6

Numerical simulation of two flash flood events in the UK

6.1 Background

Intense rainfall events may be short lived, lasting only a few hours, but have the potential to cause substantial and destructive flooding. In the UK, such storms occur generally in the Summer months, and their severity is often the result of a combination of meteorological factors such as high moisture content in the atmosphere, convective rain cell formation, orographic enhancement of rainfall, and slow-moving or stationary rain cell. The combination of one or more of these characteristic often leads to river catchments being subjected to particularly high-intensity rainfall narrowly focused in a single catchment area or even more localised area within a catchment. Antecedent conditions, such as soil-moisture content, also play a role, but in cases of the most extreme rainfall events, even catchments with a high potential to absorb incoming rainfall or slow its flow towards rivers will be overwhelmed with the rate and volume of water input to the catchment and flooding will be inevitable.

This chapter describes two events that took place in UK river catchments in the Summers of 2004 and 2005 and their representation by a series of numerical modelling experiments. The experiments are designed to investigate the role of rainfall spatial resolution in hydrological and geomorphological processes during severe storms.

The Ryedale catchment, near the town of Helmsley, North Yorkshire (2005); and the Valency catchment near the village of Boscastle, Cornwall (2004). Both catchments experienced intense rainfall leading to extensive and damaging flash flooding in each catchment. There were significant economic impacts for both communities affected by the floods, as well as natural geomorphological changes in the river channels and catchments observed in the aftermath of the flooding.

6.2 Meteorological setting

Two upland catchments in the UK were selected to represent a range of catchment sizes and shapes. The catchments were also chosen on the basis that they had experienced a severe rain storm which could be used as a basis for the experiments, such that it could be considered 'extreme' in the typical return period of flooding events for each particular catchment. Peak discharges for each of the following flood events exceed the 99th percentile for their respective catchments. The catchments and respective severe rain events chosen were located in: Ryedale, North Yorkshire, 2005; Eden, Cumbria 2012; and Boscastle, Cornwall, 2004. An overview map of their locations is given in Figure 6.1. A table (Table 6.1) summarises the key features of each catchment and associated storm.

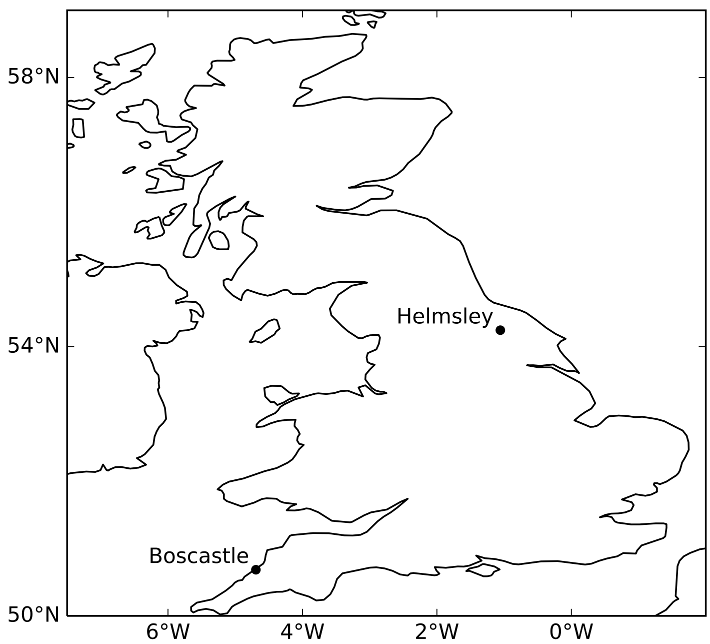

Figure 6.1: Location of the two case study catchments and main settlement within each catchment within Britain

Catchment Name	**Ryedale**	**Valency**
Main settlement	Helmsley	Boscastle
Catchment Area	270km^2	18km^2
Catchment Type	Upland, Moor/Peaty	Upland, Pasture
Storm Date	2005-06-19	2004-08-16
Peak Rainfall (mm hr $^{-1}$)	125	c.400
Meteorological Setting	Split-front, convective system	Quasi-stationary convective system
3hr Rainfall Return Period	330yr (Wass et al. 2008)	1300yr (Burt, 2005)

Table 6.1: Table showing key characteristics of each storm event.

6.2.1 Boscastle, Cornwall storm 2004

The Boscastle storm took place on the 16th August 2004 leading to flooding within the River Valency catchment and the village of Boscastle. In the preceding months March–June, the south-west region had been drier than usual, but during July the Valency catchment area experienced average rainfall conditions (Golding et al., 2005). The estimated soil moisture deficit[1] in the area, which had been lower than average due to the dry antecedent conditions, decreased during the period of 1–16th August, due to the return to average rainfall conditions in that month. The soil moisture deficit during this period was estimated to have decreased from approximately 80–220mm to 40–180mm.

On the day of the storm, the extreme rainfall accumulations of up to 200 mm in the upper Valency catchment resulted from prolonged rainfall between the hours of 1200 – 1600 UTC. Rainfall rates were thought to have reached almost 400 mm hr^{-1} (Golding et al., 2005), after correcting for under-reporting from rain gauges in the vicinity of the catchment. (Burt, 2006).

The meteorological conditions that enabled such prolonged heavy rainfall were a combination of large-scale synoptic conditions moving in from the Atlantic, with moist lower atmospheric layers readily forming convective cloud. Repeated initiation of convection along the north Cornish coast lead to what appeared to be relative stationary convective cells over the Valency catchment. Later authors refer to this type of convective storm as a 'Boscastle-type' or quasi-stationary convective storm (Warren et al., 2014).

[1] The amount of water needed to bring the soil back to field capacity, i.e. a state where the soil is holding the maximum amount of water possible against gravity. (Beven, 2011)

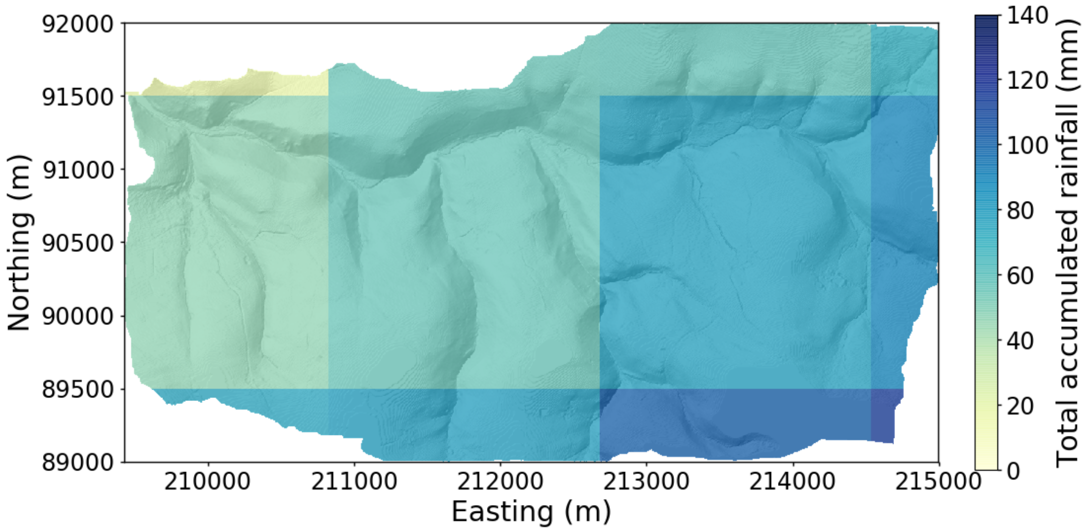

Figure 6.2: Total accumulated radar rainfall (24 hours) over the Valency (Boscastle) catchment during the 16th August 2004.

6.2.2 Ryedale, North York Moors storm 2005

The Ryedale storm occurred on 19 June 2005. Intense rainfall throughout the afternoon lead to total accumulated rainfall amounts of up to 89mm in the Ryedale valley, between the hours of 1400 – 1800 UTC. Peak instantaneous rainfall rates were estimated to have been around 32.5mm hr^{-1} (Sibley et al., 2009) to 59.4 mm hr $^{-1}$ (Hopkins et al. 2010), though one report states they reached as high as 125 mm hr $^{-1}$ (Cinderley, 2005). The antecedent conditions had been dry for a prolonged spell, leading to cracking of the surface peat in the higher elevations of the catchment.

Antecedent conditions before the Ryedale storm of 2005 had been dry over a prolonged period over much of the region (Sibley, 2009). Soil moisture deficit was estimated to be around 60mm in the catchmnet, higher than usual due to the drier conditions in the preceding months (Wass et al., 2008). With a low soil moisture content, thinner soils in the upper reaches of the catchment would have been dry before the intense rainfall.

The meteorological conditions leading to such heavy rainfall was a combination of a cold, upper-level air mass advecting over a warm moist boundary layer, leading to unstable conditions that enabled a convective thunderstorm to develop in the late afternoon. The conditions let to a particularly high amount of precipitable water present in the atmosphere which was subsequently washed out into the landscape during intense rainfall.

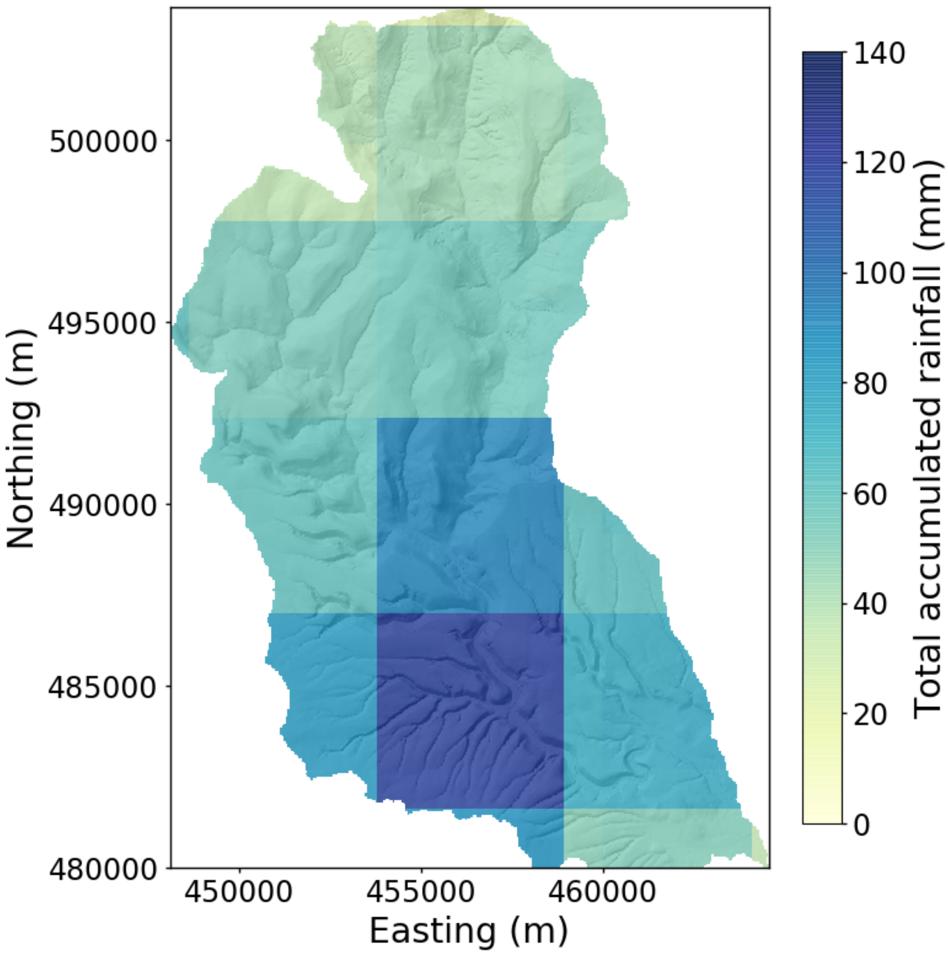

Figure 6.3: Total accumulated radar rainfall (24 hours) over the Ryedale catchment during the 19th June 2005.

6.3 Flooding and geomorphic change

6.3.1 Boscastle, Cornwall, 2004

Flooding was extensive in the area surrounding Bosacstle village, with flood levels rapidly exceeding bankfull and flooding several properties to depths of several metres. Water levels in the Valency river and its tributaries began to rise in the early afternoon from approximately 1200 UTC onwards, reaching bankfull around 1430 UTC and peaking at around 1600 UTC, by which point over 70 properties had been flooded, with several destroyed due to the force of the water (HR Wallingford, 2005). The hydraulics of the Boscastle flood were complicated due to the role of large debris blockages ('trash barriers') in the river channels. In particular, a large debris blockage occurred in the main bridge in the village crossing the Valency, which caused a significant backup of water behind the bridge, and re-routing of water through alternate pathways within the village. A reconstruction of the flood based on eyewitness accounts and water mark levels, consequently results in different reports of the peak water level in the village depending on where the observations were made (HR Wallingford, 2005).

The geomorphological impacts of the flood event were well documented in the aftermath of the flood (HR Wallingford, 2005). The Valency river channel and many of its tributaries were observed to have experienced channel avulsion[2] in places, as well as significant downcutting in the upper tributary channels of the catchment. In a number of places the channel avulsion was substantial enough to straighten the channel and increase the local gradient of the river, potentially increasing flow velocities and shear stresses acting on the channel bed. There were large amounts of sediment observed in the river flow at the time, ranging in size from fine silts to boulders. There were some areas of sediment deposition observed along the river channel banks and floodplain, and a sizeable area of sediment deposition in Boscastle harbour. However, most stretches of the main river channel and its tributaries showed net erosion in the form of channel widening (up to 3–4 metres) and deepening (of up to 2 metres) (HR Wallingford, 2005).

6.3.2 Ryedale, North Yorkshire, 2005

Flooding was widespread in the Rye catchment, with river levels reaching up to 3.5 m at Hawnby at the peak of the flood, submerging the gauging station building (Wass et al., 2008). In Helmsley, the largest settlement, further downstream, similar river level rises of up to 2m were reported at the peak of the flood in the evening and into the night.

Geomorphologically, the Ryedale catchment saw relatively rapid change considering the short duration of the storm and subsequent flood on the 19th June. In the aftermath of the flood, up to 2–3 metres of channel downcutting and erosion were reported to have take place in the upper reaches of the tributaries of the catchment (Hopkins, 2012; Wass et al., 2008) as well as significant amounts of sediment and debris deposition in the lower reaches of the catchment around the settlement of Helmsley (Hopkins, 2012). The storm was noted for the triggering of many landslides

[2]Movement of the original channel to a new position within the flood plain.

on hillslopes within the catchment, including 105 reported shallow landslides in the catchment, as well as two large peat slides in moorland areas covering up to 3.7 ha of mass movement in areal extent (Galiatsatos et al., 2007; Wass et al., 2008). Dry antecedent conditions in the area are believed to have led to the amount of landsliding reported by weakening the peat moorland within the catchment (Sibley, 2009). Dry conditions proceeding summer storms are reported to cause shrinkage and cracking in peatlands, leading to greater risk of erosion in heavy downpours (Warburton et al., 2004). The economic damage was also substantial for a sparsely populated area. Three bridges were destroyed at a cost of £2.9 million, as well as flooding of 121 properties (Wass et al., 2008). Economic loss included agricultural damage such as loss of land and livestock (Sibley, 2009). Many residents were displaced for months during repair and were reported to have suffered illness and psychological trauma from the event (Hopkins, 2012).

6.4 Experiment design

Using the two flash flood events described previously as case studies, an ensemble of simulations was designed to address the questions laid out in Chapter 1 and summarised in the hypotheses as follows:

1. **Flood inundation modelling is sensitive to the spatial detail of precipitation.**
   (a) Catchment hydrology is sensitive to the spatial distribution of rainfall inputs over the catchment area. Resolving the spatial details of a precipitation event, such as during a flash flood, allows the timing and magnitude of flood inundation to be better predicted.
   (b) Geomorphological change of the river channel and flood plain during a flash flood is substantial enough to alter the patterns of flood inundation. In a model that can account for erosional change during flooding, nuances in flood inundation can be better predicted.
2. **Erosional processes in river catchments are sensitive to the spatial distribution of rainfall inputs.**

Experiment name	**Rainfall input**	**Erosion law**
UNIFORM_HYDRO	Spatially-averaged Radar	(no erosion)
UNIFORM_DLIM	Spatially-averaged Radar	Detachment-limited
UNIFORM_TLIM	Spatially-averaged Radar	Transport-limited
GRIDDED_HYDRO	1km Radar Gridded	(no erosion)
GRIDDED_DLIM	1km Radar Gridded	Detachment-limited
GRIDDED_TLIM	1km Radar Gridded	Transport-limited

Table 6.2: Outline of the simulations carried out for both the Ryedale and Boscastle case studies.

(a) Erosion and sediment transport processes are sensitive to thresholds determining erosion initiation and sediment entrainment. If item (1a) holds true, then fluvial erosional processes should exhibit sensitivity to the spatial distribution of rainfall inputs of rainfall as well.

(b) The parameterisation of erosional processes in the model also determines the spatial pattern of erosion and deposition, but does spatial variation in rainfall inputs exert a greater control than the choice of erosion law?

To test the above hypotheses, simulations of the two case studies were repeated, varying the following conditions:

- Rainfall spatial resolution
- Erosion law parameterisation (including a 'no-erosion' control case)

The simulations were parameterised with different erosion law schemes and different rainfall input resolutions to assess which exerted the greatest control over catchment response to intense rainfall, in terms of flood inundation and sediment transport. The same set of experiments was carried out for two historic rainfall events that lead to severe flooding in UK river catchments, giving a total of 6 different simulations for each catchment outlined in Table 6.2 – a total of 12 simulations.

6.4.1 Model initialisation and configuration

The numerical landscape evolution model, HAIL-CAESAR (described in Chapter 5) is used for all simulations. HAIL-CAESAR is a hydrodynamic landscape evolution model that uses a TOPMODEL-based hydrological rainfall-runoff model to generate surface runoff in a river catchment, which is then routed through the landscape according to an adaptation of the LISFLOOD-FP shallow water routing algorithms (Bates, Horritt and Fewtrell, 2010). Fluvial erosion and sediment transport is then derived using the velocities and depths of the calculated surface water within the catchment. The equations describing the water routing, sediment erosion, and transport laws are described fully in Chapter 5.

Input data

Rainfall input data is taken from the Met Office NIMROD radar rainfall 1km composite dataset (Met Office, 2003). The same 1km rainfall radar product is used to derive the rainfall inputs for the spatially uniform rainfall simulations, by averaging out the gridded rainfall data over the input points of the catchment, thus preserving the total amount of rainfall input in each simulation, and only varying its spatial distribution for the relevant simulations.

Topographic data used to initialise the terrain surface for the Boscastle simulation is derived from the Environment Agency (England) 2m LiDAR product. The Boscastle data is resampled to 5m grid spacing to reduce the total number of grid cells and the computational demands of running a complex hydrodynamic model. Environment Agency LiDAR was not available for the whole Ryedale catchment at the time of the simulation, so the Ryedale terrain is initialised using OS Terrain 50 data, interpolated to 5m grid spacing to enable like-for-like comparison with the Boscastle terrain grid spacing. Resampling the initial topographic data sources to the same terrain grid spacing for both sets of simulations is done to minimise the potential effects that variation in grid spacing has on model output and subsequent topographic analysis (e.g Chang and Tsai, 1991; Schoorl et al., 2000; Haile and Rientjes, 2005; Zhang et al., 2008)

Simulation duration

The simulations are set to begin 24 hours before the day of each intense rainfall event. The model is allowed to run for a further 24 hours after the event, giving a total simulation tme of 72 hours. The timing of the simulations is given in Table 6.3.

Event	Start time	End time
Boscastle	2004-08-15 00:00	2004-08-17 23:59
Ryedale	2005-06-18 00:00	2005-06-20 23:59

Table 6.3: Start and end times (UTC) for each 72 simulation. The major rainfall event occurs during the 2nd day in each simulation.

Erosion-enabled simulations

A variety of erosion laws exist describing how landscapes erode from fluvial incision. The choice of erosion law for a given catchment depends on a variety of factors, such as the characteristic substrate material in the catchment – is it predominantly loose sediment or cohesive, solid bedrock? In reality, landscapes are often a mixture of these two extremes, incorporating loose sediment on top of solid bedrock. Catchments also often exhibit a transition from rockier upland headwaters, to more thickly soil-mantled flood plains. In order to address the uncertainty in choosing which erosion model applies for each catchment (Chapter 2), two erosion model end-members are used, with each one representing a different conceptual model of fluvial incision and sediment transport. These include: i) a purely sediment transport-limited model, ii) a detachment-limited bedrock incision model. The equations describing the transport-limited and detachment-limited models used in the model are discussed in detail in Chapter 5. Further models were considered, such as a hybrid transport-detachment limited erosion model, but it was deemed beyond the scope of this study, which is to focus on the sensitivity of rainfall resolution, rather than wide range of erosion and sediment transport models.

A set of control simulations parameterising only runoff and surface water routing (no erosion taking place) were also carried out for comparison against the two erosion end-member simulations. (Table 6.2.)

Rainfall spatial resolution

In order to assess the sensitivity of each erosional model to the spatial details of precipitation, rainfall spatial parameterisation is alternated in each simulation between a spatially uniform rainfall input and a 1km gridded rainfall input. Both the spatially uniform and gridded inputs are based on the same original rainfall source data - the UK Nimrod 1km-composite radar data product (Met Office, 2003). To reduce the range of variables within the set of ensemble simulations, only the spatial distribution and resolution of rainfall is assessed in this study – other studies have previously investigated the effects of the *temporal* resolution of rainfall data on discharge and erosion rates (Nicótina et al., 2008; Coulthard, Neal et al., 2013; Coulthard and Skinner, 2016). In all experiments, the temporal resolution of experiments is maintained at 5 minute intervals. To summarise, the two types of rainfall spatial input used are:

- Uniform or 'lumped' precipitation: Radar-derived rainfall rates across the catchment are spatially-averaged to produce a basin-wide rainfall rate. In other words, every grid cell in the model domain receives the same rainfall rate at each rainfall data timestep.
- Gridded rainfall input. The rainfall rate is input from a overlying gridded mesh of raincells, at the same resolution as the rainfall radar product (1km).

6.5 Summary

Using case studies from two flash flood events in the UK in recent decades, a series of simulations has been designed to investigate the effects of rainfall spatial resolution has on flood inundation modelling, sediment erosion and transport, and catchment-scale hydrogeomorphic processes. The simulations are designed to answer the questions laid out in Chapter 1 and the hypotheses summarised in Section 6.4.

The results and analysis of the simulations are discussed in the subsequent chapters. Chapter 7 analyses and discusses the effects the rainfall spatial resolution has on flood inundation prediction in a hydrodynamic model, and also looks a the effects that geomorphic change during a flood has on flood dynamics. This addresses Question 1 laid out in Section 6.4 above. Chapter 8 analyses the results of the simulations focusing on sediment erosion and transport, discussing whether the spatial patterns of rainfall control the distribution of erosion and deposition in a catchment. The implications for longer term landscape evolution modelling are also discussed. This chapter address Question 2 laid out in Section 6.4 above. Conclusions and links between rainfall inputs, hydrological, and geomorphological processes are discussed in Chapter 9.

7

Sensitivity of a flood-inundation model to rainfall distribution and erosional parameterisation

7.1 Introduction

Flooding from intense rainfall poses great risk to communities living in proximity to rivers and has the potential to cause loss of life and substantial economic damage in affected areas (Pitt, 2008). Reliable prediction and advanced warning of flooding requires an understanding of the hydrological processes that operate within a river catchment, in order that operational flood forecasting models may be better parameterised and developed to mitigate against the impact of future events. The interaction of environmental processes within the river catchment system is sensitive to a number of external and internal forcings, including but not limited to precipitation input (Nicótina et al., 2008), catchment vegetation cover (Darby, 1999; Andréassian, 2004; Bradshaw et al., 2007), preconditioning of the catchment water table and soil moisture store by antecedent conditions (Berthet et al., 2009), urbanisation (Hollis, 1975), debris mobilisation and blockage in river channels (Gippel, 1995; Jeffries et al., 2003), as well as channel morphological change during flood events (Wong et al., 2015).

The question of whether spatial detail in rainfall inputs to a river catchment affects the hydrological response is unresolved, with a number of different studies putting forward seemingly conflicting conclusions. Early studies using deterministic modelling of river catchments and synthetic rainfall fields (Wilson et al., 1979) suggested that detailed space-time representations of rainfall were needed in distributed hydrological models. However, no allusion was made to the possible effects of varying catchment scales. In terms of predicting peak discharge in a catchment (Krajewski et al., 1991), a small catchment (7.5km^2), was found to be sensitive to the temporal resolution of rainfall input data, but less so to the spatial distribution of rainfall inputs. The role of catchment size is likely to play a part in determining sensitivity to rainfall distribution, with several studies suggesting catchment size can dampen the effect of rainfall spatial variability (Segond et al., 2007; Nicótina et al., 2008). The idea of catchment-size dependence has been developed further (Gabellani et al., 2007), suggesting that sensitivity to rainfall spatial heterogeneity depends on the characteristic size of the rainfall feature and the catchment size. Systematic investigation of the role of catchment size and morphology have suggested that is specifically the ratio between characteristic hillslope length of the catchment and the rainfall feature that determine sensitivity to spatial heterogeneity (Nicótina et al., 2008). In cases where the rainfall feature is much greater in size than the typical hillslope length, the effects of rainfall heterogenity on runoff and hydrological response are muted.

Understanding how flood dynamics interact with channel and floodplain morphological change is of growing concern for flood modelling (Fewtrell et al., 2011). Morphological change during flood events has been shown to be a potential control in the extent of flooding during intense rainfall (Wong et al., 2015), particularly when river channels undergo geomorphically rapid change during repeated rainfall events of high magnitude (Slater, 2016). Within the context of a single flood, bedload sediment may become highly mobile, and the forces acting on the boundaries of the river channel are sufficient to alter channel geometry in long profile, cross-section, and channel pattern (Wong et al., 2015; Kleinhans et al., 2013). As a counterargument, it has ben put forward that during large flood events the floodplain and river channel effectively act as one channel unit, dampening any effects brought about by changes to river channel morphology (Bates, Horritt, Hunter et al., 2005). The implications of sediment transport and erosion within river catchments has been highlighted as an important factor in flood inundation modelling (Lane, Tayefi et al., 2007; Lane, Reid et al., 2008; Neuhold et al., 2009), and should form part of an effective flood modelling strategy

(Wong et al., 2015) in catchments thought to be sensitive to morphological change during large floods.

Flood inundation prediction studies rarely consider both morphological change during flooding or spatial heterogeneity in rainfall inputs to the catchment. Given the reported importance of rainfall resolution on predicting increased sediment yields and channel incision over decades (Coulthard and Skinner, 2016), can the same observation be made at the time scale of a single event, and does this in turn control the dynamics of a given flash flood event? Though there are differing conclusiions as to importance of rainfall heterogeneity and channel morphological change in flood inundation modelling, there is at least agreement that both have the potential to alter the outcome of flood prediction, under certain conditions. More investigation is needed into which of these uncertainties plays the greater role in determining flood inundation patterns during intense rainfall events and the analysis presented in this chapter attempts to address this by comparing flood inundation model predictions under different rainfall spatial resolution scenarios and erosion law parameterisations.

The following questions are explored through the use of numerical modelling experiments set out in Chapter 6, Table 6.2

1. Are predicted flood inundation extents during a storm sensitive to the spatial resolution of rainfall inputs to the catchment?
2. Are fluvial erosion and sediment transport controls on predicted flood inundation extents during a single severe storm?
3. Does geomorphic change of the floodplain and channel during a storm event significant enough to affect flood inundation predictions?

7.2 Sensitivity analysis

There are numerous user defined parameters in the HAIL-CAESAR model, and in landscape evolution models in general, that have a wide range of potential values. Parameter selection in environmental modelling comes with a degree of uncertainty, and resulting outputs from models can be highly sensitive to the user's choice of

Catchment	**TOPMODEL m parameter**
Boscastle	
Ryedale	0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.15, 0.2

Table 7.1: TOPMODEL m parameter values used to run sensitivity simulations for each catchment.

input parameters for a given simulation (Pelletier, 2012). Initial testing of the HAIL-CAESAR model, and studies using the CAESAR-Lisflood model that it is based upon show it is particularly sensitive to the TOPMODEL m parameter, a parameter that controls the rise and fall of the soil moisture store, and hence how a river catchment responds to rainfall input (Beven and Kirkby, 1979).

To assess the sensitivity of the model to the choice of TOPMODEL-m parameter, a series of simulations were carried out with a range of m values for both test cases. Simulations of each flood event were carried out with the m values shown in table 7.1.

7.3 Results

7.3.1 TOPMODEL sensitivity

The model exhibited a strong sensitivity to the choice of the TOPMODEL m parameter. In the results presented in figure 7.1 peak river discharge ranged from XX at an m value of 0.003 to XX with an m value of 0.008. The measured peak discharge reported for the 2005 storm at the Ness gauging station was 105 cumecs. In the sensitivity simulations, a value of $m = 0.005$ produced a flood peak most closely matching the observed value, peaking at XX cumecs (Note the time as well.).

There were differences between the hydrographs of the observed and simulated discharges in terms of peak discharge timing and recession limb shape. The observed hydrograph showed a sharp rise at around 50 hours after the start of the simulation period. Lower m values (m <0.005) resulted in a prediction of the flood peak being too early compared to the observed timing, with values > 0.005 predicting the flood peak timing too late. Most of the simulations failed to capture the extended duration of peak discharge, which lasted approximately 5–6 hours, before receding back to low flow levels. The simulation with $m = 0.006$ came closest to predicting this

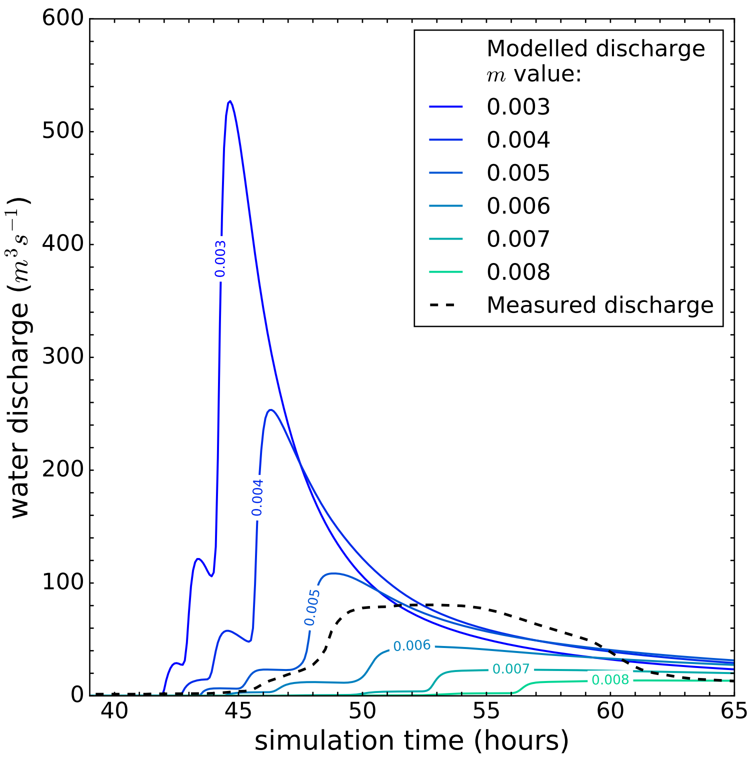

Figure 7.1: Discharge at Ryedale catchment outlet for varying values of the TOPMODEL m parameter. The measured discharge at the catchment gauging station is overlain in dashed line. The results from the simulations with $m > 0.008$ are omitted for clarity due to the low peak discharges they produced.

hydrograph shape, but failed to predict the magnitude of water discharge correctly, underestimating the peak flow by almost 50%.

For Ryedale simulations, it was decided to use an m value of 0.005, providing the closest possible match to the flood peak discharge, though not the true shape of the hydrograph and the receeding limb. As the catchment simulations include a representation of erosion and sediment transport processes, which are often threshold dependent, it was felt necessary to match the discharge peak more closely over choosing to match the hydrograph shape precisely.

7.3.2 Catchment hydrology

At the catchment scale, hydrological response was sensitive to both the rainfall resolution and the choice of erosional model. For both catchments, higher resolution rainfall

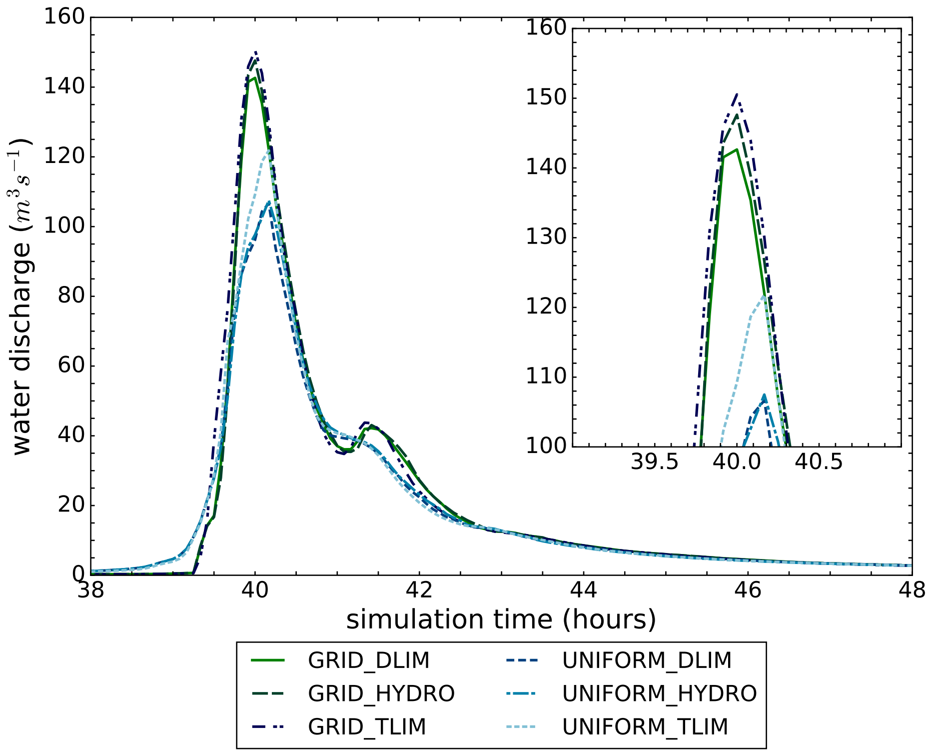

Figure 7.2: Boscastle hydrographs (discharge over time at catchment outlet) for each simulation of the 2004 Boscastle event listed in Table 6.2. Inset shows detail of main flood peaks around hour 40 of the simulation.

input data resulted in a greater maximum river discharge. In the Ryedale experiments, simulations using the gridded rainfall input experienced a flashier hydrological response, reaching peak discharge several hours before the uniform rainfall input cases. This was not observed in any of the Boscastle simulations, with all simulations reaching peak discharge within 30 minutes of each other.

The choice of erosion model also influenced the hydrological response. When catchment erosion was modelled using a transport-limited case, peak discharges were higher in all cases, but the timing of hydrograph peaks remained similar for each case. The difference in peak discharges were minimal when comparing the detachment-limited cases to the hydrological-only models.

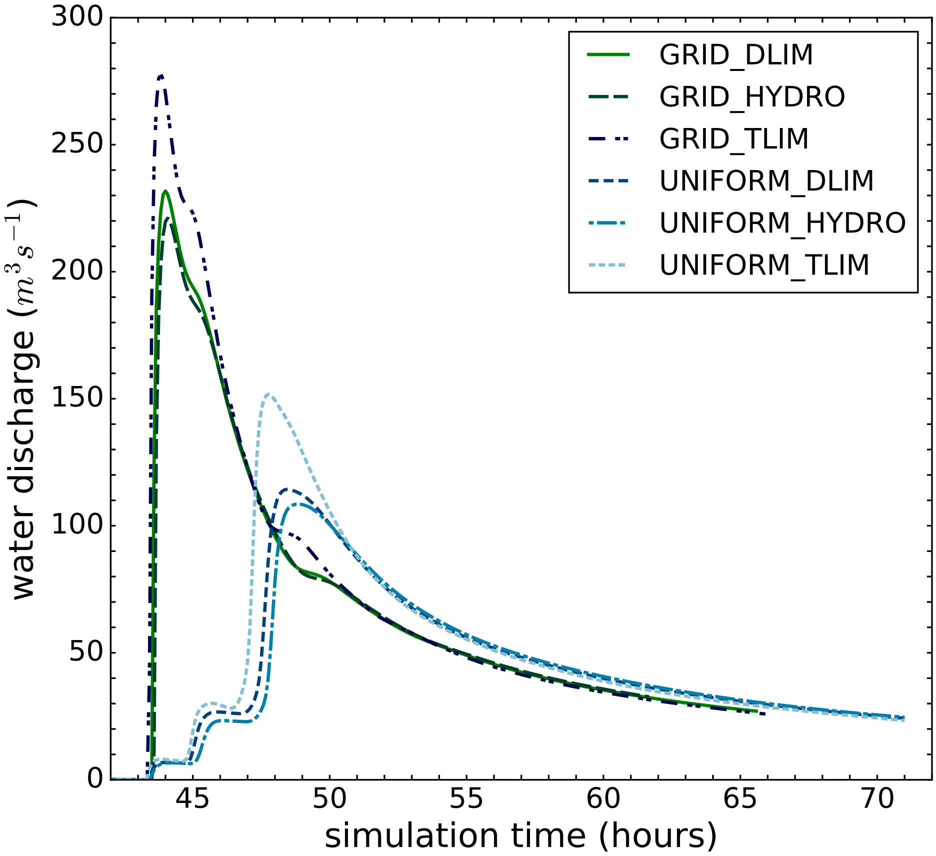

Figure 7.3: Ryedale hydrographs (discharge over time at catchment outlet) for each simulation of the 2005 Ryedale event listed in Table 6.2.

7.3.3 Spatial variation in flood inundation

Boscastle

The Boscastle catchment simulations showed minimal variation in flood inundation extent. Simulations with gridded rainfall input did not result in substantially different predictions of floodwater inundation compared to those with uniform rainfall input. Both sets of simulations reflected the general extent of reported flood water extents (HR Wallingford, 2005). Simulations that allowed erosion to take place (GRID_TLIM and UNIFORM_TLIM) showed a slight difference in the variation of floodwater depths in the floodplain area, particularly in the vicinity of Boscastle village, where Figure 7.4 is centred on. In hydrological-only simulations, the deepest water depths were predicted to occur in the confines of the river channel, whereas in erosion-enabled simulation, there appeared to be a 'smoothing' effect of water depths between the channel and the adjacent floodplain, suggesting that the channel geometry had altered during the flood event either by infilling from sediment from upstream or collapse of the adjacent river banks. Engineer's reports of the Boscastle flood noted that the river channel in the Boscastle village area had indeed been inundated with debris during the storm, which had potentially contributed to the extent of the flooding within the village.

Ryedale

The Ryedale simulations showed greater variation in flood extent between the gridded rainfall and uniform rainfall inputs. The flood extents were greater in the gridded rainfall input simulations, corresponding with the higher peak discharges predicted in these simulations. The variation in water depths appeared to be less sensitive in comparison to the Boscastle simulations. In the lower reaches of the catchment (Figure 7.5, there appeared to be little indication that flood extents or water depths were sensitive to the erosion parameterisation, in contrast to the Boscastle simulations.

7.4 Discussion

The size of the two catchments appears to be a determining factor in how sensitive hydrogeomorphic processes are to the rainfall data input resolution. The Boscastle catchment at 18 km^2 is approximately an order of magnitude smaller than the Rydedale catchment at 270 km^2. For each simulation using gridded rainfall input, the cell width of the rainfall grid is 1 km. The relative amount of increase in rainfall detail between uniform and gridded simulations is much greater in the larger Ryedale catchment than the Boscastle catchment. By using a 1 km gridded rainfall product as input data, the Ryedale simulation potentially captures 15 times more rainfall heterogeneity compared to the respective Boscastle simulation, by virtue of it simply being a much larger catchment with a greater number of rainfall input cells. Catchment size is known to be a factor in hydrological studies of rainfall resolution, and larger catchments are reported to show greater sensitivity to rainfall resolution (e.g. Nicótina et al., 2008), in terms of hydrological response.

Increasing the resolution of rainfall input data may not be enough to observe sensitivity in smaller catchments, as rainfall features themselves may not exhibit the necessary heterogeneity in structure to benefit from being resolved at finer scale. Rain cells or bands equal to or greater in size than the catchment over which they rain upon, may well be homogeneous enough in spatial extent and rainfall rate that a 'uniform' approximation of their rainfall rate is sufficiently precise enough to represent the rainfall rate at all points in the catchment. As seen in the Boscastle catchment simulations, using a detailed rainfall input data source did not notably alter the outcome of the hydrological predictions (Figures 7.4, 7.5). In the Ryedale catchment simulations, the hydrological predictions were notably different based on the choice of rainfall input data resolution, affecting both the time and magnitude of the resulting flood peak.

Talk about size of convective cell features. What is typical storm cell size and heterogeneity (decay from centre?).

7.5 Conclusions

Catchment hydrological response on the short term scale – such as during the course of single storm event – is also sensitive the spatial input pattern of rainfall, with the simulations carried out in this study also supporting similar work of (Nicótina et al., 2008) AND OTHERS.

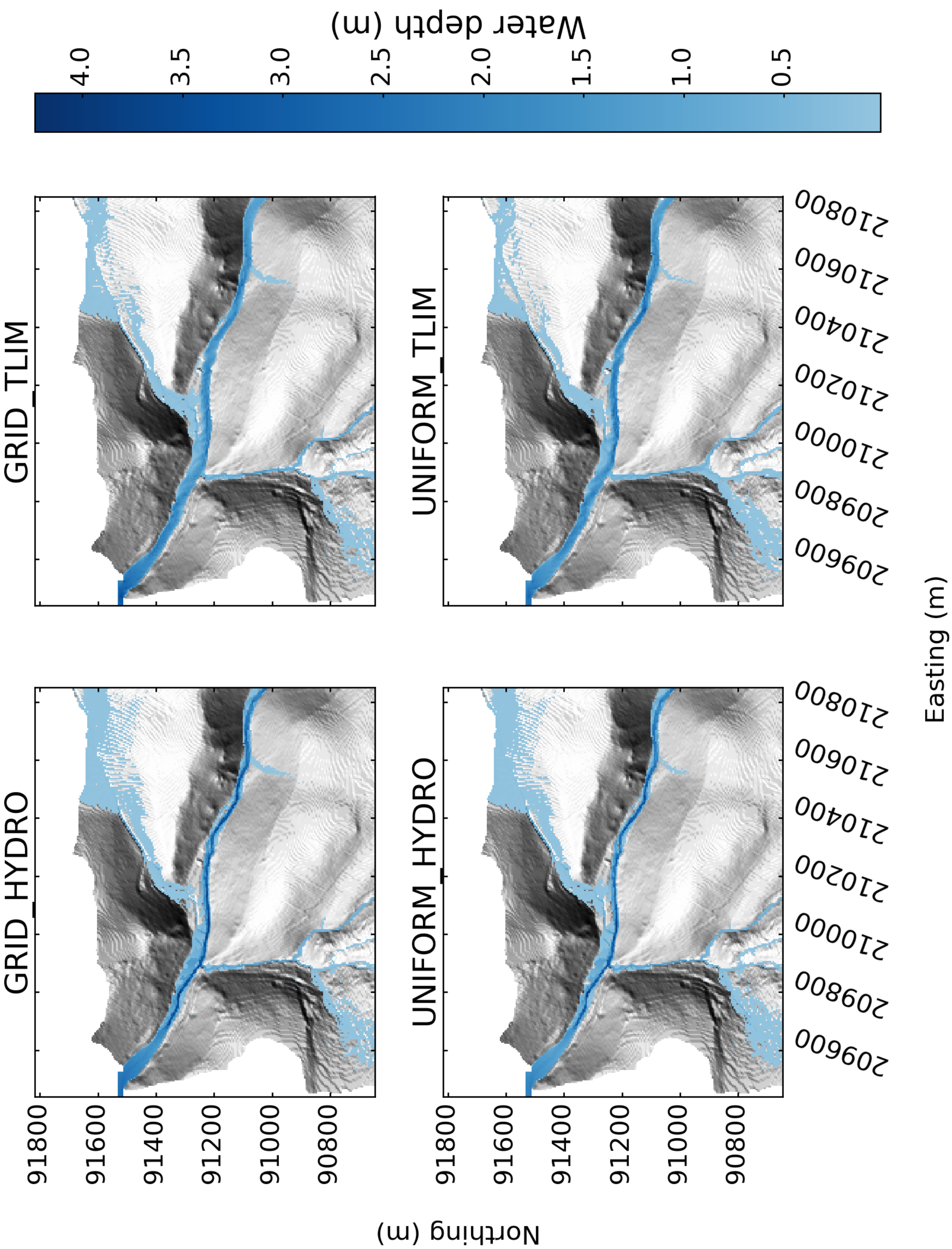

Figure 7.4: Flood extents in the Boscastle catchment at the time of maximum river discharge for each simulation.

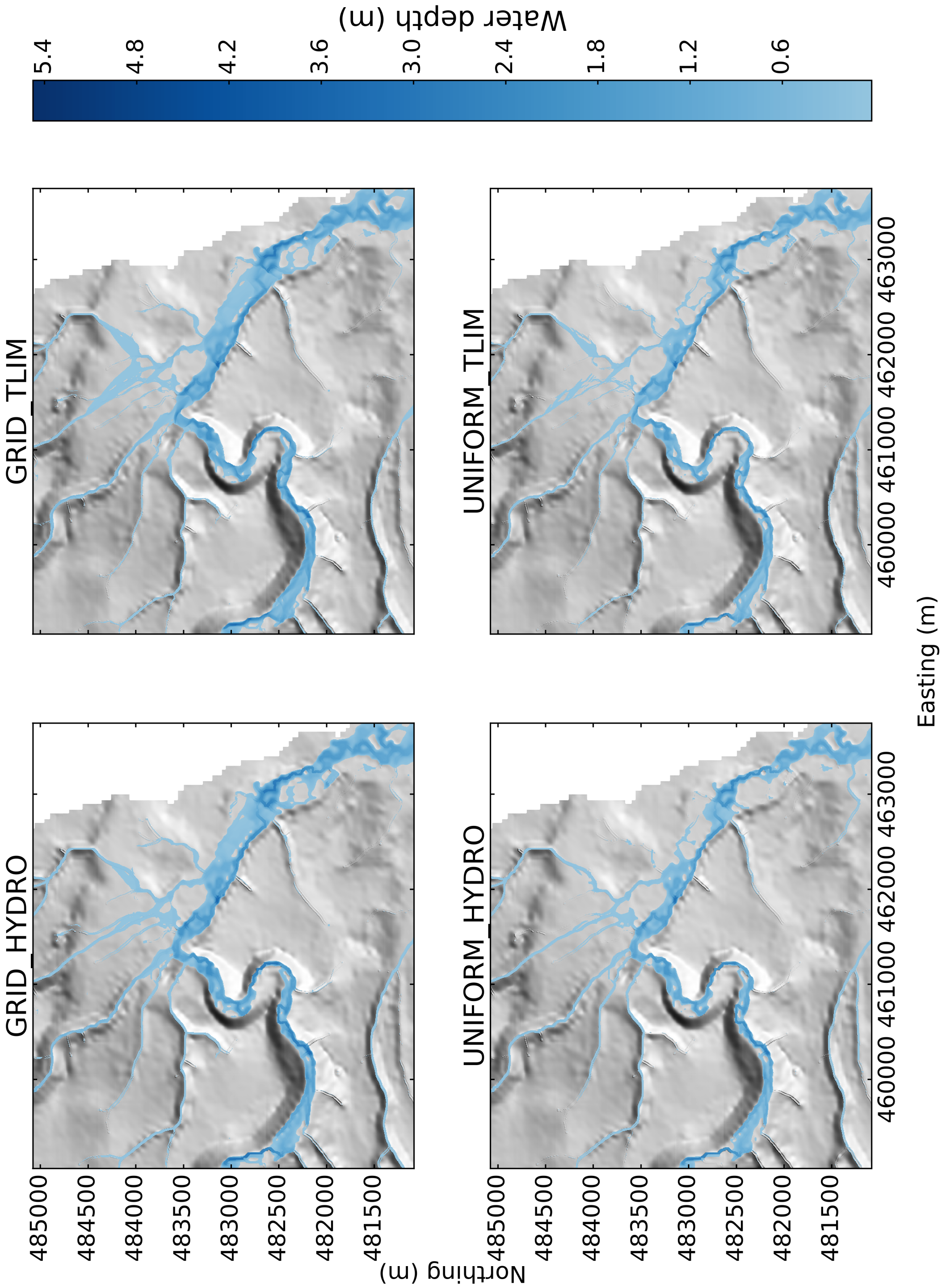

Figure 7.5: Flood extents in the Ryedale catchment at the time of maximum river discharge for each simulation.

8

Hydrometeorological controls on landscape erosion and evolution

8.1 Introduction

Landscape evolution at the catchment scale is punctuated by intense erosive episodes driven by flood events (Wolman and Miller, 1960; Newson, 1980; Costa and Connor, 1995) interspersed with periods of relative calm and little geomorphological change. It is these erosive events, driven by intense rainfall in temperate climates, separated by long periods of stasis, that cumulatively sculpt the landscape over geological time.

The importance of these rare but formative events has been revisited by recent work such as Huang and Niemann (2006), looking at the long term implications of different geomorphically effective event discharges on fluvial incision; (Gupta et al., 2007; Lamb and Fonstad, 2010; Baynes et al., 2015) where the amount of bedrock erosion during a single large flood event was quantified. Still, our understanding of catchment scale landscape evolution is far from complete - the role of individual events is highly variable. It has been reported that rapid gorge formation can be driven primarily by small to moderate sized floods (Anton et al., 2015), rather than floods of extreme magnitude. The relationship between flood magnitude and erosion rate is not always observed in case studies (Anton 2012), suggesting that the links between precipitation, hydrological response, and sediment transport are not fully understood. The behaviour of certain catchment processes also exhibits non-linearity in response to external forcings (Coulthard, Kirkby et al., 1998; Coulthard, Hicks et al., 2007), which suggests why case studies do not always exhibit a clear scaling relationship between event magnitude and catchment response. The behaviour of streams and rivers within catchments can vary in response to the same magnitude of flood event – some streams may erode during high flows, whereas others may deposit during high flows (Turowski et al., 2013). During small–medium flows their behaviour is reversed, with some rivers acting as agents of deposition during floods, rather than being primarily erosional. Catchment-scale erosional dynamics are complex, and except in the simplest cases depend on other forcings other than the magnitude of single flood events alone. The understanding of hydrogeomorphic processes during single storm events is not only important for the long-term evolution of landscapes, but also for prediction of how catchments will respond to changing hydro-meteorological conditions that may accompany climate change (Kendon et al., 2014).

The assumption of uniform rainfall over a river catchment is argued to hold true for small catchments (Sólyom and Tucker, 2004; Tucker and Hancock, 2010), but even over small areas, mesoscale rainfall features, such as localized convective storm cells, can result in spatially and temporally uneven input of precipitation into the catchment. In the case of intense convective precipitation, individual storm cells can be as small as $10km^2$ in areal extent (Weisman and Klemp, 1986; Von Hardenberg et al., 2003). Over larger catchments, or those with steep topographic gradients, precipitation is almost certain to vary spatially, due to orographic enhancement of rainfall (Roe, 2003). As such, rainfall-runoff generation, local river and tributary flow, and erosion rates may vary considerably within individual drainage basins.

As many geomorphic processes are threshold dependent (Schumm, 1979), such as fluvial incision into bedrock (Sklar and Dietrich, 2001; Snyder et al., 2003), there is potential for the spatial distribution of rainfall to control local erosion rates within a catchment. Non-linearity in geomorphic process laws (Coulthard, Kirkby et al., 1998; Phillips, 2003; Coulthard, Hicks et al., 2007) should dictate that catchments are also geomorphically sensitive to the spatial distribution of rainfall.

Rainfall resolution has been demonstrated to exert a control over sediment yields over seasonal and decadal timescales (Coulthard and Skinner, 2016). In a numerical modelling study of the River Swale catchment, Coulthard and Skinner show that local as well as catchment-wide sediment yields were predicted to increase by orders of magnitude as rainfall data resolution increases. The study looked at the effects of rainfall spatial data resolution as well the temporal resolution of data, showing both to demonstrate a control over sediment fluxes in a catchment. The study focused on landscape evolution time scales of decades to centuries, rather than individual storm events, and in this study this gap at the shorter end of the catchment evolution time scale will be filled.

As explored in Chapter 2 numerical models of landscape evolution usually omit a realistic distribution of rainfall input in favour of uniform, homogenised precipitation across the landscape. When precipitation is 'lumped', either spatially or temporally in a catchment, local minima and maxima of precipitation are lost, and with discharge being a function of rainfall rate, this uncertainty propagates through to local discharges and erosion rates. The uncertainty in erosion rates is potentially exacerbated by the non-linearity and threshold dependence of erosive processes. The variability of precipitation is considered in many cases to be as important as total precipitation amount in determining erosional effectiveness (Tucker and Bras, 2000; Tucker and Hancock, 2010).

In numerical models of landscape evolution, resolving the precise temporal and spatial details of rain storms and the hydrological response is often computationally prohibitive, especially over long timescales, and as such modellers have taken to using simpler parametrisiations of storm characteristics, such as using simple stochastic models to generate rainfall inputs and rainfall timeseries (Eagleson, 1978; Tucker, Lancaster et al., 2001). In studies of long term landscape evolution, the sensitivity of landscapes to the spatial distribution of rainfall has been investigated to some extent – particularly the imprint of orographic precipitation on landscapes (e.g Roe et al., 2002; Anders et al., 2008; Han et al., 2014)

What is currently lacking in landscape evolution modelling studies is a fuller understanding of how landscapes erode during individual storms, and in particular how erosional processes are sensitive to the details of precipitation across a catchment. The focus in this chapter is to quantify the sensitivity of catchment-scale erosional processes to the spatial distribution of rainfall during flood events, using the case studies outlined in Chapter 6.

The following questions are explored through the use of numerical modelling simulations:

- Are fluvial erosion and sediment transport processes sensitive to the details of precipitation distribution at the catchment scale during single storm events?
- Does the choice of erosional model operating within the catchment influence sensitivity to rainfall patterns?
- What are the implications of this for longer term landscape evolution?

To build on the work done in previous studies (e.g. Coulthard and Skinner, 2016), this chapter looks at the effects of individual severe rainfall events using a range of erosional end-member models. The study investigates the sensitivity of catchment-scale erosion to the spatial details of severe rain storms – the agents of long term landscape evolution. Landscape response is investigated using a numerical landscape evolution model that incorporates a dynamic (non steady-state) water-routing component and a range of fluvial incision and sediment transport laws. A series of numerical simulations are presented to test how sensitive real landscapes are to the catchment-scale details of precipitation during intense rainfall events. The simulations are each based on selected severe storms in the UK occurring in the past decade, which left significant flooding, damage, and geomorphological change in their wake.

8.2 Results

8.2.1 Catchment sediment flux

In contrast to water fluxes (Chapter 7), sediment flux from the catchments were most sensitive to the sediment erosion parameterisation, rather than the spatial detail of rainfall inputs.. For all catchments and events simulated, sediment flux from the catchment was higher in the simulations using higher resolution rainfall input data. The patterns of peak sediment discharge also mirrored that of water discharge, with sediment flux peaking earlier in the simulations with higher resolution rainfall inputs.

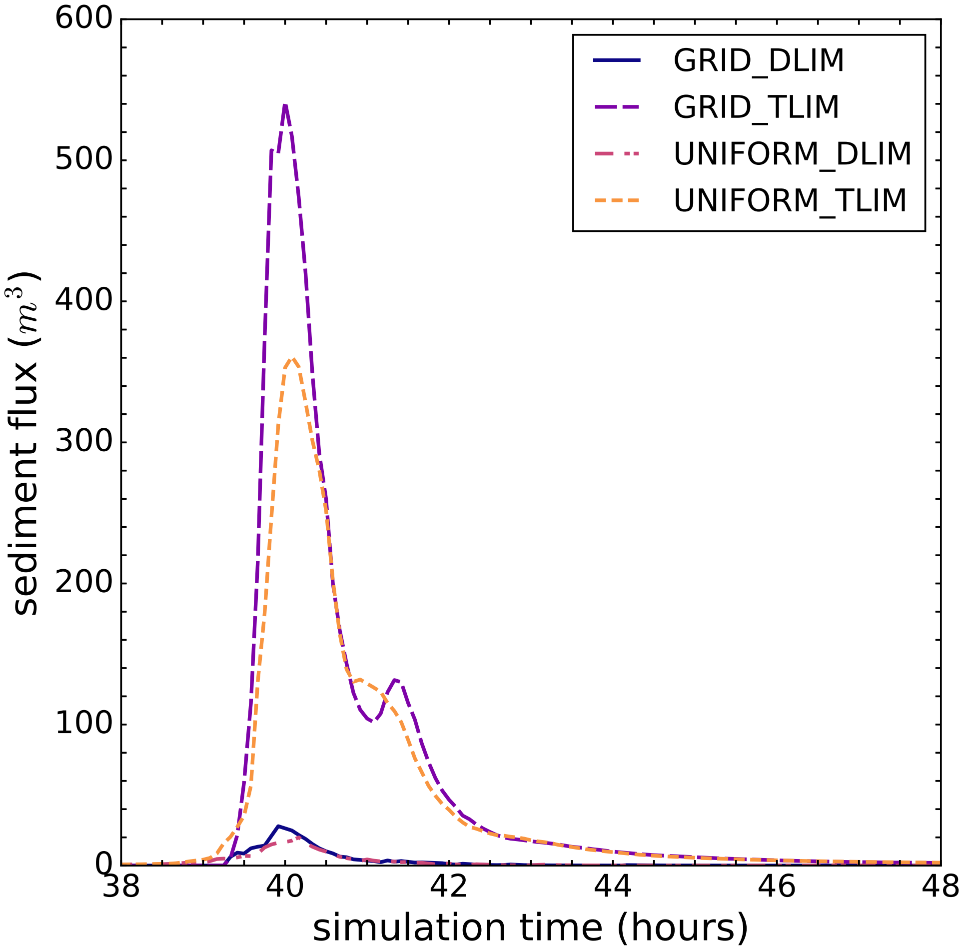

Figure 8.1: Boscastle sediment flux (total sediment volume output per hour at catchment outlet for each erosion-enabled simulation of the 2004 Boscastle event listed in Table 6.2.

8.2.2 Spatial variations in sediment and bedrock erosion

The main spatial variation seen in sediment erosion is seen in river channels, where shear stresses require to initiate erosion and sediment transport are greatest due to the flow of water. The amount of erosion in each simulation was highly sensitive to parameterisation choice of the sediment erosion and transport law, with the choice of rainfall input data (gridded vs uniform) being only a secondary controlling factor on erosion amounts, all other factors being equal. This behaviour was seen on all simulations, in Figure 8.5 and 8.7.

To highlight the variation in erosion along the river channel, longitudinal profiles showing the average change in elevation after the storm are shown in Figures 8.3 and

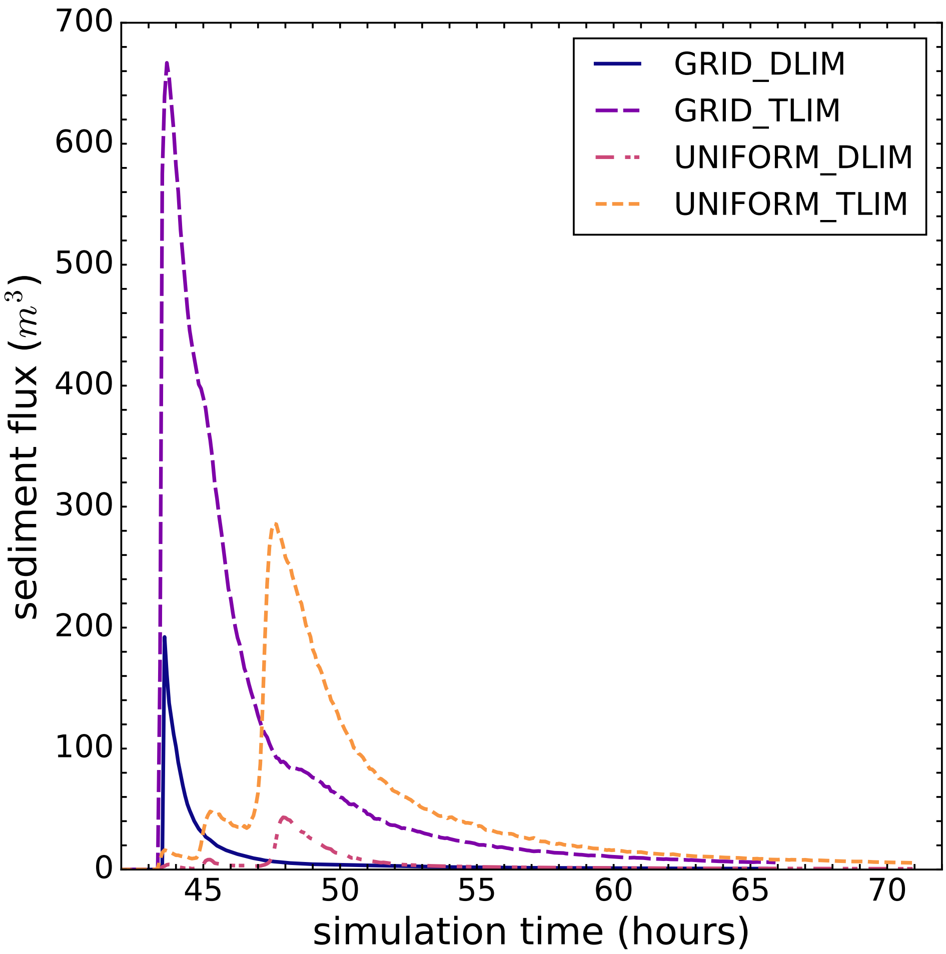

Figure 8.2: Ryedale sediment flux (Total sediment volume output per hour at catchment outlet) for each erosion-enabled simulation of the 2005 Ryedale event listed in Table 6.2.

8.4. The longitudinal profile shows the variation in erosion along the main channel within each catchment, averaged along a 10 m wide swath centred on the midpoint of the channel. The swath profiling technique is adapted from (Hergarten et al., 2014). To reduce the number of points plotted along the swath profile, erosion is also averaged longitudinally, using bins spaced every 200m in the Ryedale catchment and every 50m in the Valency catchment.

Swath profiling of the Valency river channel (Boscastle) shows overall a net incision in the channel area, under transport-limited erosion parameterisation, with only small sections of the channel showing net sediment deposition (elevation increase) on average. Most incision is predicted to occur in the mid to upper reaches of the channel, with

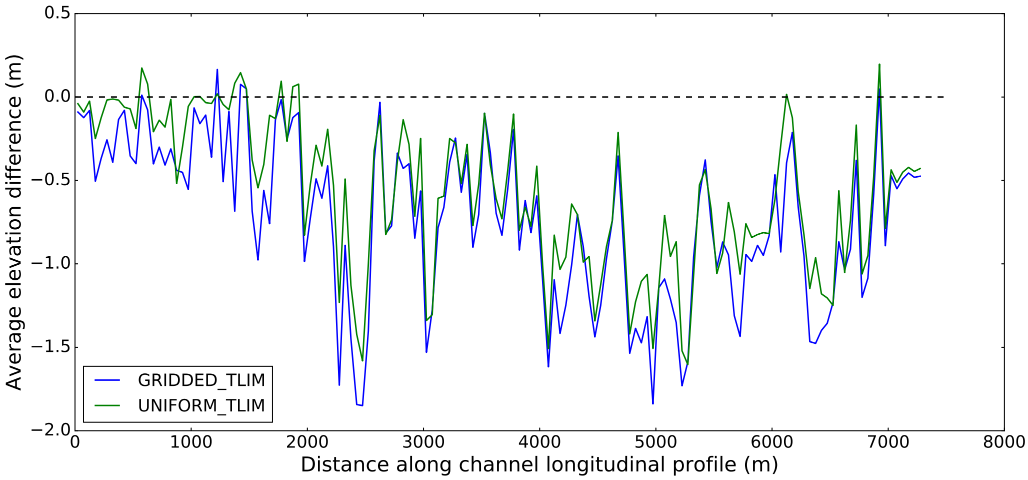

Figure 8.3: Channel averaged elevation difference along the main river channel in the Valency catchment. Simulation using the transport limited erosion parametrisation. Longitudinal profile is averaged over bins spaced every 50m. Transverse averaging (across the channel) is done over a 10m wide section centred on the channel midpoint. Results from the GRIDDED_TLIM simulation shown in blue and the UNIFORM_TLIM simulation shown in green.

relatively little incision in the lowest reach of the catchment. The difference between gridded and uniform rainfall inputs shows a minimal difference along the main profile, though there is a slight tendency for the incision seen in the gridded rainfall input simulation to be higher in most places than the simulation using uniform input, with the difference in incision amounts of the order of tens of centimetres at most.

The swath profiling of the Rye river channel within the Ryedale catchment shows a large variation in incision and deposition rates within the catchment, though there is still an overall tendency for net incision. The magnitude of both incision and deposition is higher in the mid to upper reaches of the Rye river channel, similar to the pattern observed in the Valency river. The differences in average elevation changes are not as clearly distinguishable between the gridded and uniform rainfall input parameterisations, magnitudes of erosional and depositional peaks are slightly higher in the lower reaches of the river channel, but in the mid to upper reaches the differences are more varied.

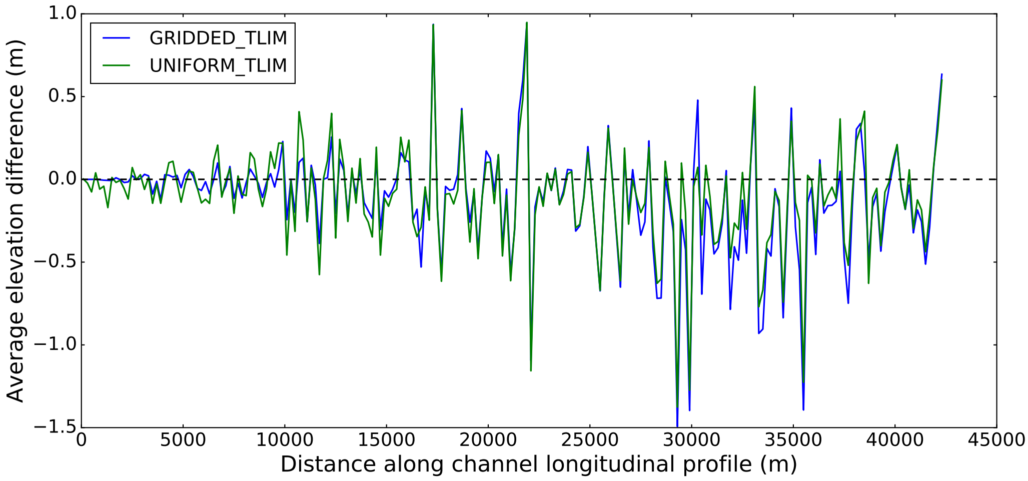

Figure 8.4: Channel averaged elevation difference along the main river channel in the Valency catchment. Simulation using the transport limited erosion parametrisation. Longitudinal profile is averaged over bins spaced every 50m. Transverse averaging (across the channel) is done over a 10m wide section centred on the channel midpoint. Results from the GRIDDED_TLIM simulation shown in blue and the UNIFORM_TLIM simulation shown in green.

8.3 Discussion

As with hydrology and flood extent (Chapter 7), sediment flux exhibits sensitivity to the input rainfall data resolution, but the more dominant sensitivity is to the sediment erosion parameterisation choice in the model. The set of erosion-enabled simulations in these experiments represented two end-members of sediment transport and erosion laws. The *TLIM*-suffixed simulations representing a purely transport limited environment and the *DLIM*-suffixed environment representing a purely detachment limited environment – with the transport limited law simulations predicting much greater sediment flux and erosion than the detachment limited counterparts. In terms of sediment flux and erosion, the role of rainfall input data spatial resolution played only a secondary role in determining erosion amounts. The size of the catchment was less important in this respect, with even the smaller Boscastle catchment showing a marked sensitivity to the choice of erosion law.

8.4 Conclusion

Over long term landscape evolution, erosional processes in catchments are known to be sensitive to the spatial distribution of rainfall input. This study has shown that catchment erosional processes are also sensitive to rainfall spatial distribution during the course of a single severe storm, and it is suggested that this is due to the spatial variation in shear stresses required brought on by heterogeneous rainfall inputs to the catchment system. As sediment transport and erosional process are highly threshold dependent, this leads to erosional patterns that differ according to the pattern of rainfall input. In other words, in the simulation of landscape evolution processes at the catchment scale, the choice of whether to use a uniform value representing the rainfall input, or to use a spatially heterogeneous gridded rainfall data, can have a marked impact on the predicted sediment yields from the catchment. In terms of sediment yields, however, these experiments have shown that it is the choice of erosional parameterisation in the model, and not necessarily the resolution of rainfall input data, that has a first-order control on the total sediment yields from a catchment and the magnitude of river channel incision during a simulated event.

Stuff amount rarity of events. Catastrophism.

8.4.1 Implications for longer-term landscape evolution

The experiments presented in this chapter have focused on the hydrogeomorphic response to single severe storm events, events which produced floods with return periods of 1 in 330 years (Ryedale) and 1 in 1300 years (Boscastle). The amounts of river channel incision predicted as a result of these storms is comparable to that predicted by studies of landscape evolution on scales of 1000 years, for example a study of a similar upland river basin by (Coulthard and Skinner, 2016) predicted channel incision amounts of 0.5–5m over 1000 years. The experiments presented here, using the same sediment transport law, predicts comparable incision amounts of channel incision during a single storm. If the flood return periods are assumed to be broadly correct, these simulations suggest that the majority of sediment erosion occurs during rare but high magnitude flood events, rather than through gradual processes or more frequent but lower magnitude events.

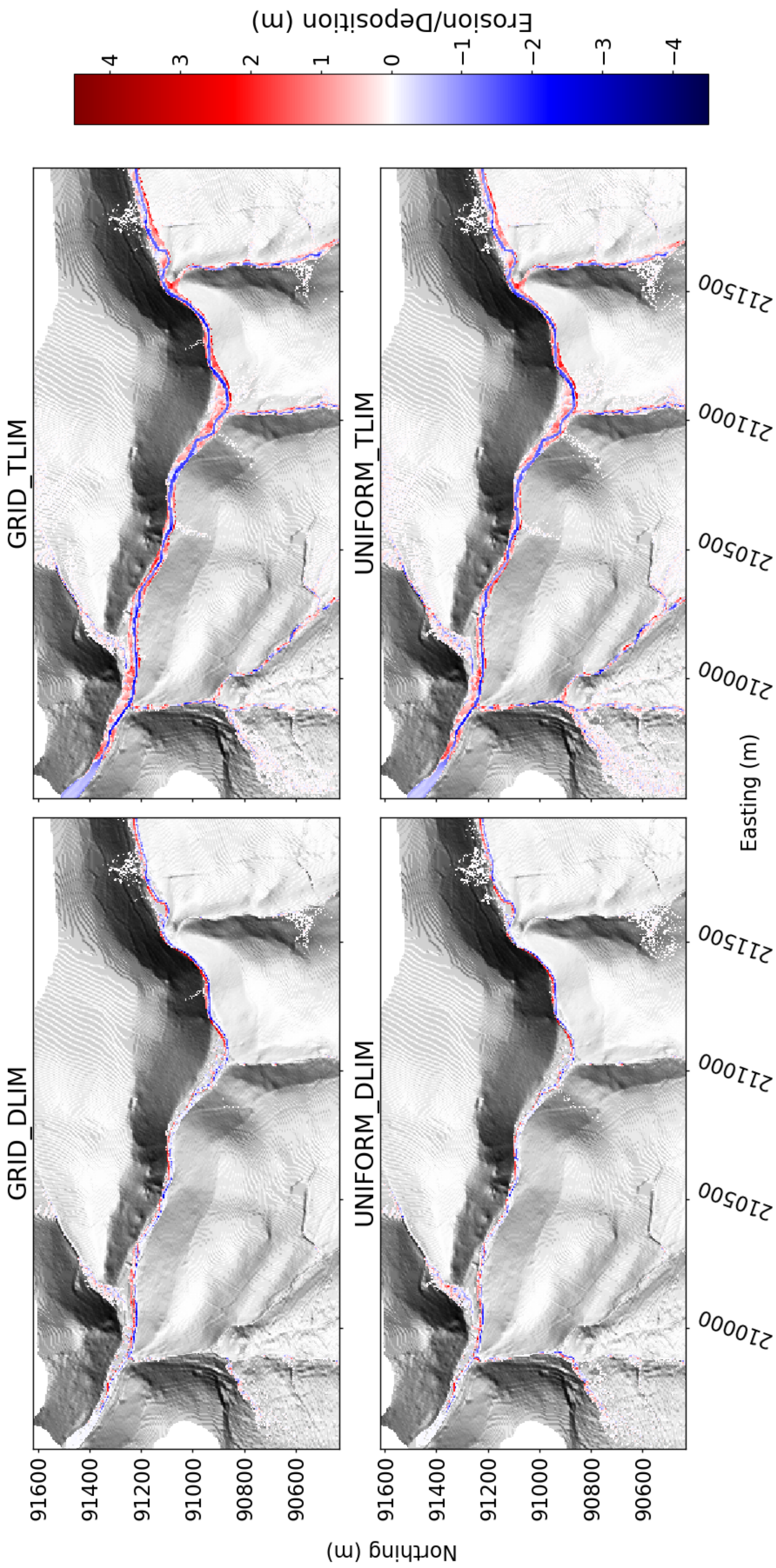

Figure 8.5: Boscastle. Erosion.

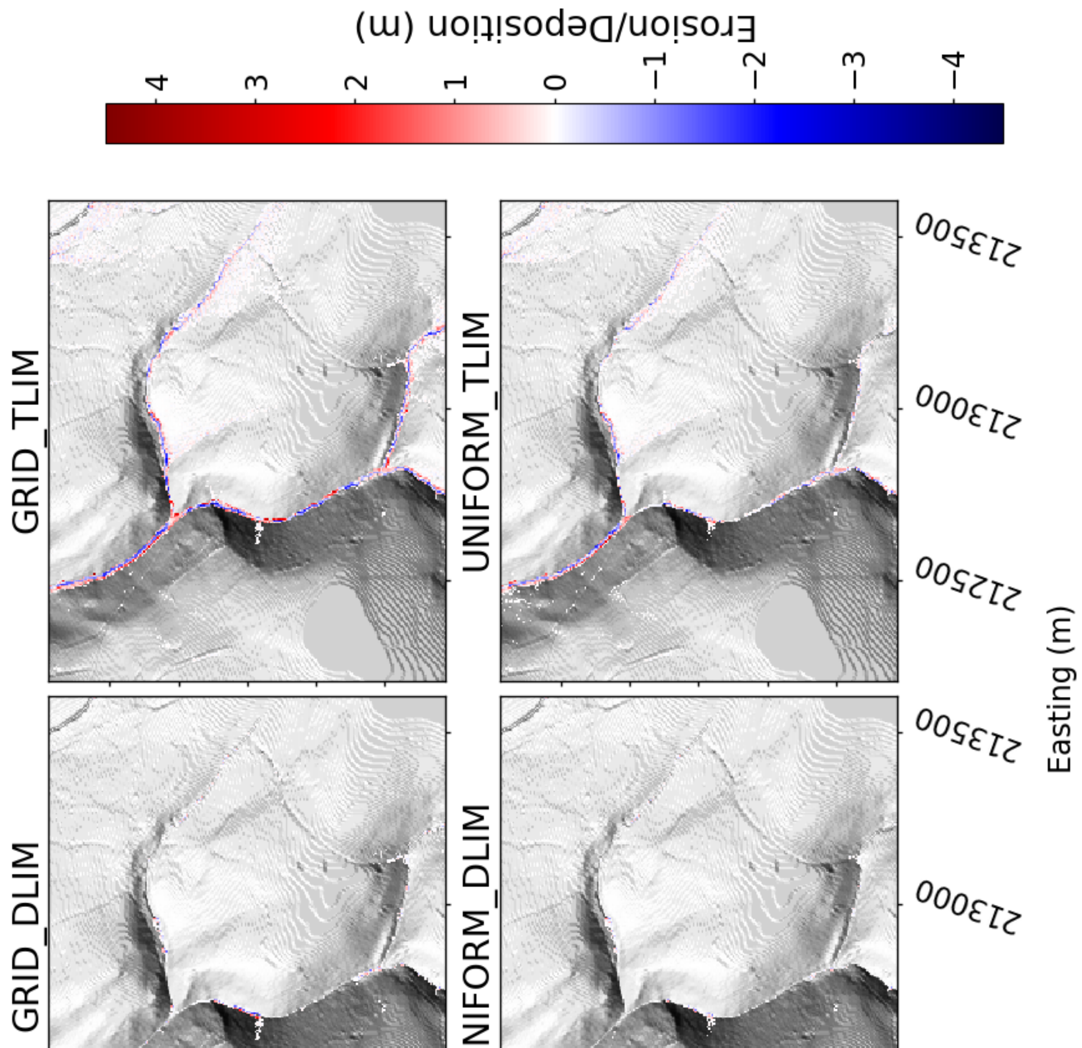

Figure 8.6: Boscastle. Erosion. SE trib

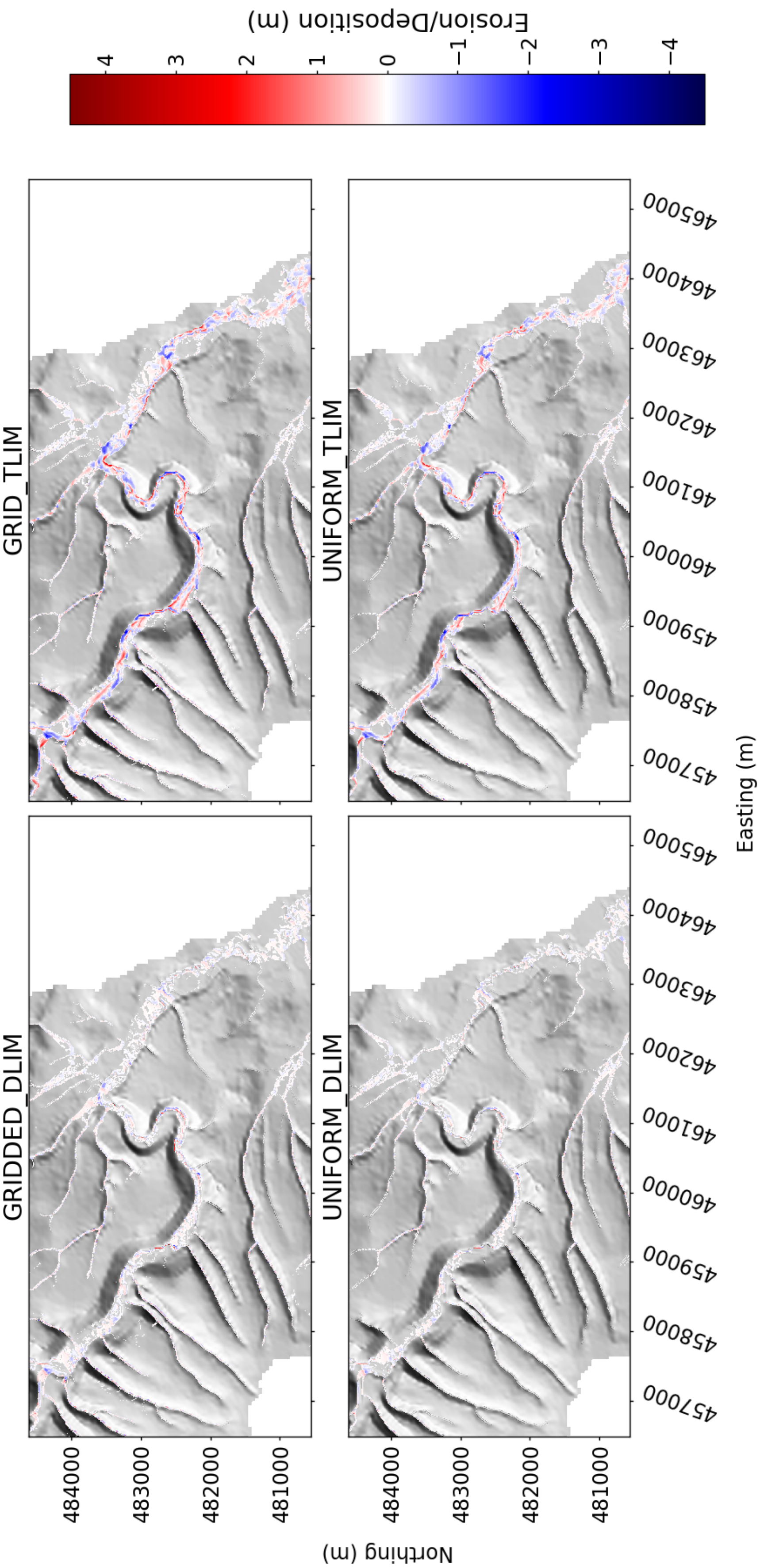

Figure 8.7: Ryedale. Erosion.

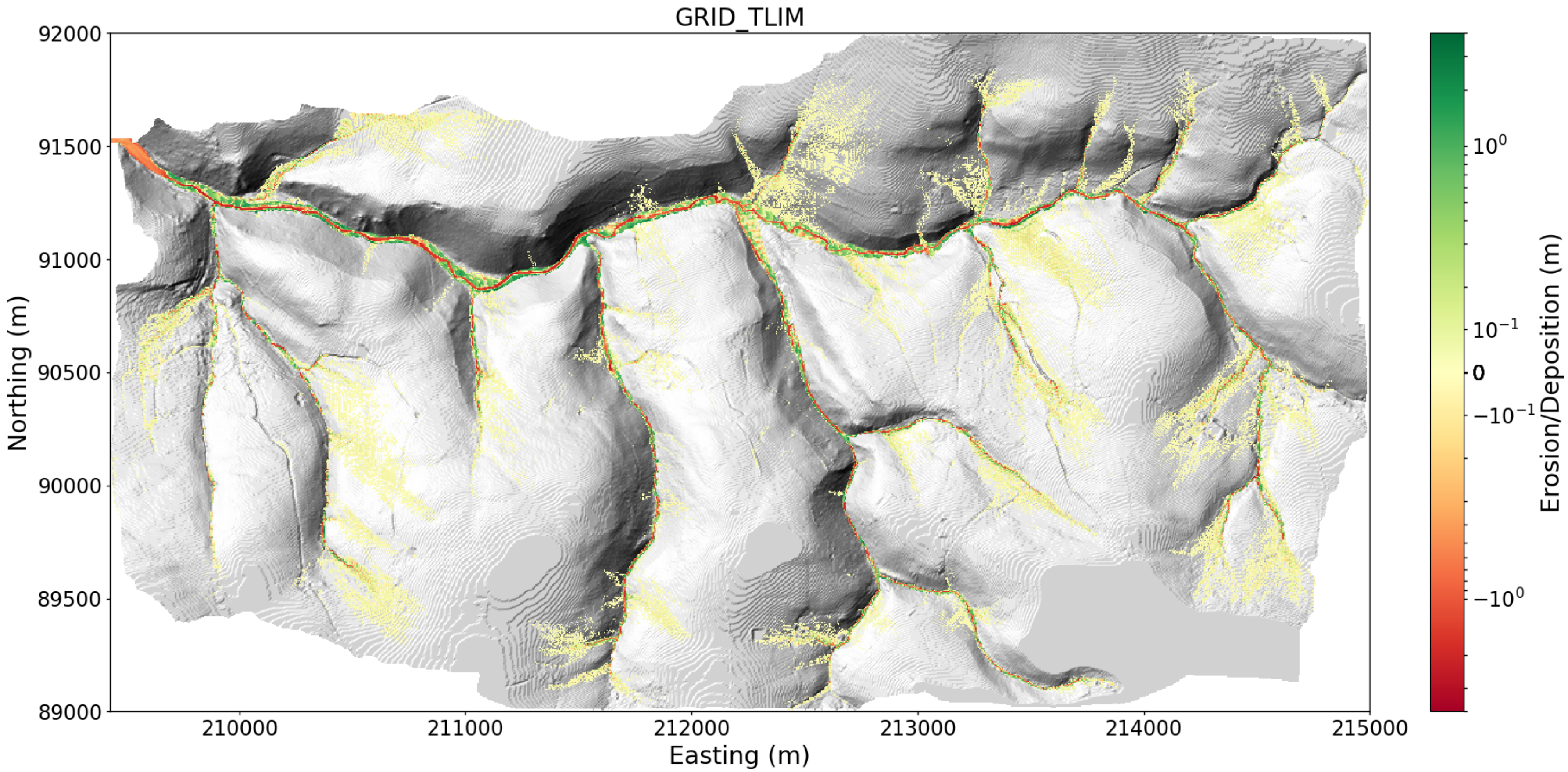

Figure 8.8: Boscastle. Map of extent of catchment change in elevation greater than 0.02m. Change in elevation shown after 72 hours of model simulation using gridded rainfall and the transport limited erosion law. (GRID_TLIM)

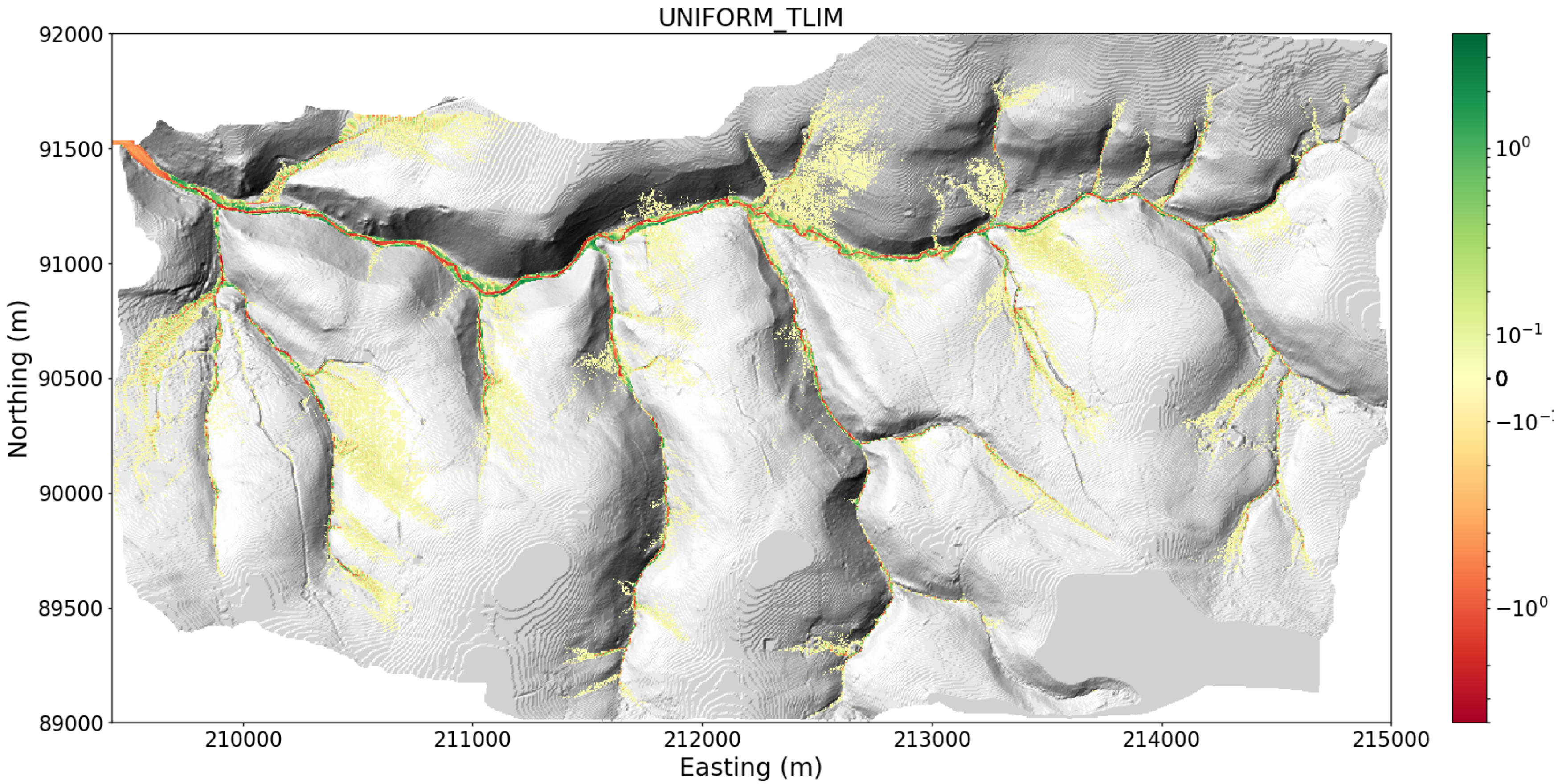

Figure 8.9: Boscastle. Map of extent of catchment change in elevation greater than 0.02m. Change in elevation shown after 72 hours of model simulation using uniform rainfall and the transport limited erosion law. (UNIFORM_TLIM)

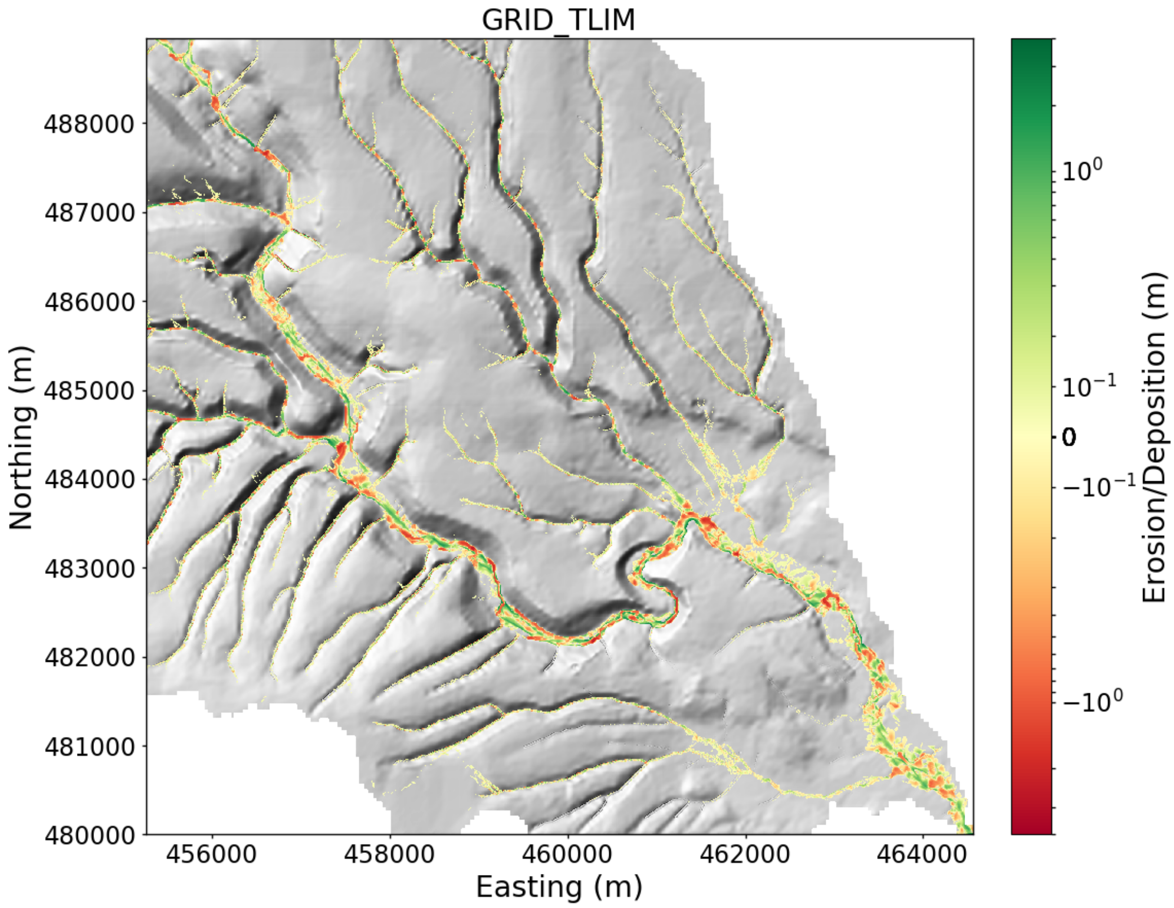

Figure 8.10: Ryedale. Map of extent of catchment change in elevation greater than 0.02m. Change in elevation shown after 72 hours of model simulation using gridded rainfall and the transport limited erosion law. (GRIDDED_TLIM)

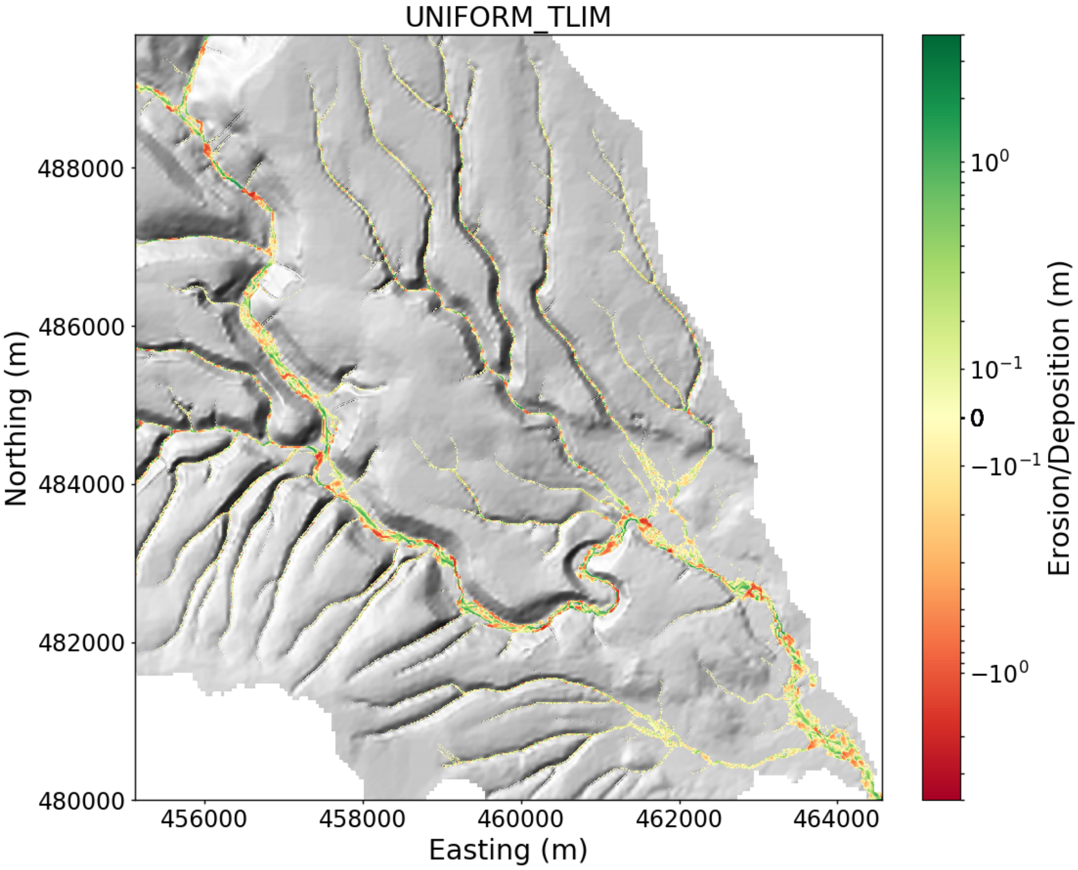

Figure 8.11: Ryedale. Map of extent of catchment change in elevation greater than 0.02m. Change in elevation shown after 72 hours of model simulation using uniform rainfall and the transport limited erosion law. (UNIFORM_TLIM)

Bibliography

Anders, Alison M. et al. (2008). 'Influence of precipitation phase on the form of mountain ranges'. In: *Geology* 36.6, p. 479. ISSN: 0091-7613. DOI: 10.1130/G24821A.1. URL: http://geology.gsapubs.org/cgi/doi/10.1130/G24821A.1.

Andréassian, Vazken (2004). 'Waters and forests: from historical controversy to scientific debate'. In: *Journal of hydrology* 291.1, pp. 1–27.

Anton, L et al. (2015). 'Exceptional river gorge formation from unexceptional floods'. In: *Nature communications* 6.

Bates, Paul D, Matthew S Horritt and Timothy J Fewtrell (2010). 'A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling'. In: *Journal of Hydrology* 387.1, pp. 33–45.

Bates, Paul D, MS Horritt, NM Hunter et al. (2005). 'Numerical modelling of floodplain flow'. In: *Computational Fluid Dynamics*. John Wiley and Sons Ltd.: Chichester, UK.

Baynes, Edwin RC et al. (2015). 'Erosion during extreme flood events dominates Holocene canyon evolution in northeast Iceland'. In: *Proceedings of the National Academy of Sciences* 112.8, pp. 2355–2360.

Berthet, L et al. (2009). 'How crucial is it to account for the antecedent moisture conditions in flood forecasting? Comparison of event-based and continuous approaches on 178 catchments'. In: *Hydrology and Earth System Sciences Discussions* 13, p–819.

Beven, Keith J (2011). *Rainfall-runoff modelling: the primer*. John Wiley & Sons.

Beven, KJ and Michael J Kirkby (1979). 'A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant'. In: *Hydrological Sciences Journal* 24.1, pp. 43–69.

Bradshaw, Corey JA et al. (2007). 'Global evidence that deforestation amplifies flood risk and severity in the developing world'. In: *Global Change Biology* 13.11, pp. 2379–2395.

Chang, Kang-tsung and Bor-wen Tsai (1991). 'The effect of DEM resolution on slope and aspect mapping'. In: *Cartography and geographic information systems* 18.1, pp. 69–77.

Costa, John E and Jim E O Connor (1995). 'Geomorphically Effective Floods'. In: *Natural and Anthropogenic Influences in Fluvial Geomorphology; Geophysical Monograph Series; vol. 89*. Vol. 18. Natural and Anthropogenic Influences in Fluvial Geomorphology, pp. 45–56.

Coulthard, Thomas J, Michael J Kirkby and Mark G Macklin (1998). 'Non-linearity and spatial resolution in a cellular automaton model of a small upland basin'. In: *Hydrology and Earth System Sciences* 2.2/3, pp. 257–264.

Coulthard, TJ, DM Hicks and Marco J Van De Wiel (2007). 'Cellular modelling of river catchments and reaches: advantages, limitations and prospects'. In: *Geomorphology* 90.3, pp. 192–207.

Coulthard, Tom J., Jeff C. Neal et al. (2013). 'Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution'. In: *Earth Surface Processes and Landforms* 38.15, pp. 1897–1906. ISSN: 01979337. DOI: 10.1002/esp.3478. URL: http://doi.wiley.com/10.1002/esp.3478.

Coulthard, Tom J and Christopher J Skinner (2016). 'The sensitivity of landscape evolution models to spatial and temporal rainfall resolution'. In: *Earth Surface Dynamics* 4.3, p. 757.

Darby, Stephen E (1999). 'Effect of riparian vegetation on flow resistance and flood potential'. In: *Journal of Hydraulic Engineering* 125.5, pp. 443–454.

Eagleson, Peter S (1978). 'Climate, Soil, and Vegetation: Introduction to Water Balance Dynamics'. In: *Water Resources Research* 14.5, pp. 705–712.

Fewtrell, Timothy J et al. (2011). 'Geometric and structural river channel complexity and the prediction of urban inundation'. In: *Hydrological Processes* 25.20, pp. 3173–3186.

Gabellani, S et al. (2007). 'Propagation of uncertainty from rainfall to runoff: A case study with a stochastic rainfall generator'. In: *Advances in water resources* 30.10, pp. 2061–2071.

Galiatsatos, N, DNM Donoghue and L Warburton (2007). 'Assessment of sediment delivery from shallow landslides in upland terrain using 3D remote sensing'. In: *RSPSoc2007: Challenges for earth observation–scientific, technical and commercial, Newcastle, UK.*

Gippel, Christopher J (1995). 'Environmental hydraulics of large woody debris in streams and rivers'. In: *Journal of Environmental Engineering* 121.5, pp. 388–395.

Golding, Brian, Peter Clark and Bryony May (2005). 'The Boscastle flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004'. In: *Weather* 60.8, pp. 230–235.

Gupta, Sanjeev et al. (2007). 'Catastrophic flooding origin of shelf valley systems in the English Channel'. In: *Nature* 448.7151, pp. 342–345.

Haile, Alemseged Tamiru and THM Rientjes (2005). 'Effects of LiDAR DEM resolution in flood modelling: a model sensitivity study for the city of Tegucigalpa, Honduras'. In: *Workshop on Laser scanning 2005, Enschede, the Netherlands, September 12-14, 2005* 3.

Han, Jianwei et al. (2014). 'Modeling the influence of rainfall gradients on discharge, bedrock erodibility, and river profile evolution, with application to the Big Island, Hawai'i'. In: *Journal of Geophysical Research: Earth Surface* 119.6, pp. 1418–1440. ISSN: 21699011. DOI: 10.1002/2013JF002961. URL: http://doi.wiley.com/10.1002/2013JF002961.

Hergarten, S, J Robl and K Stüwe (2014). 'Extracting topographic swath profiles across curved geomorphic features'. In: *Earth Surface Dynamics* 2.1, p. 97.

Hollis, GE (1975). 'The effect of urbanization on floods of different recurrence interval'. In: *Water Resources Research* 11.3, pp. 431–435.

Hopkins, Jonathan (2012). 'Knowledge of, and response to, upland flash flooding: a case study of flood risk management of the 2005 flash flood in upper Ryedale, North Yorkshire, UK'. Doctoral dissertation. Durham University.

HR Wallingford (2005). *Flooding in Boscastle and North Cornwall, August 2004. Phase 2 studies report.* HR Wallingford.

Huang, Xiangjiang and Jeffrey D Niemann (2006). ‘Modelling the potential impacts of groundwater hydrology on long-term drainage basin evolution’. In: *Earth Surface Processes and Landforms* 31, pp. 1802–1823. DOI: 10.1002/esp.

Jeffries, Richard, Stephen E Darby and David A Sear (2003). ‘The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England’. In: *Geomorphology* 51.1, pp. 61–80.

Kendon, Elizabeth J et al. (2014). ‘Heavier summer downpours with climate change revealed by weather forecast resolution model’. In: *Nature Climate Change* June, pp. 1–7. DOI: 10.1038/NCLIMATE2258.

Kleinhans, Maarten G et al. (2013). ‘Splitting rivers at their seams: bifurcations and avulsion’. In: *Earth Surface Processes and Landforms* 38.1, pp. 47–61.

Krajewski, Witold F et al. (1991). ‘A Monte Carlo study of rainfall sampling effect on a distributed catchment model’. In: *Water resources research* 27.1, pp. 119–128.

Lamb, Michael P and Mark A Fonstad (2010). ‘Rapid formation of a modern bedrock canyon by a single flood event’. In: *Nature Geoscience* 3.7, pp. 477–481.

Lane, SN, SC Reid et al. (2008). ‘Reconceptualising coarse sediment delivery problems in rivers as catchment-scale and diffuse’. In: *Geomorphology* 98.3, pp. 227–249.

Lane, SN, V Tayefi et al. (2007). ‘Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment’. In: *Earth Surface Processes and Landforms* 32.3, pp. 429–446.

Met Office (2003). *1 km Resolution UK Composite Rainfall Data from the Met Office Nimrod System.* URL: http://catalogue.ceda.ac.uk/uuid/27dd6ffba67f667a18c62de5c

Neuhold, C, P Stanzel and HP Nachtnebel (2009). ‘Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application’. In: *Natural Hazards and Earth System Sciences* 9.3, pp. 789–799.

Newson, Malcolm (1980). ‘The geomorphological effectiveness of floods—a contribution stimulated by two recent events in mid-wales’. In: *Earth Surface Processes* 5.1, pp. 1–16.

Nicótina, L et al. (2008). ‘On the impact of rainfall patterns on the hydrologic response’. In: *Water Resources Research* 44.12.

Pelletier, Jon D. (2012). ‘Fluvial and slope-wash erosion of soil-mantled landscapes: detachment- or transport-limited?’ In: *Earth Surface Processes and Landforms*

37.1, pp. 37–51. ISSN: 01979337. DOI: 10.1002/esp.2187. URL: http://doi.wiley.com/10.1002/esp.2187.

Phillips, Jonathan D (2003). 'Sources of nonlinearity and complexity in geomorphic systems'. In: *Progress in Physical Geography* 27.1, pp. 1–23.

Pitt, Michael (2008). 'The Pitt Review: Lessons learned from the 2007 floods'. In: *Cabinet Office, London* 505.4.

Roe, Gerard H. (2003). 'Orographic precipitation and the relief of mountain ranges'. In: *Journal of Geophysical Research* 108.B6, p. 2315. ISSN: 0148-0227. DOI: 10.1029/2001JB001521. URL: http://doi.wiley.com/10.1029/2001JB001521.

Roe, Gerard H, David R Montgomery and Bernard Hallet (2002). 'Effects of orographic precipitation variations on the concavity of steady-state river profiles'. In: *Geology* 30, pp. 143–146. DOI: 10.1130/0091-7613(2002)030<0143.

Schoorl, JM, MPW Sonneveld, A Veldkamp et al. (2000). 'Three-dimensional landscape process modelling: the effect of DEM resolution'. In: *Earth Surface Processes and Landforms* 25.9, pp. 1025–1034.

Schumm, Stanley Alfred (1979). 'Geomorphic thresholds: the concept and its applications'. In: *Transactions of the Institute of British Geographers*, pp. 485–515.

Segond, Marie-Laure et al. (2007). 'Simulation and spatio-temporal disaggregation of multi-site rainfall data for urban drainage applications'. In: *Hydrological Sciences Journal* 52.5, pp. 917–935.

Sibley, Andrew M (2009). 'Analysis of the North York Moors storms–19 June 2005'. In: *Weather* 64.2, pp. 39–42.

Sklar, Leonard S and William E Dietrich (2001). 'Sediment and rock strength controls on river incision into bedrock'. In: *Geology* 29.12, pp. 1087–1090.

Slater, Louise J (2016). 'To what extent have changes in channel capacity contributed to flood hazard trends in England and Wales?' In: *Earth Surface Processes and Landforms* 41.8, pp. 1115–1128.

Snyder, Noah P et al. (2003). 'Importance of a stochastic distribution of floods and erosion thresholds in the bedrock river incision problem'. In: *Journal of Geophysical Research: Solid Earth* 108.B2.

Sólyom, Peter B. and Gregory E. Tucker (2004). 'Effect of limited storm duration on landscape evolution, drainage basin geometry, and hydrograph shapes'. In:

Journal of Geophysical Research 109.F3, F03012. ISSN: 0148-0227. DOI: 10.1029/2003JF000032. URL: http://doi.wiley.com/10.1029/2003JF000032.

Tucker, Gregory E and Rafael L Bras (2000). 'A stochastic approach to modeling the role of rainfall variability in drainage basin evolution'. In: *Water Resources Research* 36.7, pp. 1953–1964.

Tucker, Gregory E and Gregory R Hancock (2010). 'Modelling Landscape Evolution'. In: *Earth Surface Processes and Landforms* 50, pp. 28–50. DOI: 10.1002/esp.

Tucker, Gregory E., Stephen T. Lancaster et al. (2001). 'An object-oriented framework for distributed hydrologic and geomorphic modeling using triangulated irregular networks'. In: *Computers & Geosciences* 27.8, pp. 959–973. ISSN: 00983004. DOI: 10.1016/S0098-3004(00)00134-5. URL: http://linkinghub.elsevier.com/retrieve/pii/S0098300400001345.

Turowski, Jens M et al. (2013). 'Large floods, alluvial overprint, and bedrock erosion'. In: *Earth Surface Processes and Landforms* 38.9, pp. 947–958.

Von Hardenberg, J, L Ferraris and A Provenzale (2003). 'The shape of convective rain cells'. In: *Geophysical research letters* 30.24.

Warburton, Jeff, Joseph Holden and Andrew J Mills (2004). 'Hydrological controls of surficial mass movements in peat'. In: *Earth-Science Reviews* 67.1, pp. 139–156.

Warren, Robert A et al. (2014). 'A 'Boscastle-type'quasi-stationary convective system over the UK Southwest Peninsula'. In: *Quarterly Journal of the Royal Meteorological Society* 140.678, pp. 240–257.

Wass, P, D Faulkner and A Curini (2008). 'An investigation into the North Yorkshire floods of June 2005'. In: *JBA Consulting, Skipton.*

Weisman, Morris L and Joseph B Klemp (1986). 'Characteristics of isolated convective storms'. In: *Mesoscale meteorology and forecasting*. Springer, pp. 331–358.

Wilson, Charles B, Juan B Valdes and Ignacio Rodriguez-Iturbe (1979). 'On the influence of the spatial distribution of rainfall on storm runoff'. In: *Water Resources Research* 15.2, pp. 321–328.

Wolman, M Gordon and John P Miller (1960). 'Magnitude and Frequency of Forces in Geomorphic Processes'. In: *The Journal of Geology* 68.1, pp. 54–74.

Wong, Jefferson S et al. (2015). 'Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding'. In: *Hydrological Processes* 29.2, pp. 261–279.

Zhang, Jane Xinxin, Kang-Tsung Chang and Joan Qiong Wu (2008). 'Effects of DEM resolution and source on soil erosion modelling: a case study using the WEPP model'. In: *International Journal of Geographical Information Science* 22.8, pp. 925–942.