslope area of each channel network is labelled in brackets. 3000 cell = 1.2km$^2$, 500 cell = 0.2km$^2$, 250 cell = 0.1km$^2$

#### 6.3.2.2 Random Patch Scenarios

A group of random patch land cover change scenarios is introduced to investigate land cover principle (2) in East Dart catchment. The 10% and 20% area sets of land cover change scenarios are illustrated in Figure 6.43 and Figure 6.44. Land cover change patches in each scenario are picked through a spatial uniform distribution as employed in the previous patch scenario studies.

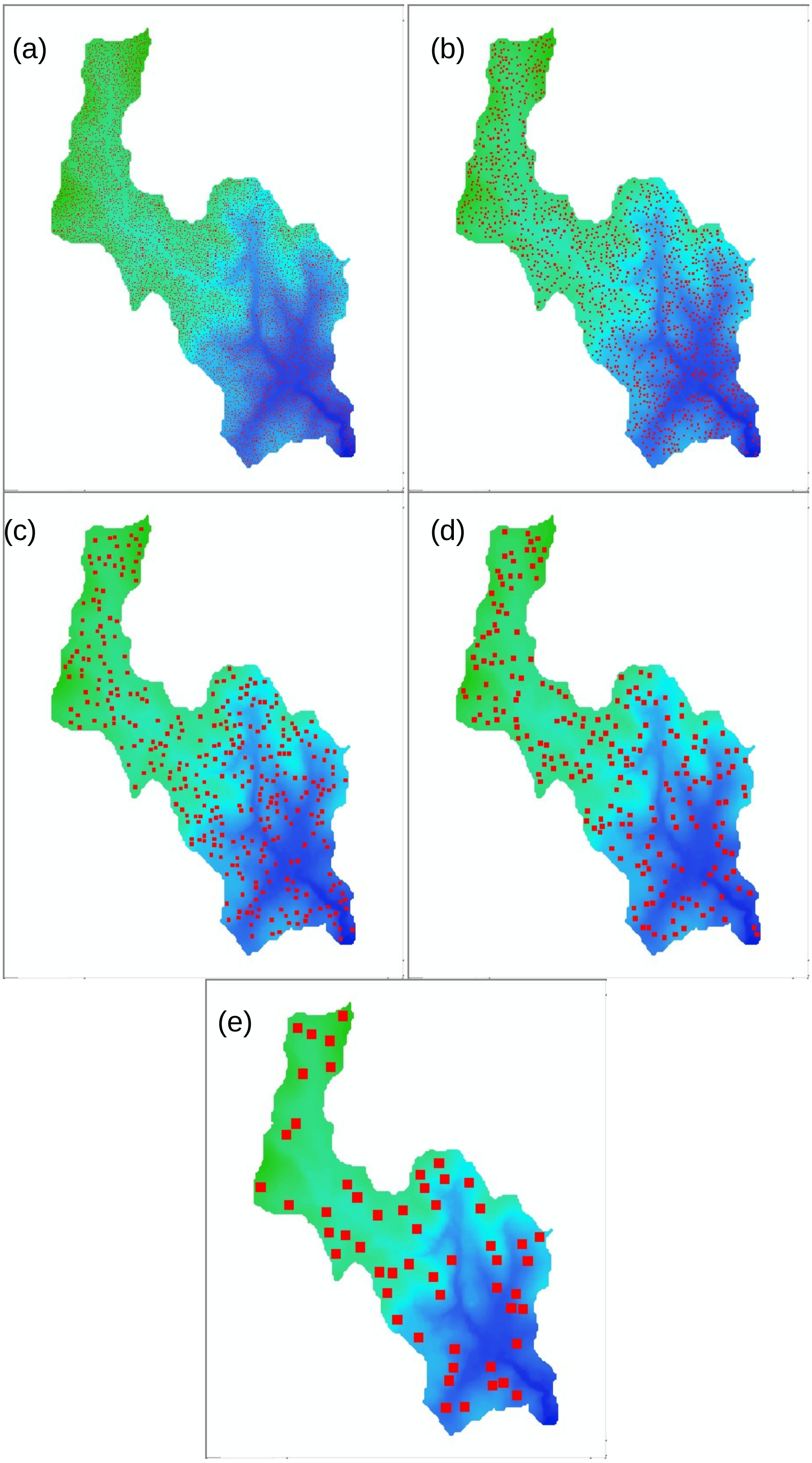


**Figure 6.43** Scenarios of random patches covering a total of 10% of the area of the catchment in each case; (a) 400m$^2$-patch scenario, (b) 1600m$^2$-patch scenario, (c) 6400m$^2$-patch scenario, (d) 10000m$^2$-patch scenario, (e) 40000m$^2$-patch scenario.

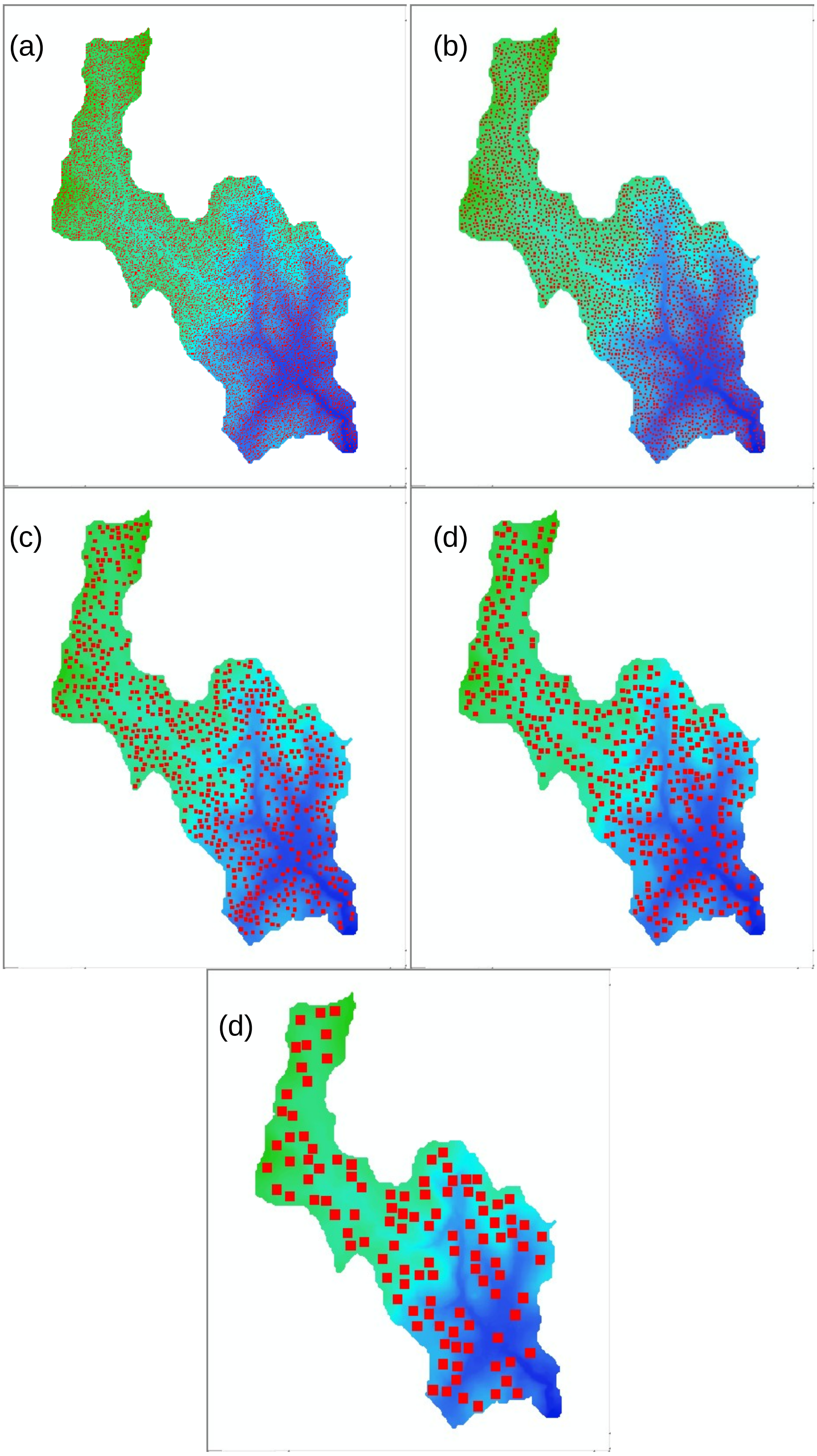


**Figure 6.44** Scenarios of random patches covering a total of 20% of the area of the catchment in each case; (a) 400m$^2$-patch scenario, (b) 1600m$^2$-patch scenario, (c) 6400m$^2$-patch scenario, (d) 10000m$^2$-patch scenario, (e) 40000m$^2$-patch scenario.

From the simulation results of the bare peat patch scenarios, they have higher and earlier flow peaks than the normal one (see Figure 6.45 and Figure 6.46). The flow peaks of the 10% area scenario group are 4% higher than the normal one, and the advantages of the 20% group run up to 9%. The 20% area scenario groups have much earlier rising limbs of the flow peaks than the 10% area scenario group.

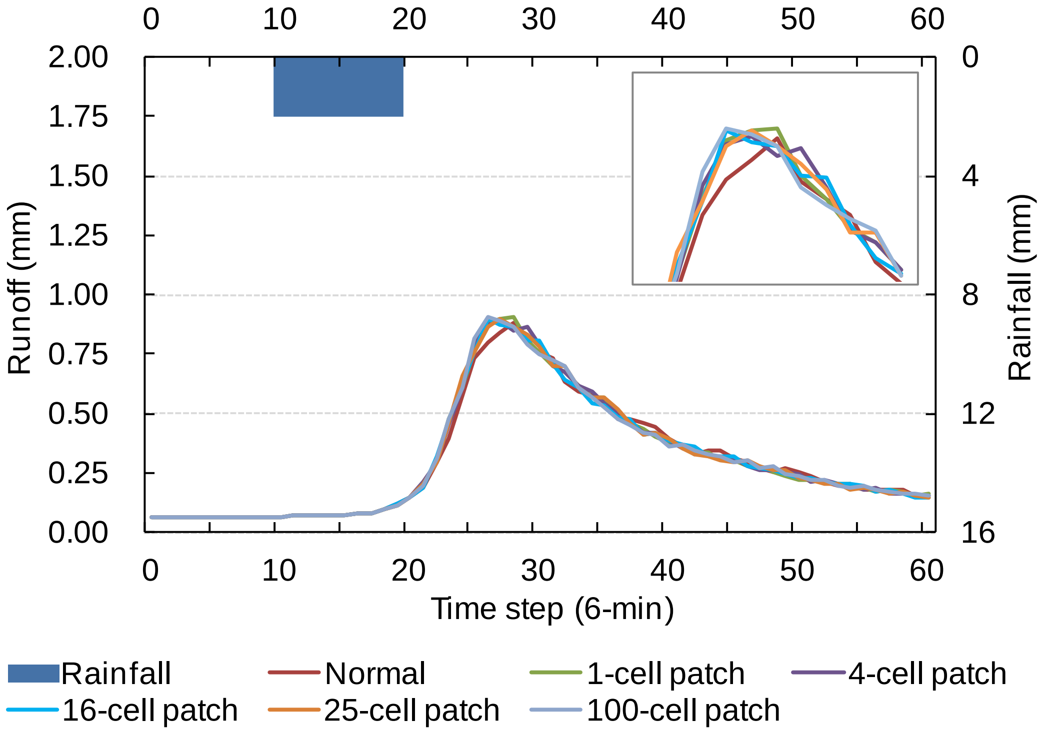


**Figure 6.45** Simulation hydrographs of 10% area bare peat patch scenarios.

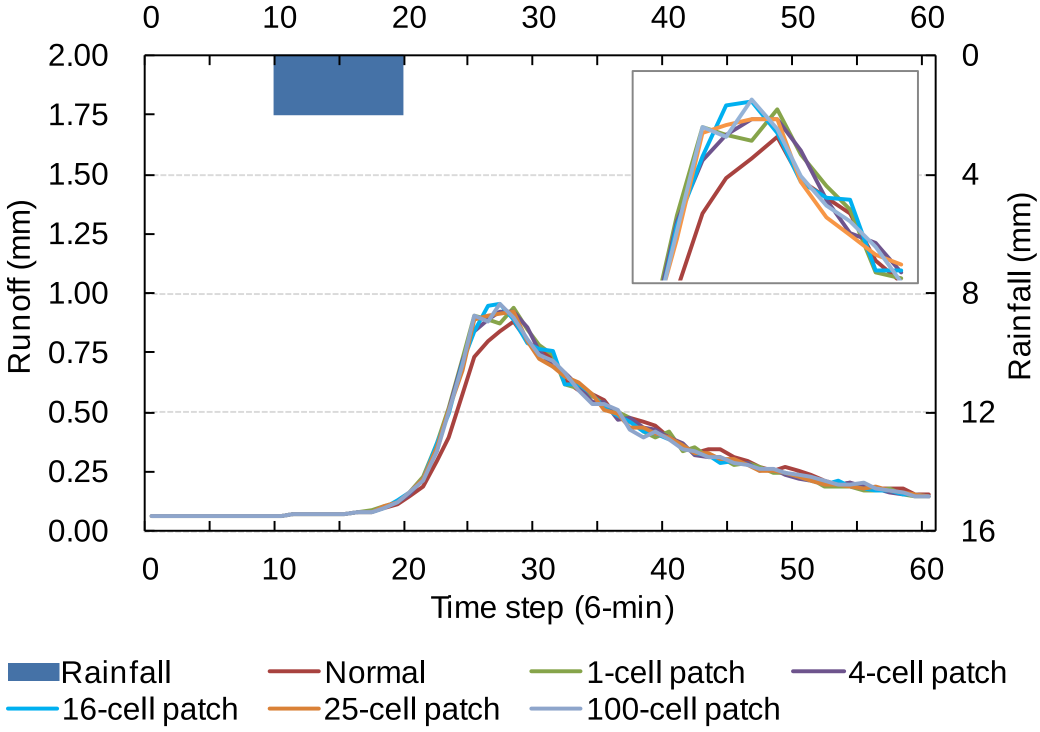


**Figure 6.46** Simulation hydrographs of 20% area bare peat patch scenarios.

For the *Sphagnum* patch scenarios (shown as Figure 6.47 and Figure 6.48), the results indicate that both the groups of 10% and 20% *Sphagnum* area have later peaks than the normal scenario, and the rising limbs of the peaks of the 20% area group are further delayed than in the case of the 10% area group. The 20% area scenario groups produce peak flows 5% lower than the normal peak flow, while the 10% area scenario groups results in a mean difference of around 2%.

From looking at both the bare peat patch and *Sphagnum* patch scenarios, there seems to be no evident relationship between patch size and river flow peak. This finding corroborates principle (2) from the previous land cover change scenario studies on the Trout Beck and Wye catchments.

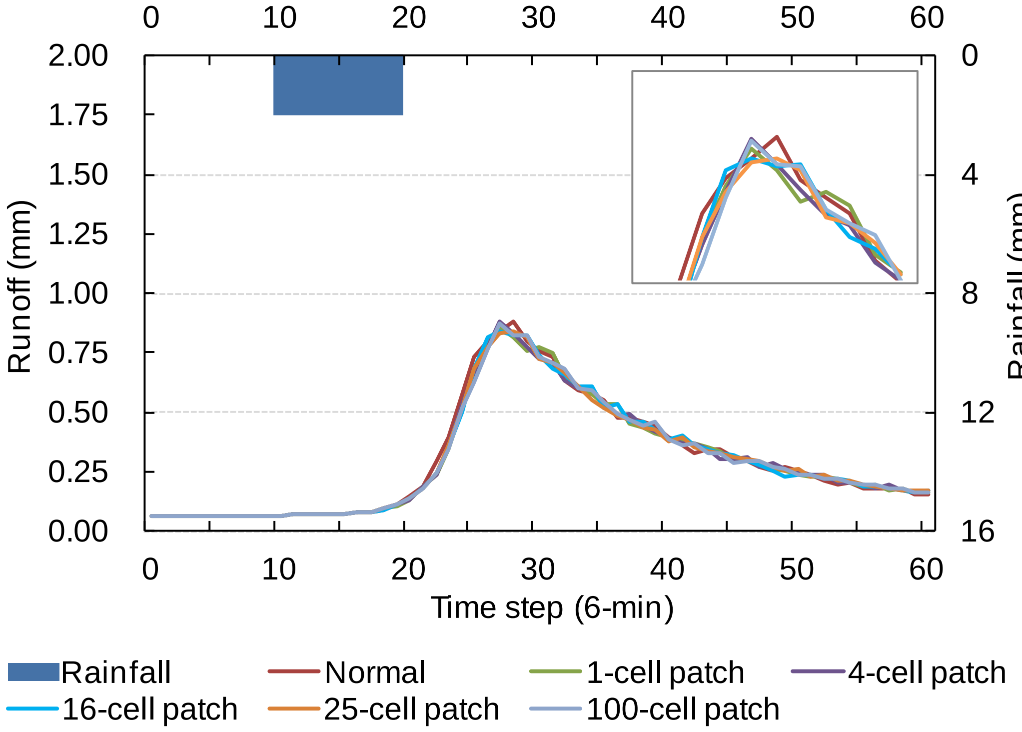


**Figure 6.47** Simulation hydrographs of 10% area *Sphagnum* patch scenarios.

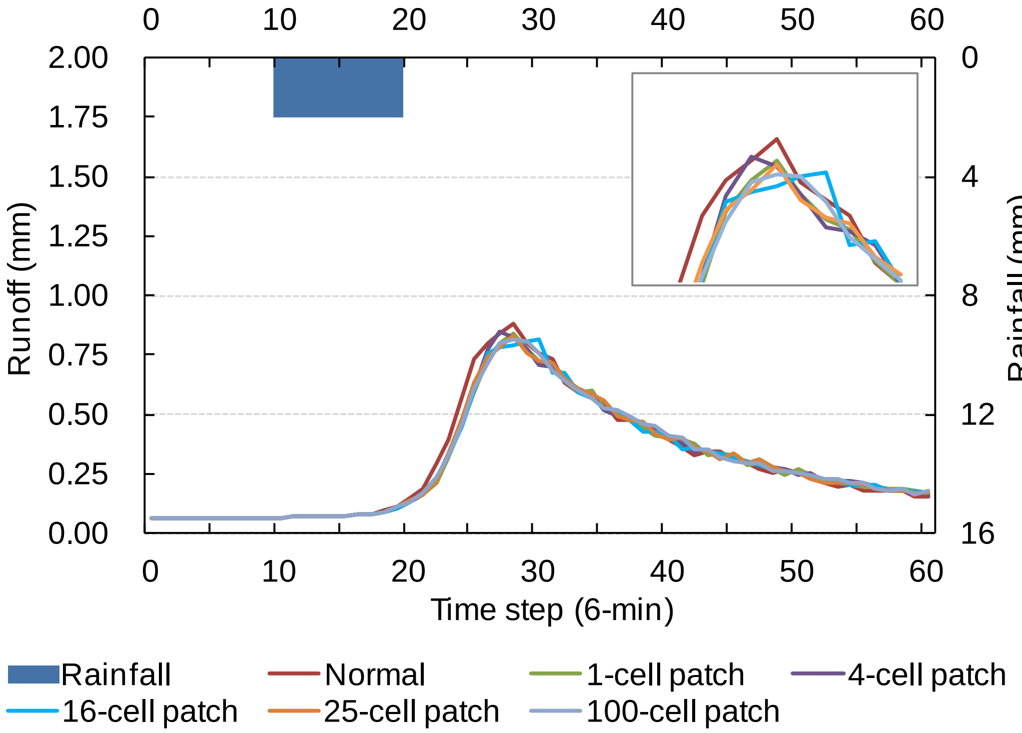


**Figure 6.48** Simulation hydrographs of 20% area *Sphagnum* patch scenarios.

### 6.3.2.3 Slope-patch Scenarios

The East Dart catchment has a quite gentle gradient with a mean slope of 9.4% similar to the 9.1% mean slope of the Trout Beck catchment. However, a large area with most of the gentlest slopes occurs at the upstream (northern) region of the catchment (Figure 6.49), which is converse to the situation in the Trout Beck catchment.

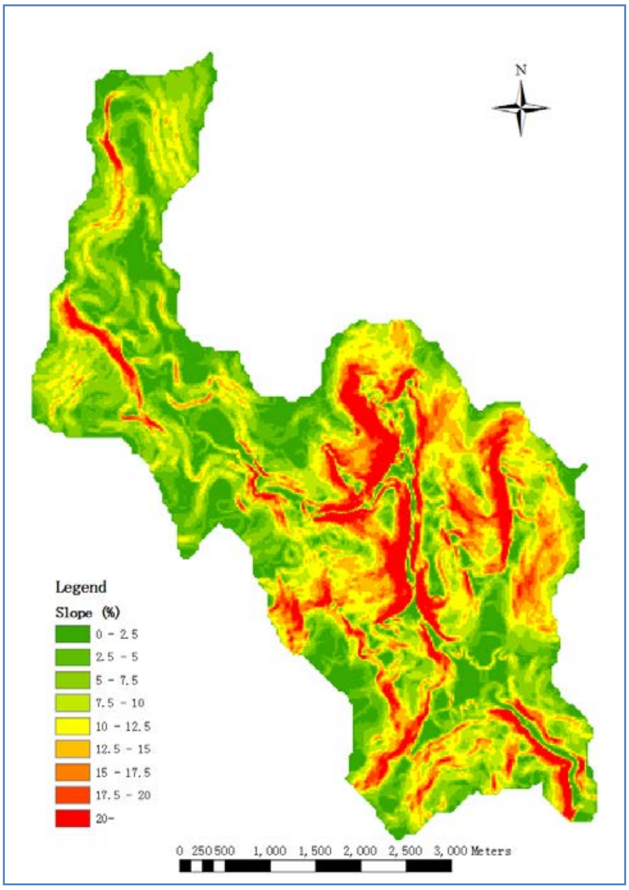


**Figure 6.49** The slope map of the East Dart catchment.

Slope-patch scenarios were formulated to test principle (3) in the East Dart catchment. Figure 6.50 and Figure 6.51 display the 10% area scenario group and 20% area scenario group experimental designs respectively.

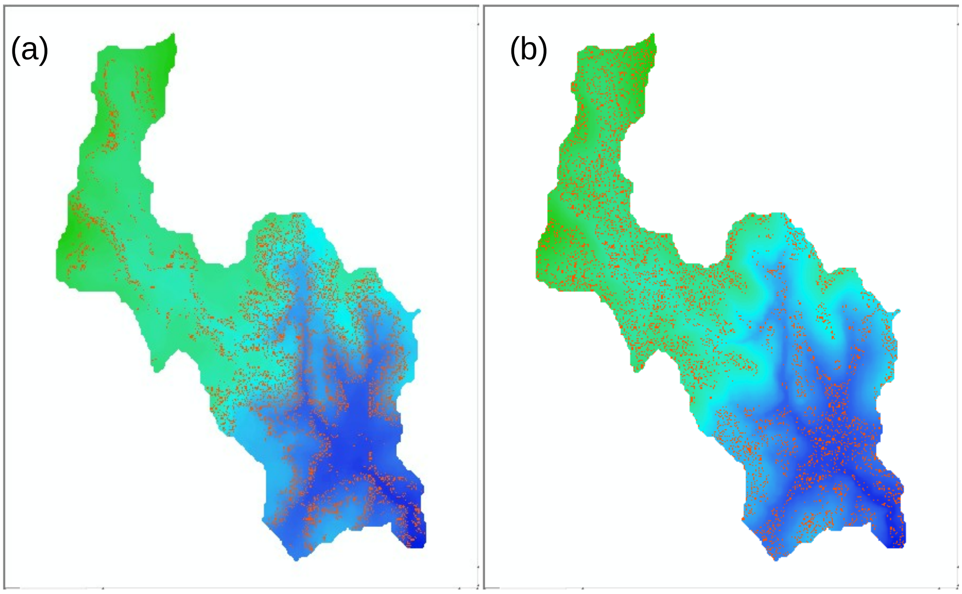


**Figure 6.50** Scenarios of 10% area random patches on slopes greater than 10% (a), and on slopes less than 10% (b).

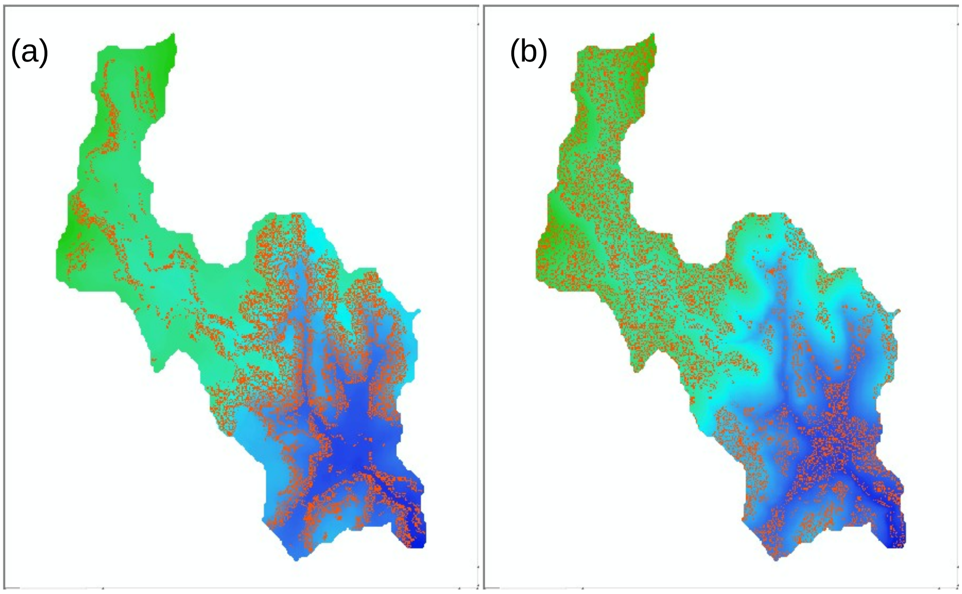


**Figure 6.51** Scenarios of 20% area random patches on slopes greater than 10% (a), and on slopes less than 10% (b).

The flow peaks generated by bare peat gentle slope patches are higher and earlier than for the scenarios where the bare peat is located on steep slopes for both the 10% and the 20% area scenario groups (Figure 6.52 and Figure 6.53). In the 20% area scenario group, the rising limb of the hydrograph occurs earlier leading to peak flow which is two time steps earlier than that of the steep slope patch scenario.

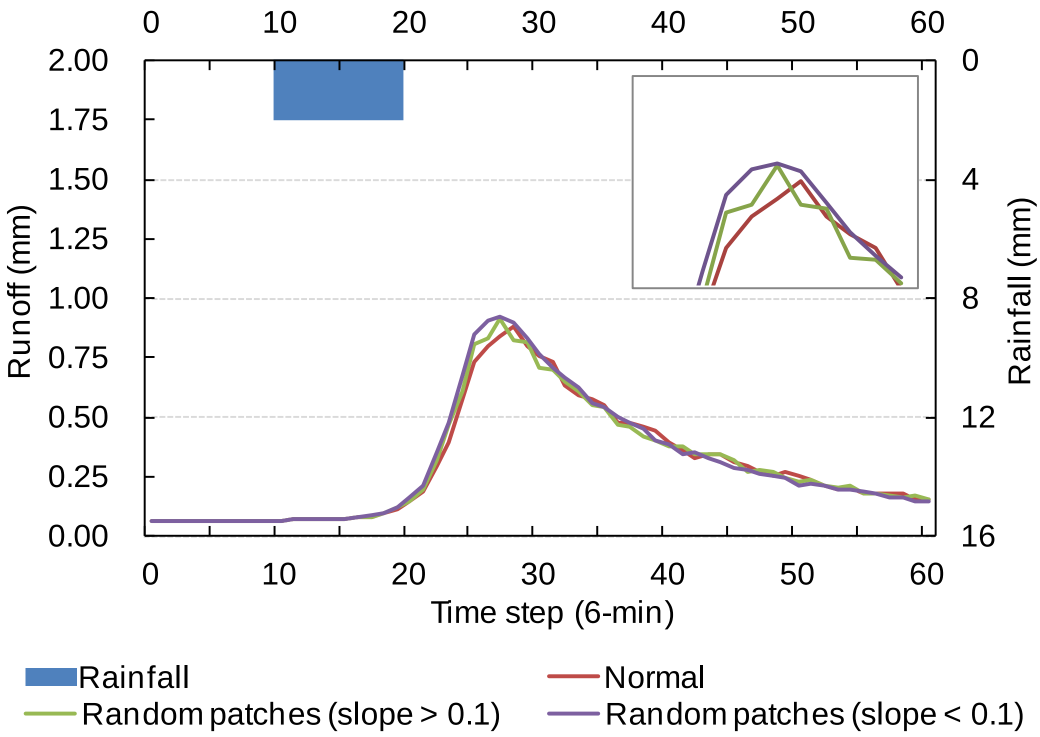


**Figure 6.52** Simulation hydrographs of scenarios with 10% area bare peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

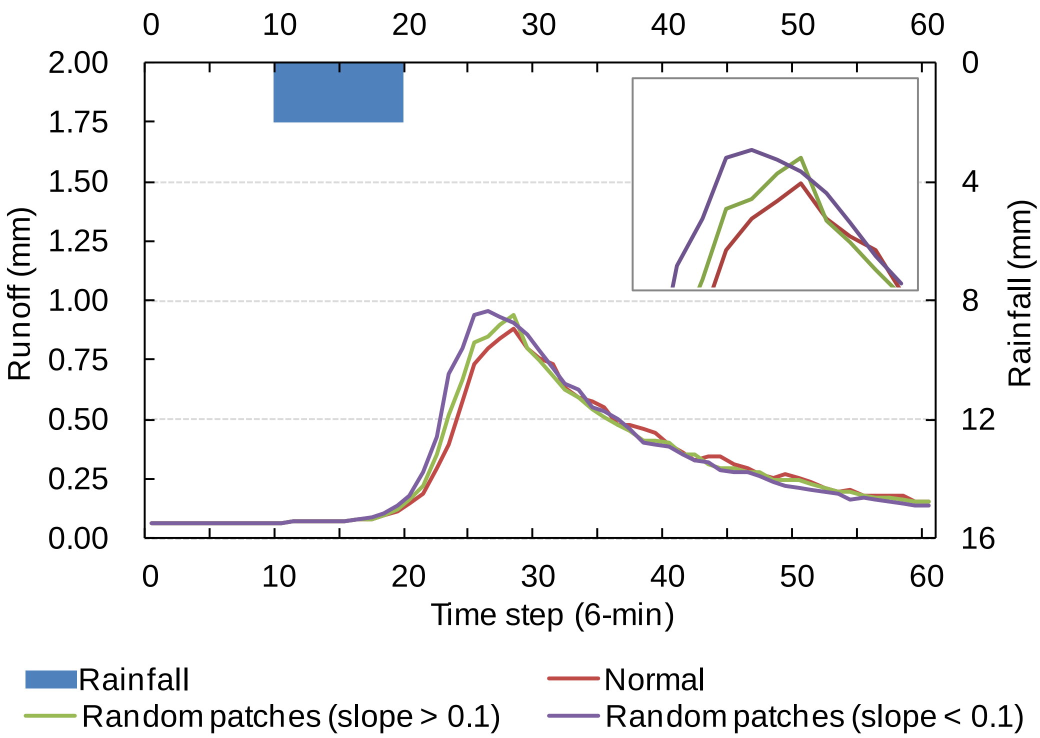


**Figure 6.53** Simulation hydrographs of scenarios with 20% area bare peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

For the *Sphagnum* slope-patch scenario groups, the gentle slope patch scenario produces a lower and later flow peak than the steep slope patch scenario for both 10% and 20% area scenarios (Figure 6.54 and Figure 6.55).

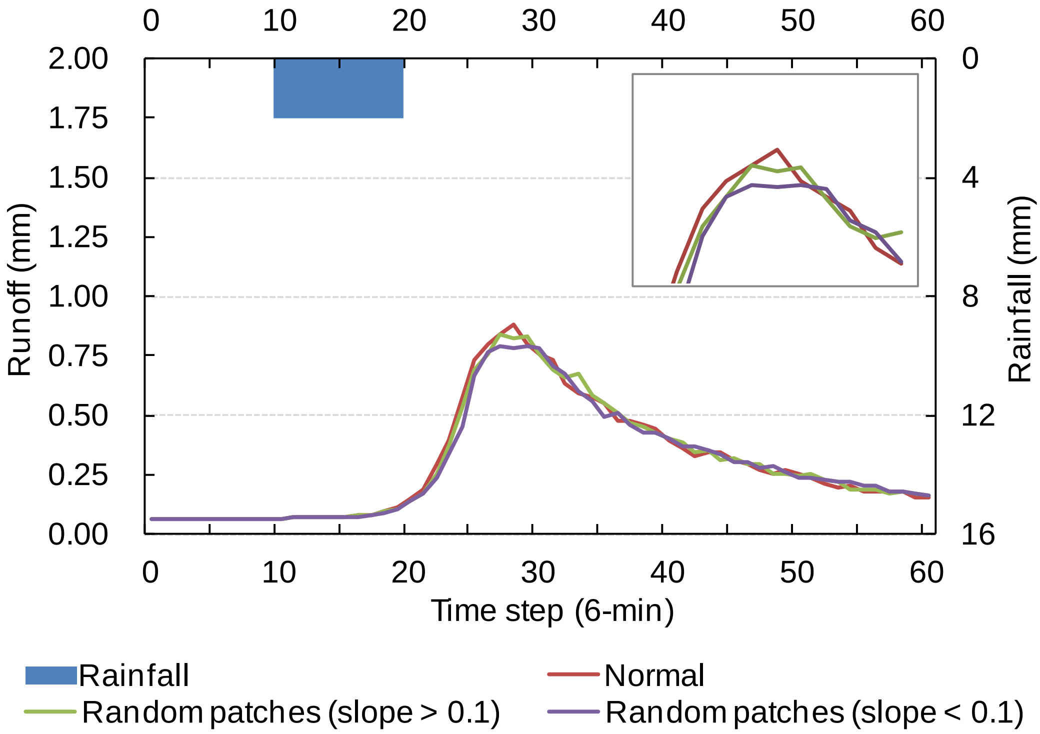


**Figure 6.54** Simulation hydrographs of scenarios with 10% *Sphagnum* peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

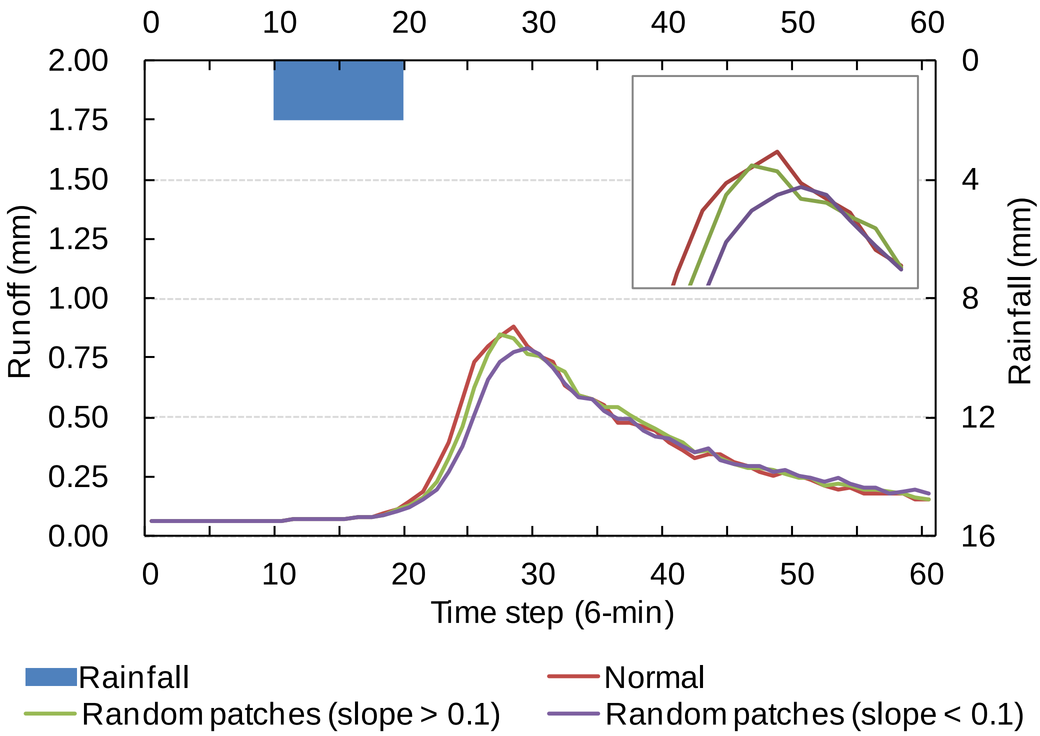


**Figure 6.55** Simulation hydrographs of scenarios with 20% *Sphagnum* peat patches on steep slopes (> 0.1) and gentle slopes (< 0.1).

In both groups of slope-patch scenarios for the East Dart catchment, the modelling results support principle (3), corresponding to results from the two previously studied catchments. Despite the different configurations of gentle slope patches for Trout Beck (more located downstream) and East Dart (more located upstream) the overall outcomes on the stream hydrograph were similar. This provides good evidence to suggest that land cover change patches on gentle slopes have a greater impact on stream flow than the same changes on steeper slopes, regardless of the position of the patches or slope configuration on the hillslope.

### 6.3.3 Summary of the scenario study in the East Dart catchment

The results of the three scenario groups examined in the East Dart catchment are consistent with the three principles that were tested. Figure 6.56 and Figure 6.57 illustrate comparisons of peak flow and peak time between the representative scenarios for the East Dart. Figure 6.58 summarises these two comparisons together and indicates the representative scenario impact on peak flow volume and peak timing. From these comparisons, the scenarios of land cover change in the 250-cell buffer strip, representing the buffer strip surrounding the upstream and downstream channel network, have the largest impact on river flow of all land cover scenarios in the East Dart catchment. The gentle slope patch scenario is more effective than the random patch scenario in altering peak flow and the timing of peak flow.

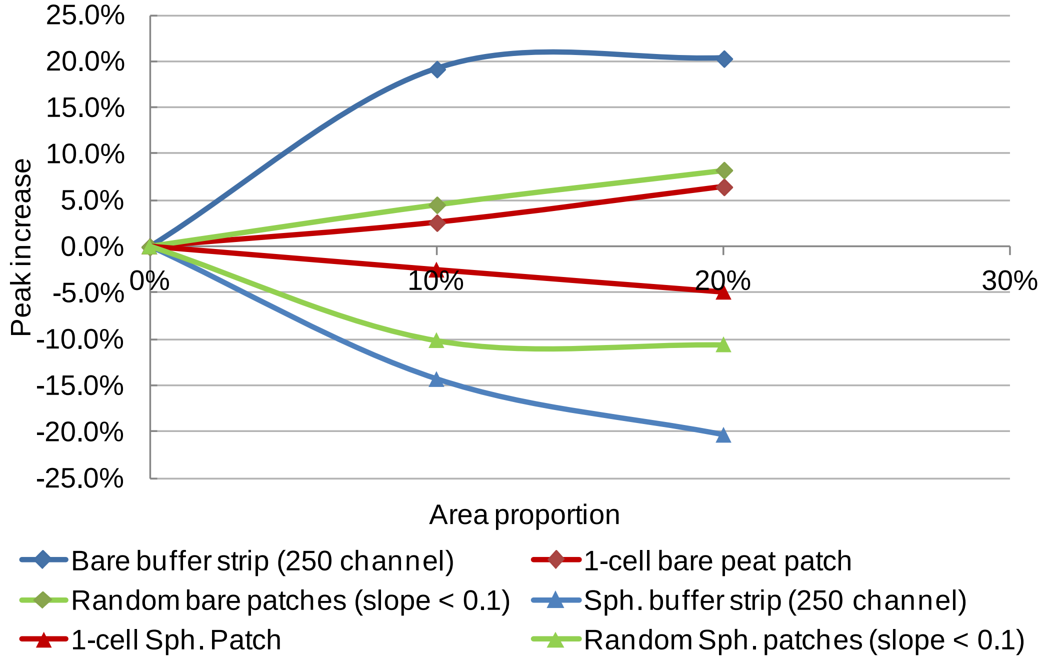


**Figure 6.56** Scenario comparison of impact on peak flow increase compared to the ‘normal’ scenario.

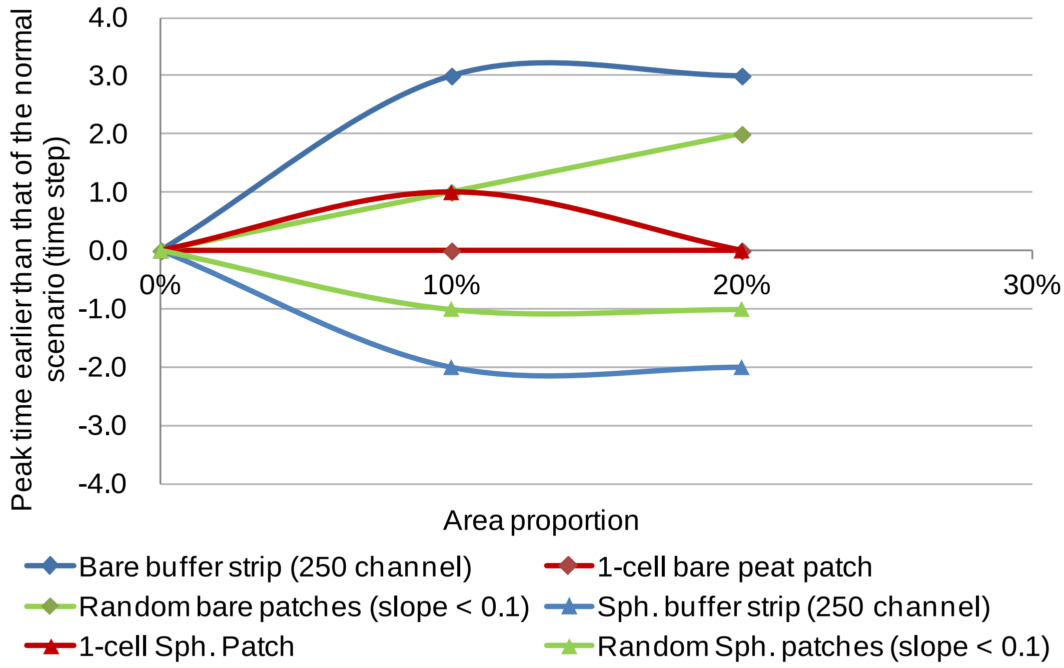


**Figure 6.57** Scenario comparison of impact on peak time compared to the ‘normal’ scenario.

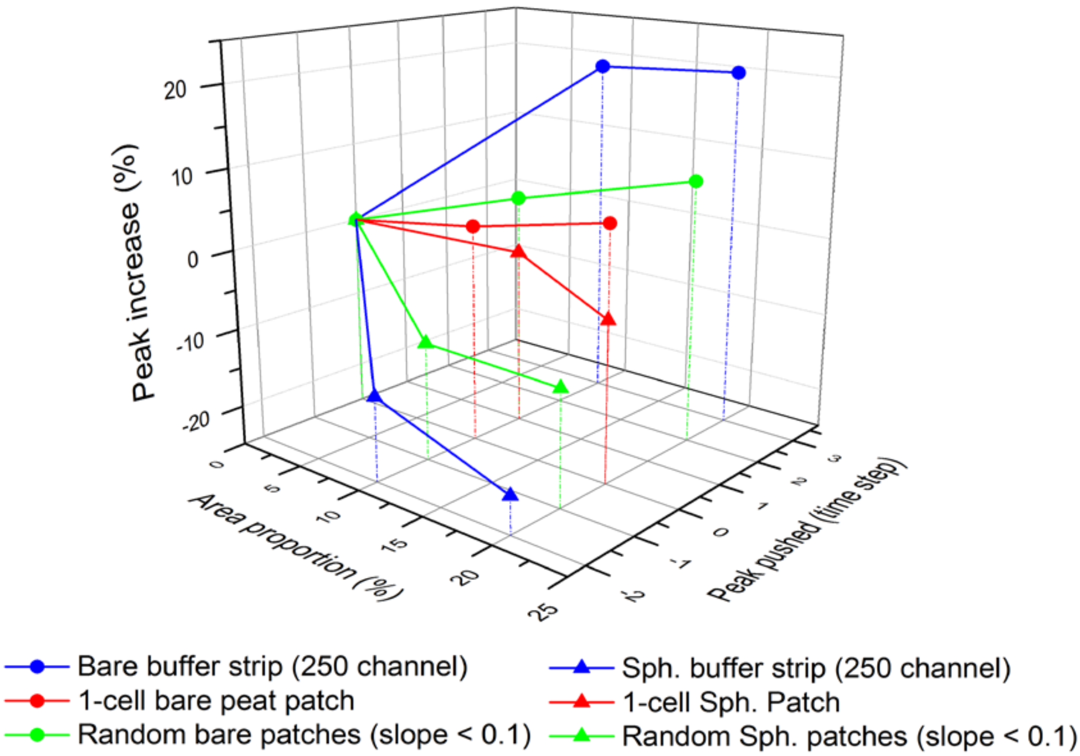


**Figure 6.58** Scenario comparison of the combined impacts on flow peak in the East Dart catchment.

## 6.4 Summary

This section gives a summary for the application of the distributed TOPMODEL in the Wye catchment and the East Dart catchment and a further discussion on comparisons of the scenario results from these two catchments with Trout Beck.

In this chapter, the distributed TOPMODEL with the new overland flow module was calibrated and validated in two additional headwater peatland catchments (the Wye and the East Dart) in different parts of the UK from that studied in Chapter 5. Summer storm events with observed data were used for this process. The model performed satisfactorily in the tests for these two catchments. Land cover change scenarios were adopted in the two catchments to check the three land cover change impact principles modified from the three hypotheses as described in chapter 5. These principles are:

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

Principle (2): The size of the land cover change patch does not have noticeable effect on river flow for patch sizes no more than 10000m$^2$.

Principle (3): Bare peat on a gentle slope area gives a faster flow response and higher peak value at the catchment outlet, while high density vegetation or re-vegetation on a gentle slope area has larger positive impact on peak river flow delay when compared with the same practices on steeper slopes.

The scenarios were modelled with optimized parameter sets acquired from the calibration and validation processes. The three land cover change impact principles were corroborated. For the Wye catchment, which has much steeper mean slopes than for Trout Beck, the steep slopes accelerate the movement of overland flow and thus narrowed the differences to normal (current) conditions for the outlet hydrographs for each land cover change scenario when compared to Trout Beck even though catchment areas were similar. However, generally, the scenario results for the Wye catchment were in the same direction as those found in Trout Beck and therefore supported the three land cover change principles, even though a couple of scenario sets like the 10% slope-patch scenario set did not quite fall in line with the principles. For the East Dart catchment all of the results were consistent with the three principles. The catchment has about twice the area compared to Trout Beck, but a mean slope similar to that of Trout Beck, which is a key factor for overland flow movement. Comparing the scenario results in Trout Beck and East Dart catchments, land cover change scenarios in the larger catchment seem to have more impact on peak river flow relative to the peaks of the normal scenarios. It could be speculated that land cover change in larger catchments may be more effective on areal-weighted river flow than in small catchments where proportionally there is the same land cover change.

# Chapter 7
# Discussion and conclusions

## 7.1 Introduction

The overall objective of the research presented in this thesis was to provide a modelling method to evaluate land cover impacts on downstream river discharge in upland peat catchments. In previous chapters, a distributed differential version of TOPMODEL was developed and tested. The model with its overland flow module was used to study land cover scenarios applied across three upland peat-covered catchments. The research focussed on producing and then testing three principles which have management applications. This chapter aims to discuss the key research findings of the thesis and present ideas for future work.

## 7.2 Model development

This section reviews the main model developments that were produced by this thesis.

### 7.2.1 Transforming TOPMODEL into a distributed hydrological model suitable for simulating land cover change impacts in peatlands

The original TOPMODEL, developed in the University of Leeds (Beven and Kirkby, 1979) has been used worldwide in thousands of research papers. Among these, are examples of TOPMODEL applications in peatland catchments (e.g. Ambroise et al., 1996; Beven et al., 1984; Blazkova and Beven, 1997; Lane et al., 2004). However, the model, which is a lumped catchment hydrological model, is limited in that it does not represent the spatial distribution of all hydrological features in catchments. In particular, recent work (Holden et al., 2008) has shown that overland flow travels more slowly and at more variable velocities than is assumed in the original TOPMODEL, so that overland flow re-infiltrates downslope after a significant time delay. This delayed input partially violates the TOPMODEL assumption of spatially uniform rainfall input. For upland peatlands such spatial representation is important to land managers who seek to understand how vegetation cover in different parts of the headwater peatland (primarily the shift from eroding bare peat to well vegetated peat) might impact river flow peaks (Acreman and Holden, 2013; Haigh, 2006). While there has been some work to produce a distributed TOPMODEL (e.g. Pinol et al., 1997), there has been little work on using the model to simulate how land cover change in different parts of catchments might impact river flow, particularly with regard to the specific requirements of peatlands. This is despite the features of TOPMODEL that make it particularly relevant to upland peatlands such as the focus on saturation-excess overland flow (Holden and Burt, 2003).

This thesis has developed novel work to transform the traditional TOPMODEL into a distributed differential model, retaining classical key ideas on runoff production but focusing on land cover change impacts on overland flow velocities leading to river flow hydrographs. The main points of this work are as below:

- The new model is totally distributed with a computational unit of a grid cell.
- The core equations representing subsurface flow in the original TOPMODEL are inherited by the distributed version of TOPMODEL. The equations were downscaled from the catchment level to the cell level for the transformation to the distributed model.
- The downscaled equations constitute the main part of the subsurface flow module and the runoff produced by each cell is divided to subsurface flow and saturation-excess overland flow in this module before an overland flow calculation takes place (the work on the overland flow module is reviewed in next section).

In the new distributed model, land cover change with spatial features in the catchment can be reflected. The impacts of land cover change on in situ water movement and downstream river flow can both be represented and simulated by this model improvement. At the same time, the distributed model has another crucial advantage in that it can represent the spatial variability of precipitation for rainfall-runoff simulations. The spatial variability of rainfall can greatly affect the timing and shape of peak flow hydrographs (Singh and Woolhiser, 2002; Syed et al., 2003; Wilson et al., 1979), no matter which scale of catchment is being investigated (e.g. 4-5 ha. Faures et al., 1995). On the other hand, rainfall variability in space can also produce problems in calibrating hydrological models (Arnaud et al., 2002; Segond et al., 2007). Distributed hydrological models allow the distribution pattern of rainfall input to be provided in the model. This means every cell can be assigned rainfall inputs for every time step, which is a disaggregated way to describe the spatial and temporal variability of rainfall. Thus, the model can utilise more accurate precipitation data (e.g. rainfall radar) to decrease the negative influence of rainfall spatial variability on flow modelling. Of course the availability of distributed rainfall data is a practical problem for many upland sites but it is thought that such data availability will improve over time and thus the model is ready and fit-for-purpose for future flow modelling in upland systems.

### 7.2.2 Modelling the land cover impact on overland flow (overland flow movement module)

Simulating saturation-excess overland flow movement and the land cover change impact on overland flow movement is a key task to modelling the land cover impact on river discharge in upland peat catchments. Due to the lumped structure of the original TOPMODEL, there was no model component to simulate overland flow transportation on hillslopes. Thus, a new module with a series of distributed algorithms representing water routing and velocity was built to model the movement of overland flow and the surface cover impact on overland flow. A set of stochastic algorithms for overland flow transport were designed and applied in an overland flow module, in which the overland flow produced in each cell is treated as many parcels (e.g. 100 parcels) of water. Each parcel undergoes a statistical algorithm to choose the direction and distance of its movement for each time step applied by the model user.

For overland flow direction, the idea of the algorithm of multi-direction flow (O'Callaghan and Mark, 1984) using DEM data (at a grid cell level) is involved to model the overland flow path on hillslopes. The weight of each direction in the flow routing process is transferred to the probability of the direction for a moving water parcel. The moving distance of each water parcel in a time step is calculated by a stochastic method with an algorithm determining the ‘stop moving condition’ of a water parcel in a cell. The flow velocity is calculated by the local slope, the overland flow depth, and the land surface roughness (associated with land cover type) based on empirical data collected by Holden et al. (2008). The probability distribution of the distance of a water parcel movement is based on Poisson’s Distribution. Thus, overland flow parcels emerging from a cell may not have the same routing on the hillslope to each other, with flow splitting into different downstream directions and stopping at different distances due to the stochastic algorithm of overland flow movement.

After the overland flow routing process, a water parcel stops at a downstream cell in which it is treated as input water for the cell and may infiltrate into the soil to contribute to subsurface flow produced in this cell or it may add to further overland flow production associated with changes in flow depth for the cell for the given time step. This mechanism reflects the real process of overland flow generation on hillslopes and may be influenced by land cover. Land cover change increasing or decreasing the overland flow velocity decreases or increases transportation time for overland flow and thus decreases or increases the opportunity for the infiltration of overland flow. This interactive hillslope overland flow-infiltration mechanism represented in the distributed TOPMODEL is rarely considered in catchment hydrological models. A similar mechanism can only be found in a few hydrological modelling studies such as the work of Wang et al. (2011) by which the mechanism was used in the model for rainfall-runoff simulations for a macro-scale (> 10000 km$^2$) catchment with a resolution of 1-km grid cells or rather larger than the hillslope scale overland flow process. At the same time as providing this significant new advance which could have wide applicability, there is only one key parameter ($k_v$) which has been added for overland flow compared to the original TOPMODEL, limiting the possibilities of over-parameterization (Perrin et al., 2001). The small number of parameters required to run the model is an obvious benefit for the application of the model, and makes it easier to calibrate and validate in practice.

### 7.2.3 Application of the distributed TOPMODEL in upland peatland catchments

The distributed TOPMODEL was developed to simulate the land cover change impacts on river hydrographs, but it has to be tested in upland peat catchments in advance. Three catchments were involved in the model test; Trout Beck in the north Pennines of England, the Upper Wye catchment of mid Wales and the East Dart catchment in southwest England.

For the Trout Beck catchment, the distributed model was tested by a process of the modified GLUE method (Beven and Binley, 1992) through two one-week summer periods with big storm events. Several simulation runs were operated in the calibration period with the parameter sets systematically picked up in a justified parameter space. The parameter sets, of which the simulated hydrographs have top-20% best fit to the observed flow, are selected to be used in the validation period, producing a hydrograph band to compare with the observed river discharge. The test showed a strong result for model performance which was much better than the original TOPMODEL. As indicated in Table 7.1, the Nash-Sutcliffe efficiencies of result hydrograph band of the distributed TOPMODEL are higher than those of the original TOPMODEL (from chapter 4).

**Table 7.1** Comparison of result hydrograph bands of the distributed TOPMODEL and the original TOPMODEL for the validation period.

| Hydrograph | Validation efficiency | |
|---|---|---|
| | The distributed TOPMODEL | The original TOPMODEL |
| Highest fitted hydrograph | 0.833 | 0.797 |
| Upper boundary | 0.778 | 0.772 |
| Lower boundary | 0.644 | 0.533 |

As the GLUE process takes thousands of model runs and the distributed algorithm would add significantly to computational time, it was decided that for the Wye and East Dart a simplified test to evaluate model performance between observed and predicted flow would be conducted. The method involved producing a linear regression between the simulated and observed runoff, and analysing the coefficient of determination. The result of the calibration and validation for the two additional upland peatland catchments indicates that the distributed model gives good simulations for summer storm events. The optimized parameter set created for each catchment was then used in the study of land cover change scenarios for each catchment.

## 7.3 Land cover change experiments and recommendations for land management policy

Land cover change scenarios were investigated to determine the impact of land cover change on river flow. These investigations focussed on comparing the impacts of surface cover patches of different sizes and locations for different surface cover conditions which upland peatland managers are concerned about. These concerns include removal of vegetation (e.g. by erosion processes, pollution, overgrazing) or good revegetation of peat with sedges such as *Eriophorum* or mosses such as *Sphagnum.* In each scenario study for the catchments, a presumed 'normal' situation was presented in which *Eriophorum* dominates the vegetation cover in the catchments. This normal situation is set as the standard or baseline scenario to enable results to be compared across scenarios. Other land cover scenarios were created by changing part of the *Eriophorum* land cover to *Sphagnum* or bare peat cover.

Three specific hypotheses concerning the impact of land cover change on river flow were determined based on the literature before work began in the Trout Beck system.

Hypothesis (1): A wider bare peat buffer strip nearer to the river channels brings a higher peak and reduced delay to the peak; conversely, a wider buffer strip with higher density vegetation (e.g. *Sphagnum*) leads to a lower peak and postpones the peak. In both cases, buffer strips surrounding downstream channels have a greater effect than further upstream.

Hypothesis (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 catchment; 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 catchment outlet.

Hypothesis (3): Bare peat on steep slope areas, where overland flow predominantly moves faster, gives a faster response and higher peak value at the catchment outlet, while high density vegetation or re-vegetation on a steep slope area has a larger positive impact on peak river flow delay and reduces the size of peak flow.

Based on the result of scenario runs in the Trout Beck catchment, which showed that some elements of these hypotheses did not hold, these hypotheses were subsequently modified to produce three principles which were then tested in the Wye and East Dart to ensure wider applicability. The three principles are:

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

Principle (2): The size of the land cover change patch has no effect on river flow for patch sizes up to 40000m$^2$.

Principle (3): Bare peat on gentle slopes gives a faster flow response and higher peak value at the catchment outlet, while high density vegetation or re-vegetation on a gentle slope area has larger positive impact on peak river flow delay when compared with the same practices on steeper slopes.

Three groups of scenarios (i.e. buffer strip scenarios, random patch scenarios, and slope-patch scenarios) were formulated and modelled in each catchment, aligning to the three land cover impact principles which were based on the first sets of scenario studies that took place in the Trout Beck catchment.

The results from the Wye catchment were in line with the above principles but the magnitude of differences was not as strong as they were for Trout Beck. The differences in stream flow peak and lag times between land cover change scenarios and the normal scenario were in the direction as found in Trout Beck, but were much narrower. This may be due to the steeper slopes of the Wye catchment in Plynlimon compared to those of the Trout Beck catchment and this in itself would be in line with principle (3). For the East Dart catchment, which has a mean slope similar to that in the Trout Beck catchment, the result was also consistent with the three principles. The catchment area of the East Dart is around twice that of Trout Beck and differences between land cover change scenario impacts and the normal scenario on aerially-weighted flow peaks (mm runoff) were larger than at Trout Beck.

The overall confirmation of the three principles across three different types of peat-covered headwater catchment should be of great interest to land managers concerned about impacts of peatland degradation and vegetation cover on river flows. Thinking about results from tests on principle 1 (and principle 3 where peat slopes are gentle in the riparian zone) the riparian buffer strip is likely to be the most sensitive area for land cover change in the catchment when flood peaks are the matter of concern. This is inconsistent with the results of some modelling work in imaginary simple-shaped catchments (e.g. Huang and Lee (2009) and Maske and Jain (2014)). Vegetation deterioration in these areas is highly likely to lead to more severe impacts on river discharge, while re-vegetation work along stream channel buffer strips may be more effective to mitigate flood risk when compared to revegetation elsewhere. Furthermore, revegetating narrow riparian buffer strips around a long channel network will be more effective than such interventions using wider buffer strips only focussing on the main channels. However, considering the ease of changing land cover in a more confined block area rather than having tiny buffer strips along every single tiny ditch or stream throughout a peatland catchment, wider buffer strips along the main channels may be a more economic practice for migrating flood risk than narrow strips associated with a longer channel network.

The spatial distribution of bare peat or different vegetation zones can sometimes be very marked in peat systems. Sometimes these are natural patterns but often such mosaic-like spatial distributions are caused by human interventions such as rotational burning, overgrazing or accidental fires. Principle (2) was upheld across the three study catchments showing that 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 catchment undergoes that vegetation cover change. This conclusion does not quite support the suggestion about the burning patch size form the Defra Heather and Grass Burning Code (Defra, 2007) in the perspective of impacts on river flow, even though this suggestion may be beneficial to prevent soil erosion. Correspondingly, in a vegetation restoration project in upland peat systems, practitioners can focus more on the total re-vegetation area in the catchment, rather than the size of the re-vegetation patch. Similarly 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 catchment which has undergone the removal of vegetation, However, there is a limitation to the interpretation of these recommendations because the scenario study for principle (2) just covers patch sizes less than 10000 $m^2$.

The scenario study for principle (3) implies that gentle slope areas are more important than steep slope areas for land cover change impacts on river flow in peat catchments. This reveals the combined impacts of local slope and land cover change on downstream river flow. It could be inferred that vegetation deterioration on more gentle slopes will produce a greater impact on flood risk than the same deterioration on more gentle slopes. At the same time, for a re-vegetation project, efforts in revegetating gentle gradient sub-catchments will bring greater benefits for flood reduction than for steeper sloped sub-catchments. Extending the idea to the catchment scale, land cover change in steep catchments (e.g. the Plynlimon catchments) produces less influence on the storm hydrograph than those in gentle sloped catchments (e.g. Trout Beck). Thus, on a regional scale, practitioners looking to invest in peat restoration and who are looking for added downstream flow regime benefits might be able to prioritise investment between catchments based on their slope configuration.

Clearly all three principles have some overlap between them. Large differences occur when interventions operate on more gentle slopes and at the same time riparian buffer zones (most commonly on gently slopes in peatlands) are found to be beneficial. Thus these two principles and findings re-enforce each other. While the width of buffer zones was found to be important (which might seem to be contrary to the patch size principle) this may be because as buffer strip narrows (and total area of buffer strip is maintained) buffer strips have to be extended further upstream and this conforms to principle 1. Therefore, in practice and in general terms, the three principles can be used as guides for land management in upland peat catchments. If planners would like some quantification of effects of surface cover management interventions then the model can be utilized to simulate such effects and assess the land cover change impact on river flow. While the research presented in this thesis so far has focussed on a few land cover change types and patterns, in practice any pattern of land cover change can be modelled and assessed by the model as long as the land cover data in the catchment is provided.

## 7.4 Limitations and recommendations for future research

In this thesis, as with all research projects, there are limitations and there are also new directions and additional areas of work that would be useful. This section briefly covers some of these main features.

### 7.4.1 Distributed data on vegetation cover

Better resolution land cover data is required for peatland systems to improve model performance. There is a shortage of such data (e.g. 20 m $\times$ 20 m grid cell data or smaller) on vegetation cover distributions in peat catchments. Improvements in remote sensing and automation of land cover classification which may give higher resolution data may support more detailed studies of land cover impacts on overland flow paths and improve the description of overland flow delay in the model. This would aid the modelling applications developed in this thesis.

### 7.4.2 Quantitative relationships between vegetation cover type and overland flow velocity

In the overland flow module of the distributed TOPMODEL, the overland flow velocity equation builds a quantitative connection between the velocity of overland flow, roughness of vegetation cover, slope and overland flow depth. The roughness parameter of each type of vegetation cover in the equation is the critical factor to represent the impact of this type vegetation cover on overland flow movement in the model. This is a key part of the model to reflect the land cover type and translate its impact to river flow hydrographs. The roughness of each land cover type is defined as relative roughness to *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 peatland catchments. However, the land cover categories of *Sphagnum*, *Eriophorum*, and bare peat are not detailed enough to classify the hydraulic roughnesses of a greater variety of land cover types on peatland hillslopes. Indeed for non-peat systems more data is also required on overland flow velocity relating to vegetation cover. The quantitative relationship between each vegetation cover type and overland flow velocity needs to be further investigated, and laboratory experiments and in-situ surveys with new approaches may be necessary as the field data collection can be laborious. It is possible that developments in terrestrial laser scanning might enable more routine measurements of overland flow velocity on hillslopes with complex and heterogeneous surface forms (Smith et al., 2011ba). Promising research in Mediterranean semi-arid catchments (Smith et al., 2011ab) may be applicable to a wider range of environments including peatlands.

### 7.4.3 Modelling the distributions of soil erosion and contaminant transportation in peatland catchments

The linkage of hydrological models with those of geochemistry, ecology and geomorphology is widespread (Singh and Woolhiser, 2002). Many catchment hydrology models have water-quality components built into them, e.g. SWAT (Soil Water Assessment Tool) (Arnold et al., 1998), SHETRAN (Ewen et al., 2000), and HSPF (Hydrologic Simulation Program Fortran)

(Bicknell et al., 2001). The original TOPMODEL and its developed versions has also been employed and modified to simulate water quality and erosion in a few studies (e.g. Kirkby et al., 2008; Page et al., 2007)

TOPMODEL can act as an engine of contaminant transportation simulations. Because of the establishment of an overland flow module describing the routing and velocity of overland flow, the distributed model has the ability to represent the velocity vector field of overland flow on hillslopes. With this advantage, it is possible to simulate the movement of eroded soil or contaminants on hillslopes with the necessary knowledge of eroded soil yield or contaminant stores, and their transportation mechanisms. A module with the algorithms representing these mechanisms for transportation could be built to couple with the overland flow module that was developed in this thesis. The model could give distributed simulation results demonstrating, for example, the distribution of vulnerable areas of erosion or contaminant concentration maps during storm events.

### 7.4.4 Scale issues

#### 7.4.4.1 Spatial scale

Land cover scenario studies in this thesis have focused on mid-scale catchments (10 - 20 km$^2$) with impacts on local hydrographs at the catchment outlet clearly identified. The impact of land cover changes on mid-scale catchment hydrographs has been found in many previous studies (as reviewed in Chapter 2) but the modelling undertaken in this project is the first that has looked at the impact of land cover type in peatlands and the impacts of the vegetation cover type on river flow. However, there are still questions about how such land cover change ‘signals’ in the hydrograph propagate and how readily they become attenuated downstream in the river channel. Further work is required for peatland restoration scenarios to understand at which point in the river (i.e. which accumulative area or spatial scale) the impact can no longer be detected and hence cannot be considered for flood risk. Addressing this issue in a follow on project to this thesis may be very helpful for practitioners and for those seeking to understand the ecosystem services value of flood mitigation provided by peatland restoration practices (Acreman and Holden, 2013; Reed et al., 2013).

Another spatial scale issue worth investigating is the question of how land cover change impacts on river flow may vary with catchment scale as you move from 10$^1$ to 10$^4$ km$^2$ (keeping an identical proportion of land cover change area in different catchments). Land cover scenario studies in the

Trout Beck catchment (11.4 $km^2$) and the East Dart catchment (21.5 $km^2$), of which the mean slopes are similar (9.4% vs. 9.1%), indicates that the same percentage land cover change area (e.g. 10% or 20% of the whole catchment) in the larger catchment produces (relatively) more impact on the river flow peak than that in the smaller catchment. This seems to imply that land cover change in same area proportion in larger catchments for both vegetation removal or re-vegetation work are more efficient than for smaller catchments. However, the two catchments have different shapes and topographic features (e.g. the East Dart catchment is narrower and longer than the Trout Beck catchment in shape) which may also affect the overland flow concentration on hillslopes. Due to this, the scaling implications are somewhat ambiguous and there is a need for clarification which could involve research on land cover change in a series of nested catchments along a river system.

#### 7.4.4.2 Influence of precipitation scale on land cover change impact

The impact of land cover change may vary for different sizes of rainfall events. To conduct clear and comparable land cover change scenario experiments one-hour 20 mm rainfall events were used for the three catchments in chapters 5 and 6. In this section, rainfall events with variety of precipitation rates are investigated to demonstrate the influence of land cover change.

Three sets of representative scenarios with bare peat and *Sphagnum* were simulated with 30mm, 40mm and 50mm 1-hour storm events for the Trout Beck catchment. The results indicate that the relative impact of land cover change compared to the normal scenario decreases with the increase of rainfall intensity (from Figure 7.4, Figure 7.5 and Figure 7.6). In other words the land cover change impact seems to be attenuated for extremely high intensity rainfall events. However, in each case an effect of land management change can still be demonstrated and of course such large events such as 50 mm of rainfall in an hour on an upland blanket peat system in the UK is a very rare occurrence. Another 5-hour 50 mm storm event with 10 mm rain for each hour was run for the three sets of representative scenarios. There was little impact on peak flow of running a longer storm event. The order of the rising limbs of the flow peaks was the same as found in earlier chapters linked to representative scenarios, i.e. the riparian buffer strip scenario, the gentle slope patch scenario and the random patch scenario for bare peat land cover change, and the converse order for the *Sphagnum* land cover change (see Figure 7.7 and Figure 7.8

for the result of 20% area scenarios). A lower rainfall intensity with the same rainfall total leads to steady-state where input equals output so there is no impact on peak flow. However, there is still a delay to peak and these delays are in the same order as for the more intense storms simulated. Nevertheless, further work may be fruitful in understanding the interactions between rainfall intensity and land management which includes impacts from moderate (e.g. once monthly events) through to rare and extreme events (one in a hundred year rainfall events).

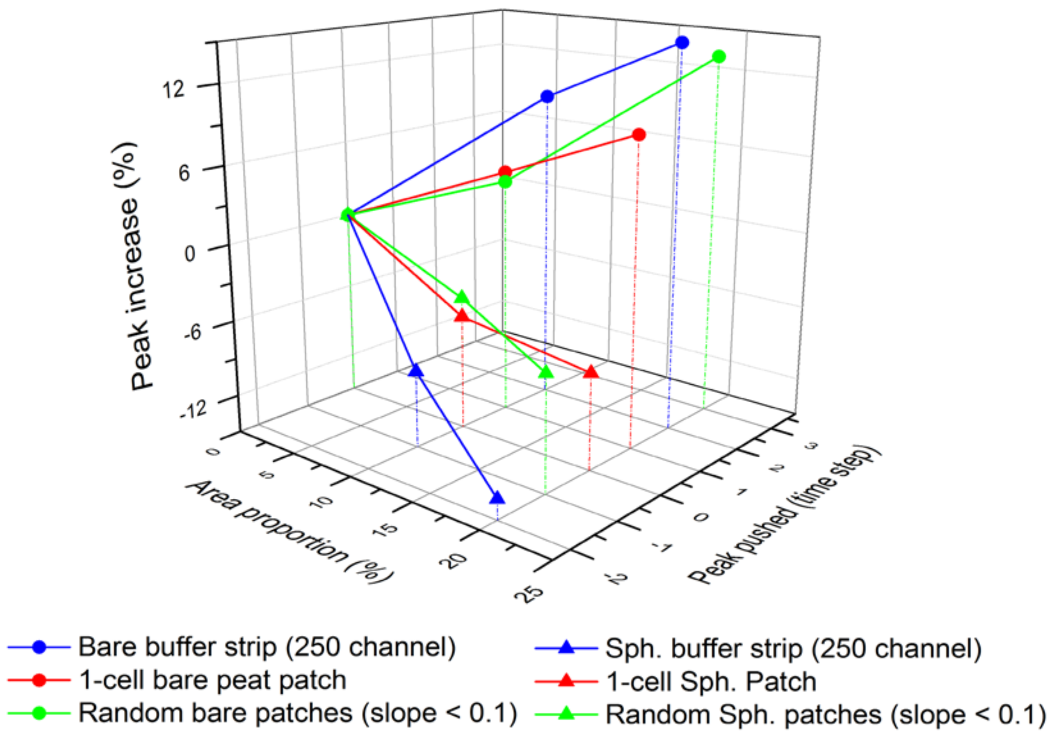


**Figure 7.1** Comparison of the combined impacts of representative land cover change scenarios on river flow peak under a 1-hour 20mm rainfall event in the Trout Beck catchment.

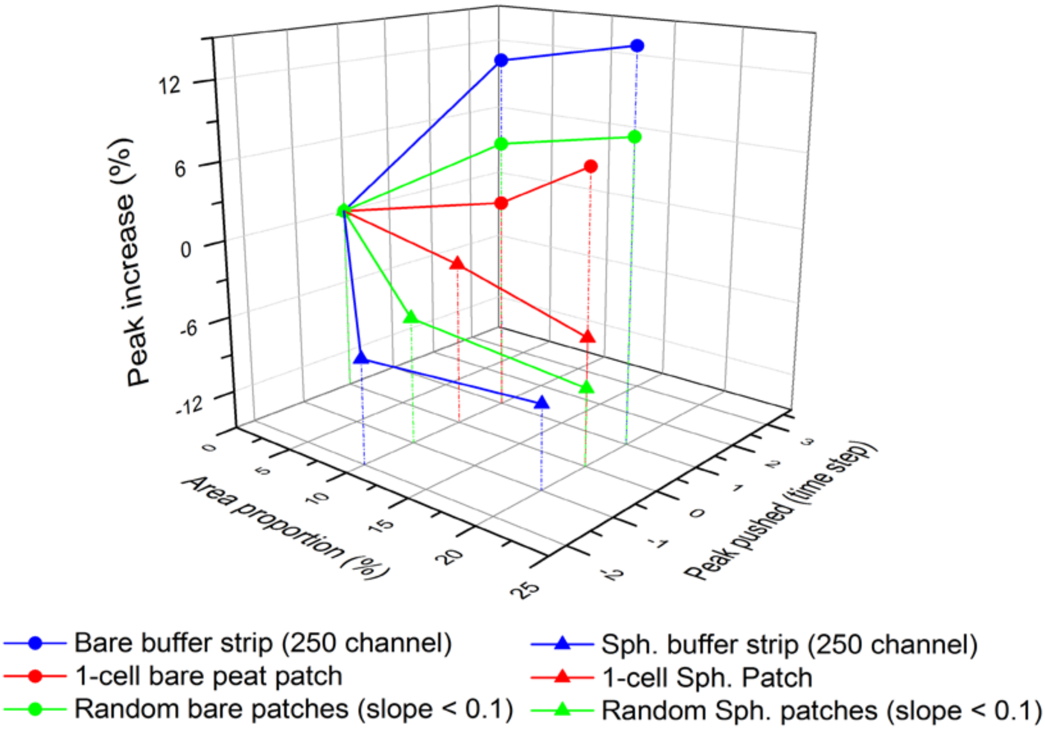


**Figure 7.2** Comparison of the combined impacts of representative land cover change scenarios on river flow peak under a 1-hour 30mm rainfall event in the Trout Beck catchment.

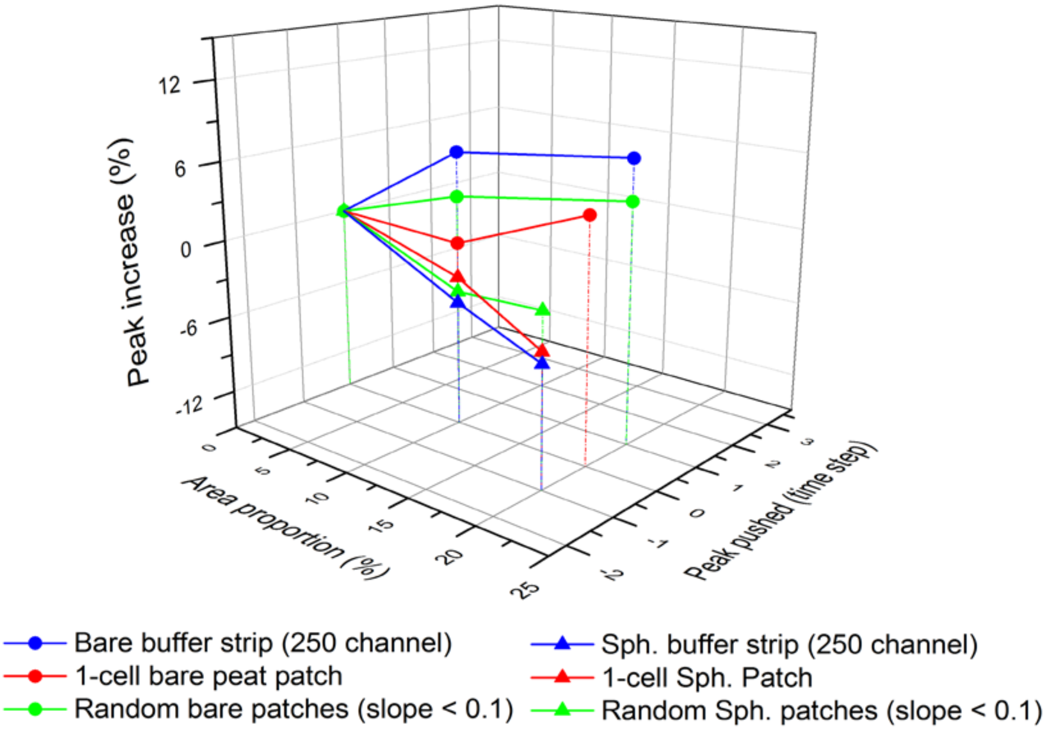


**Figure 7.3** Comparison of the combined impacts of representative land cover change scenarios on river flow peak under a 1-hour 50mm rainfall event in the Trout Beck catchment.

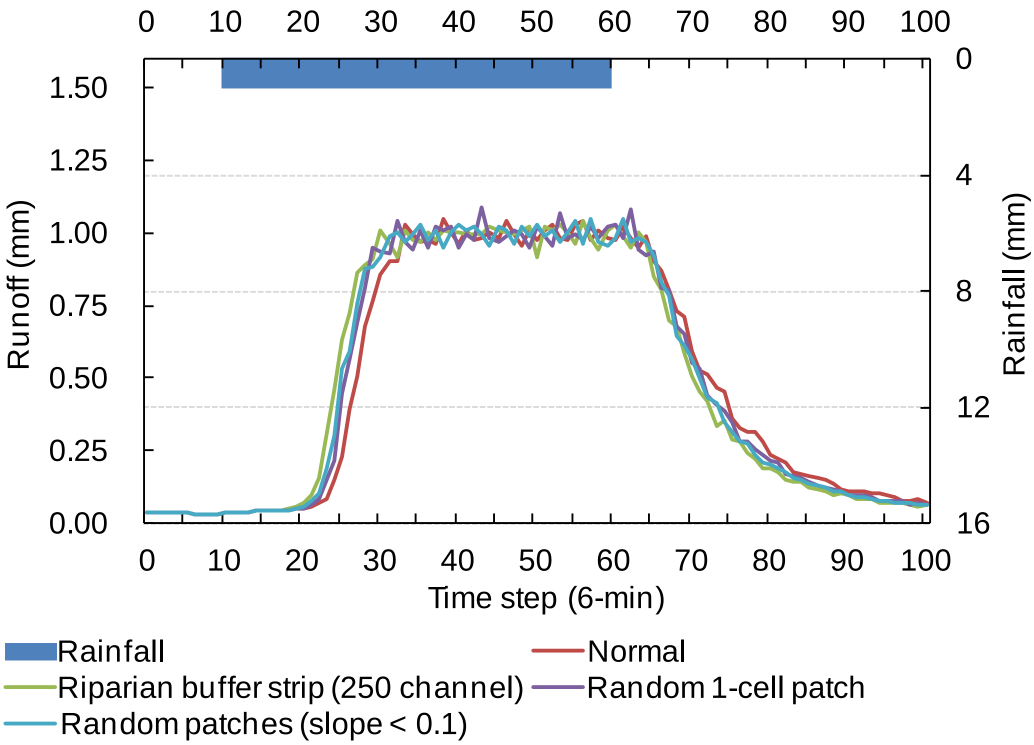


**Figure 7.4** Simulation hydrographs of representative scenarios with 20% area bare peat for a 5-hour 50 mm storm event.

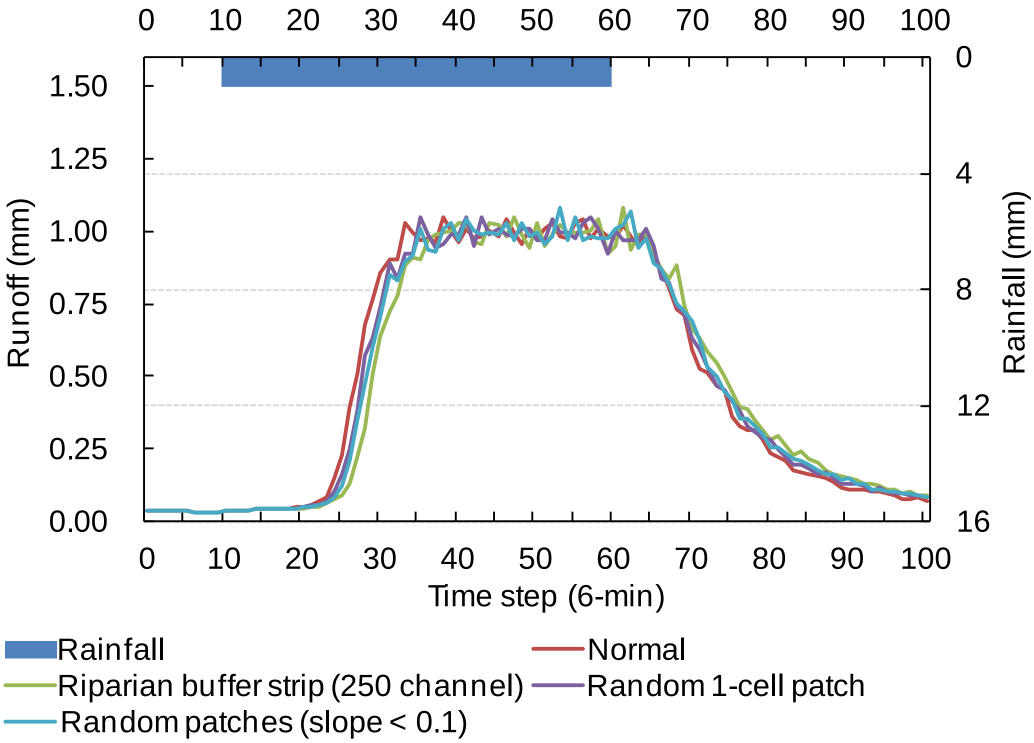


**Figure 7.5** Simulation hydrographs of representative scenarios with 20% area *Sphagnum* with a 5-hour 50 mm storm event.

## 7.5 Research conclusions

In this thesis, the main research questions that were tackled at the outset were:

1. What is the impact of upland management on downstream river discharge, especially on peak flow and timing in upland peat catchments?

2. Can we adequately characterise upland land management impacts as impacts on surface vegetation cover, roughness and hydrological flowpaths that affect the speed and timing of delivery of water to river channels?

3. To simulate the impacts what would be a robust approach? Is a modified TOPMODEL competent to address the two key questions above?

It was necessary to answer these questions in reverse order. In order to answer question 1 it was necessary to first address question 3 and then question 2.

Based on these questions, a distributed version of TOPMODEL was developed with a special overland flow module describing surface vegetation roughness influences on saturation-excess overland flow movement. The model was tested and operated with good performance in three upland peat catchments in different parts of England and Wales. The development of the new version of TOPMODEL includes the distributed modification of the original TOPMODEL and the implanted overland flow module, in which the overland flow movement and re-infiltration process are involved. Comparison of the simulation results of the two models implies that the new distributed TOPMODEL performed better than the original version in the Trout Beck catchment, and the distributed configuration and the new overland flow module seem to improve the model's ability to predict river flow. Clearly this is in addition to the benefits developed including the spatial distribution and the fact that users of the new model can also determine overland flow volumes and velocities across any point in the catchment for each time step used. At the same time, the modelling results indicate that it is an effective way to characterise land cover change impacts on river flow. The distributed TOPMODEL appears to be a good tool to simulate and evaluate land cover change impacts on stream discharge in upland peat catchments.

Land cover change scenarios were studied in the three experimental catchments which addressed research question 1. The key outcome from this work was the production of three land cover hydrograph impact principles.

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

Principle (2): The size of the land cover change patch has no effect on river flow for patch sizes up to $40000m^2$.

Principle (3): Bare peat on gentle slopes gives a faster flow response and higher peak value at the catchment outlet, while high density vegetation or re-vegetation on a gentle slope area has larger positive impact on peak river flow delay when compared with the same practices on steeper slopes.

There principles should be useful for communicating the story of land cover change impacts on river flow and supporting decision-making among practitioners.

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