6

Modelling catchment hydrogeomorphic sensitivity to rainfall spatial distribution

6.1 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 O'Connor, 1995) interspersed with periods of relative calm and little geomorphic change, an idea that harks back to the early ideas of geological 'catastrophism' (Cuvier, ?). 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); and 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. Anton (2014) report that rapid gorge formation can be driven primarily by small to moderate sized floods, rather than floods of extreme magnitude. Further, there was no observed relationship between flood magnitude and erosion rate. Turowski et al. (2011) report that streams within catchments can exhibit different behaviour in response to the same flood event – some streams may erode during high flows, whereas others may deposit during high flows. During small–medium flows their respective behaviour is reversed. Wong et al. (2015) establish through numerical modelling that geomorphic changes in channel geometry during severe flood events are substantial enough to change hydrological response of a river catchment. Catchment-scale erosional dynamics are complex, and except in the simplest cases depend on other forcings other than the magnitude alone of single flood events. 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 focus in this paper is to quantify the sensitivity of catchment-scale erosional processes to the spatial distribution of rainfall during flood events. The assumption of uniform rainfall over a river catchment is argued to hold true for small catchments (Solyom and Tucker 2004; Tucker 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, 2005). As such, rainfall-runoff generation, local river flow, and erosion rates may vary considerably within individual drainage basins.

Patterns of rainfall distribution across a catchment can affect hydrograph response, including the peak discharge and local water levels (Nicotina et al., 2008). 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 (e.g. Coulthard et al., 1998; Phillips, 2003; Coulthard and Van de Wiel, 2007) should dictate that catchments are also geomorphically sensitive to the spatial distribution of rainfall.

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, 2010). What is currently lacking in landscape evolution 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.

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 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 2002; Anders 2008; Han and Gasparini, 2015).

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.

In contrast to previous studies, this paper 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 model experiments is 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 Great Britain occurring in the past decade, which left significant flooding, damage, and geomorphic change in their wake.

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

- Are modelled flood inundation extents sensitive to the spatial resolution of rainfall inputs to the catchment?
- Are fluvial erosion and sediment transport processes sensitive to the details of precipitation 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?

6.2 Experiment Design & Method

An ensemble of simulations was designed to address the questions laid out in the previous section. The simulations were parametrised with different erosion law schemes and different rainfall input resolutions to assess which environmental factors exerted the greatest control over catchment response to intense rainfall, in terms of flood inundation and sediment transport. The same ensemble of experiments was carried out for two historic rainfall events that lead to severe flooding in UK river catchments. The summary of the ensemble events is given in the table below:

The numerical landscape evolution model, HAIL-CAESAR (described in Chapter **??**) is used to investigate landscape and hydrological response to varying rainfall input resolution. 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

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

Table 6.1: Outline of the ensemble simulations carried for all case studies.

adaptation of the LISFLOOD-FP shallow water routing algorithms (Bates et al., 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 **??**.

HAIL-CAESAR can be configured in a number of different ways to simulate the experiments outlined XXXX.

6.2.1 Study area

Overview

Three 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 **??**. A table (Table 6.2) summarises the key features of each catchment and associated storm.

Catchment Name	**Ryedale**	**Valency**
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
Peak Discharge		
Meteorological Setting	Split-front, convective system	Quasi-stationary convective system
3hr Rainfall Return Period	330yr (Wass et al. 2008)	1300yr (Burt, 2005)

Table 6.2: Table showing key characteristics of each storm event.

6.2.2 Hydro-Meteorological conditions

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} (**?**), 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. (bev)

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 instability was enhanced by a split-frontal system. [More? Too much met here?]. 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.

6.2.3 Numerical model configuration

Model initialisation

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.

Erosion model choice

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

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.

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 (Section **??**), 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 are discussed in Section **??**. 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 6.1.)

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 et al., 2013; Coulthard and Skinner,

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

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).

6.3 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 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 6.4.

6.4 Results

I intend to discuss the spatial differences in erosion, as well as any differences in basin-wide average erosion rates, and explain these differences by referring back to the Theory section.

The discussion will be aided by figures showing (for each of the three rainfall input variations for each catchment):

- Total accumulated rainfall maps for each storm (Figure **??**).
- Profiles of erosion along main channels in each catchment (Figure **??**).
- Plots of the hydrographs and sediment yields for each storm (Figure **??**).
- 2D Planform maps of distribution of erosion (and deposition if applicable).

Indicative figures. Note these will change in the final version as I have decided to re-run some simulations after tweaking the model set-up.

6.4.1 TOPMODEL sensitivity

The model exhibited a strong sensitivity to the choice of the TOPMODEL m parameter. In the results presented in figure 6.1 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. (UTC XX XX XX to X). 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

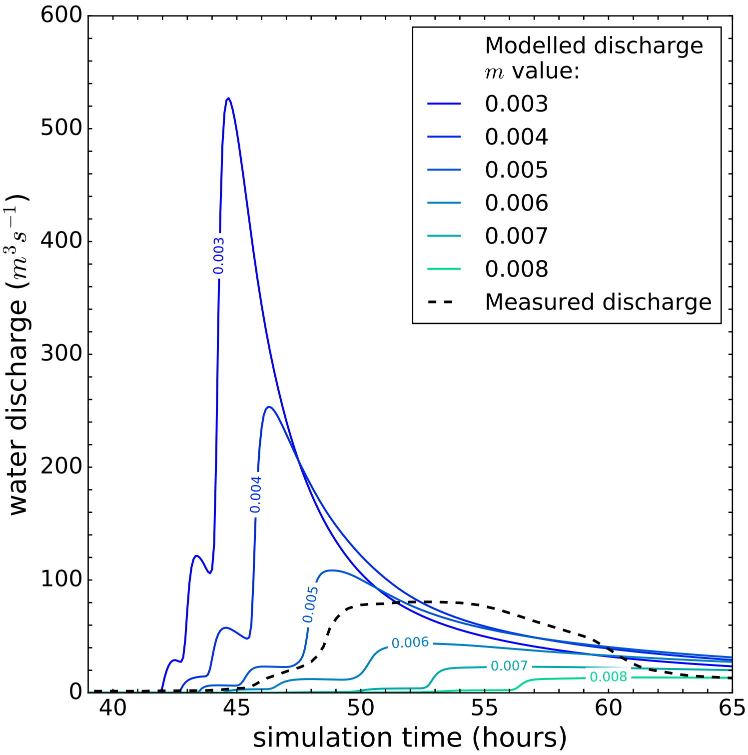

Figure 6.1: Discharge at Ryedale catchment outlet for varying values of the TOPMODEL m parameter. The measured discharge at the catchment gauging station is overlain in dashed line. The results from the simulations with $m > 0.008$ are omitted for clarity due to the low peak discharges they produced.

closest to predicting this 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.

6.4.2 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

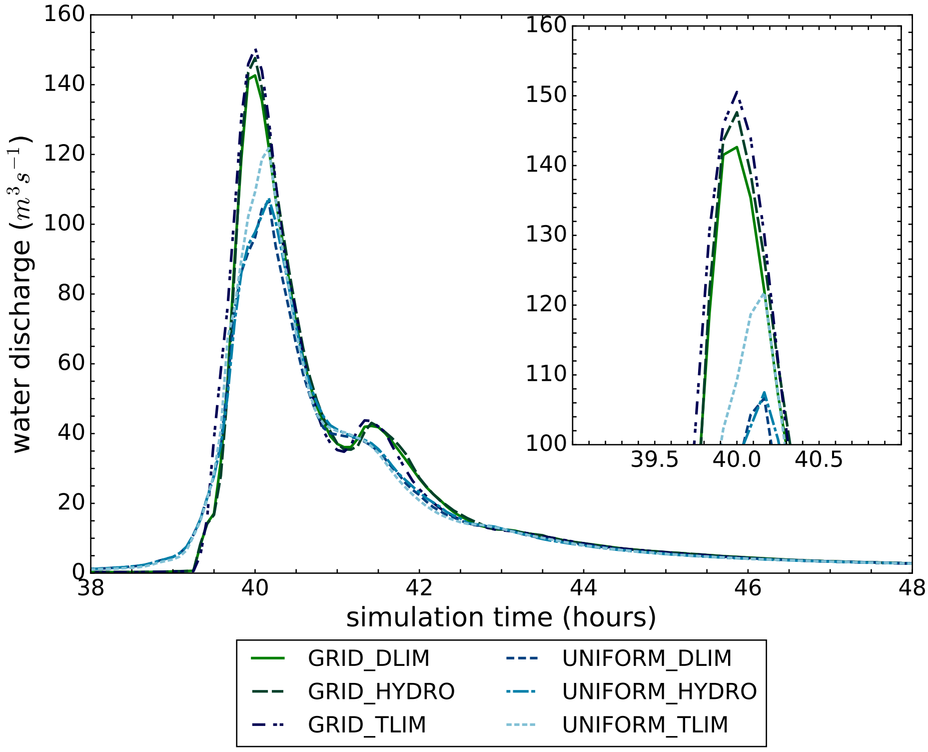

Figure 6.2: Boscastle hydrographs (discharge over time at catchment outlet) for each simulation of the 2004 Boscastle event listed in Table 6.1. Inset shows detail of main flood peaks around hour 40 of the simulation.

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.

6.4.3 Catchment sediment flux

In contrast to water fluxes, sediment flux from the catchments were most sensitive to the sediment erosion parameterisation, rather than the spatial detail of rainfall inputs..

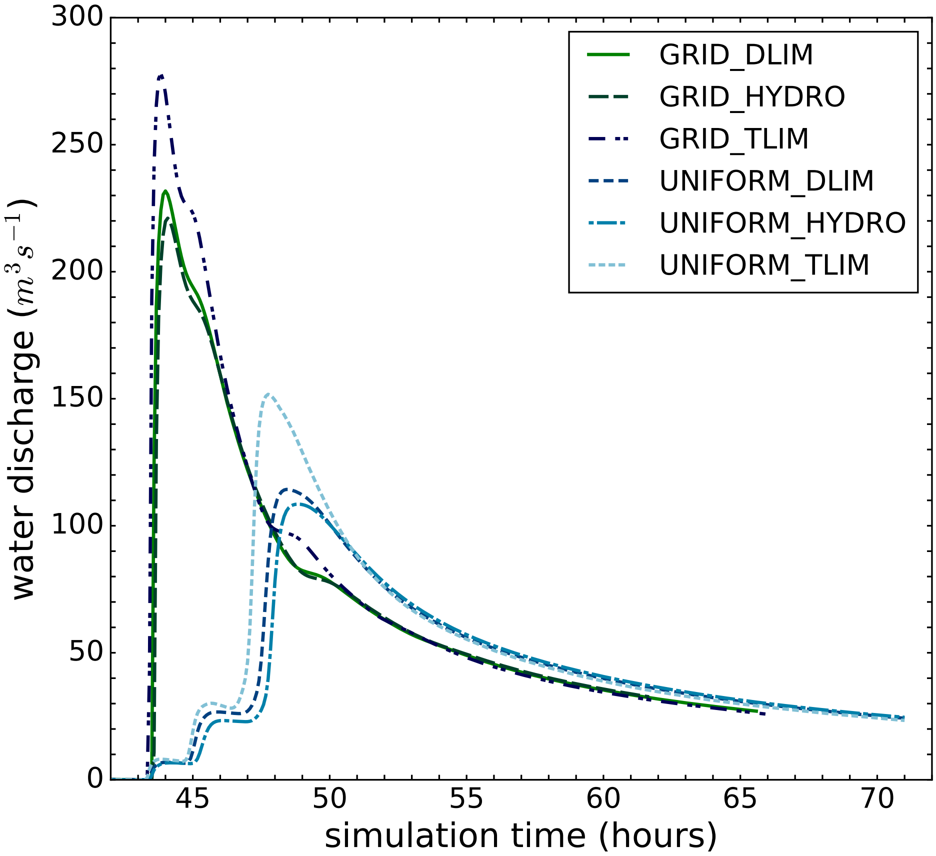

Figure 6.3: Ryedale hydrographs (discharge over time at catchment outlet) for each simulation of the 2005 Ryedale event listed in Table 6.1.

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.

6.4.4 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 (Cite Engineers Report XXXX). Simulations that allowed erosion to take place

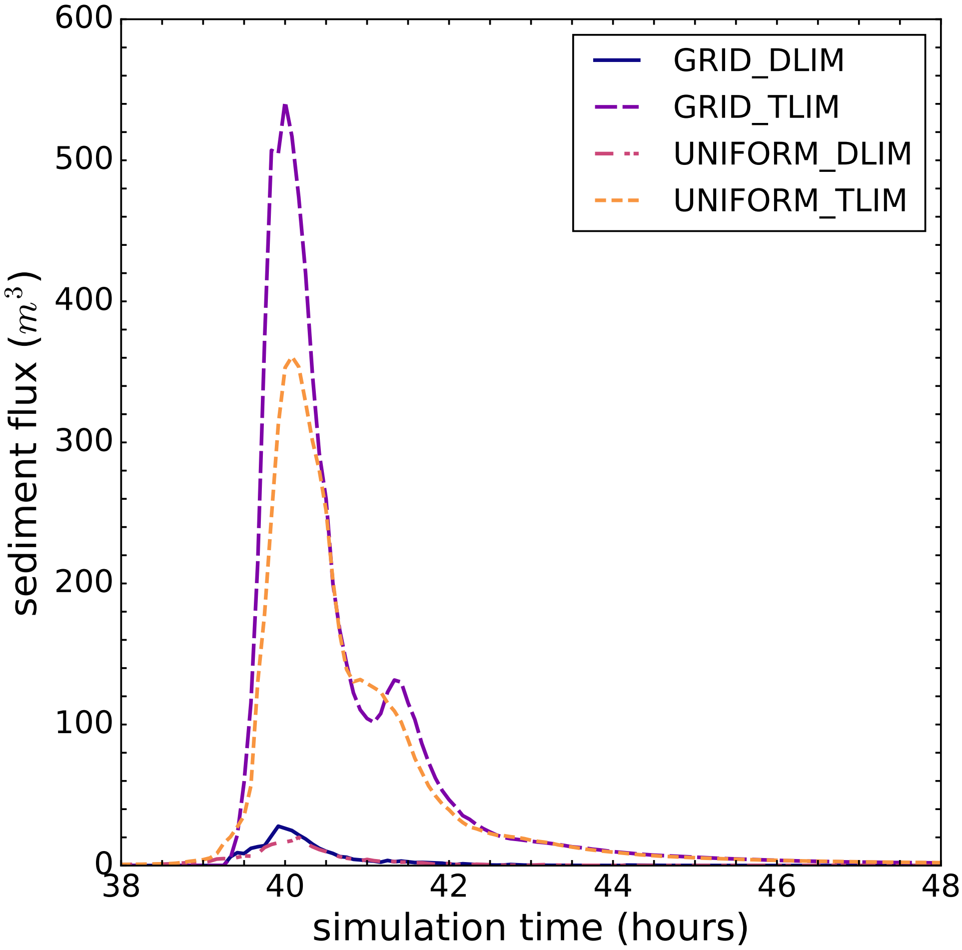

Figure 6.4: Boscastle sediment flux (total sediment volume output per hour at catchment outlet for each erosion-enabled simulation of the 2004 Boscastle event listed in Table 6.1.

(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 6.6 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

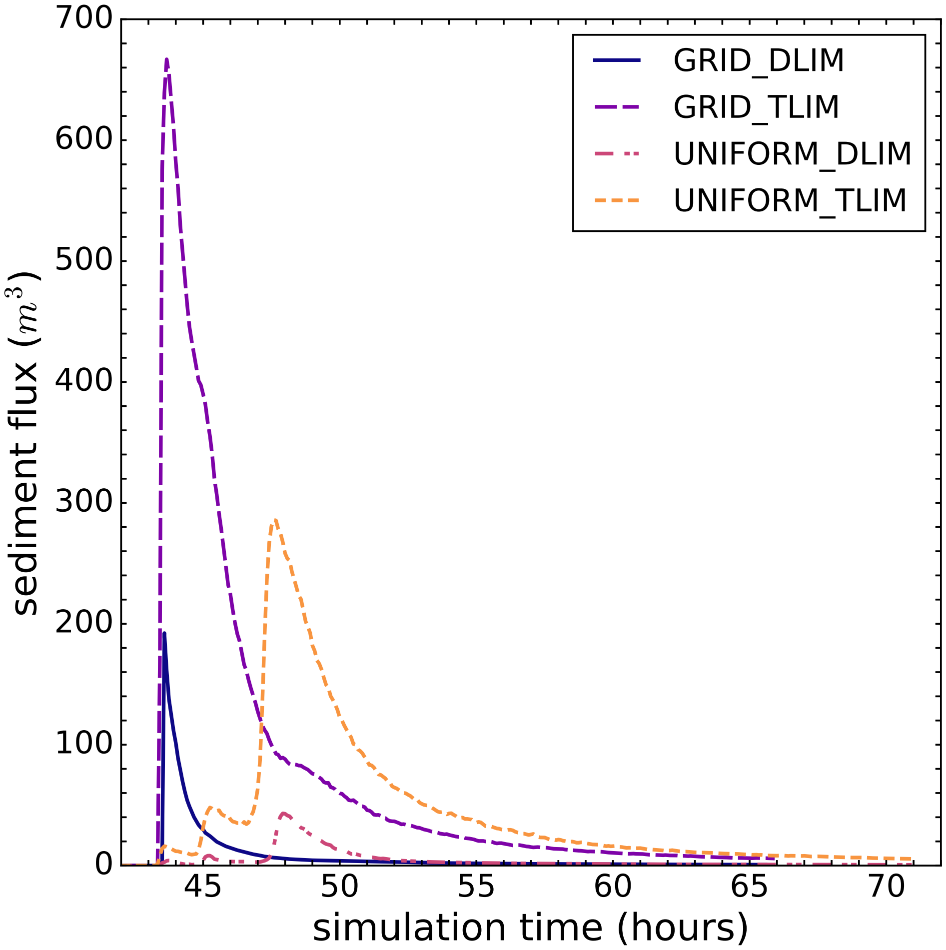

Figure 6.5: Ryedale sediment flux (Total sediment volume output per hour at catchment outlet) for each erosion-enabled simulation of the 2005 Ryedale event listed in Table 6.1.

within the village.

Ryedale

6.4.5 Spatial variations in sediment and bedrock erosion

6.5 Discussion

6.5.1 Implications for longer-term landscape evolution

Some discussion on how these results scale-up to longer term landscape evolution. I.e. How many storms of similar magnitude would be needed to reach longer term erosion *rates? Does this correspond to known longer term erosion rates of similar upland landscapes?*

6.6 Conclusions

Text.

6.7 Fixed parameters

A table showing the other parameters used in the simulations (All of which remain fixed for each simulation)

The following table lists the parameters that were held constant for all simulations.

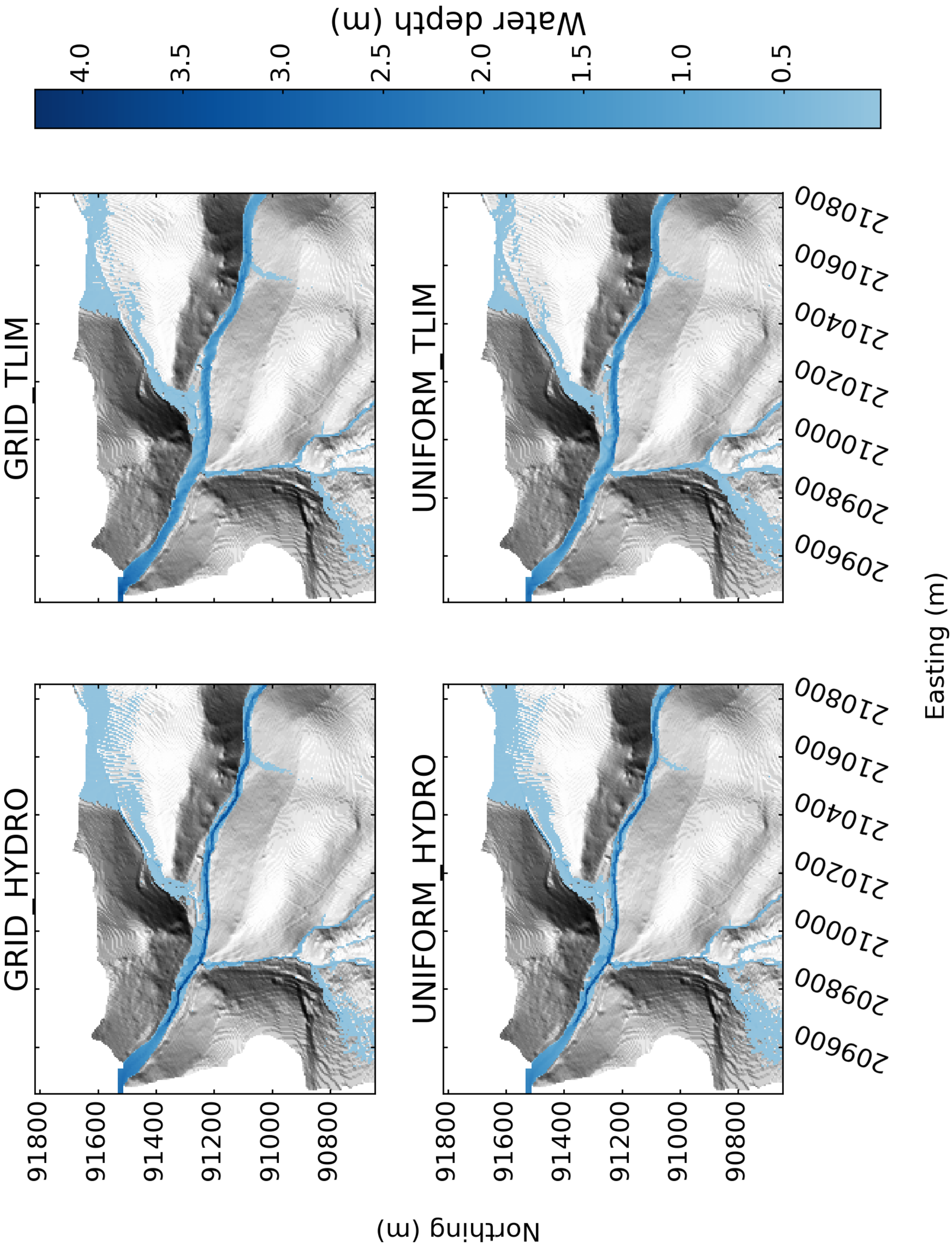

Figure 6.6: Flood extents in the Boscastle catchment at the time of maximum river discharge for each simulation.

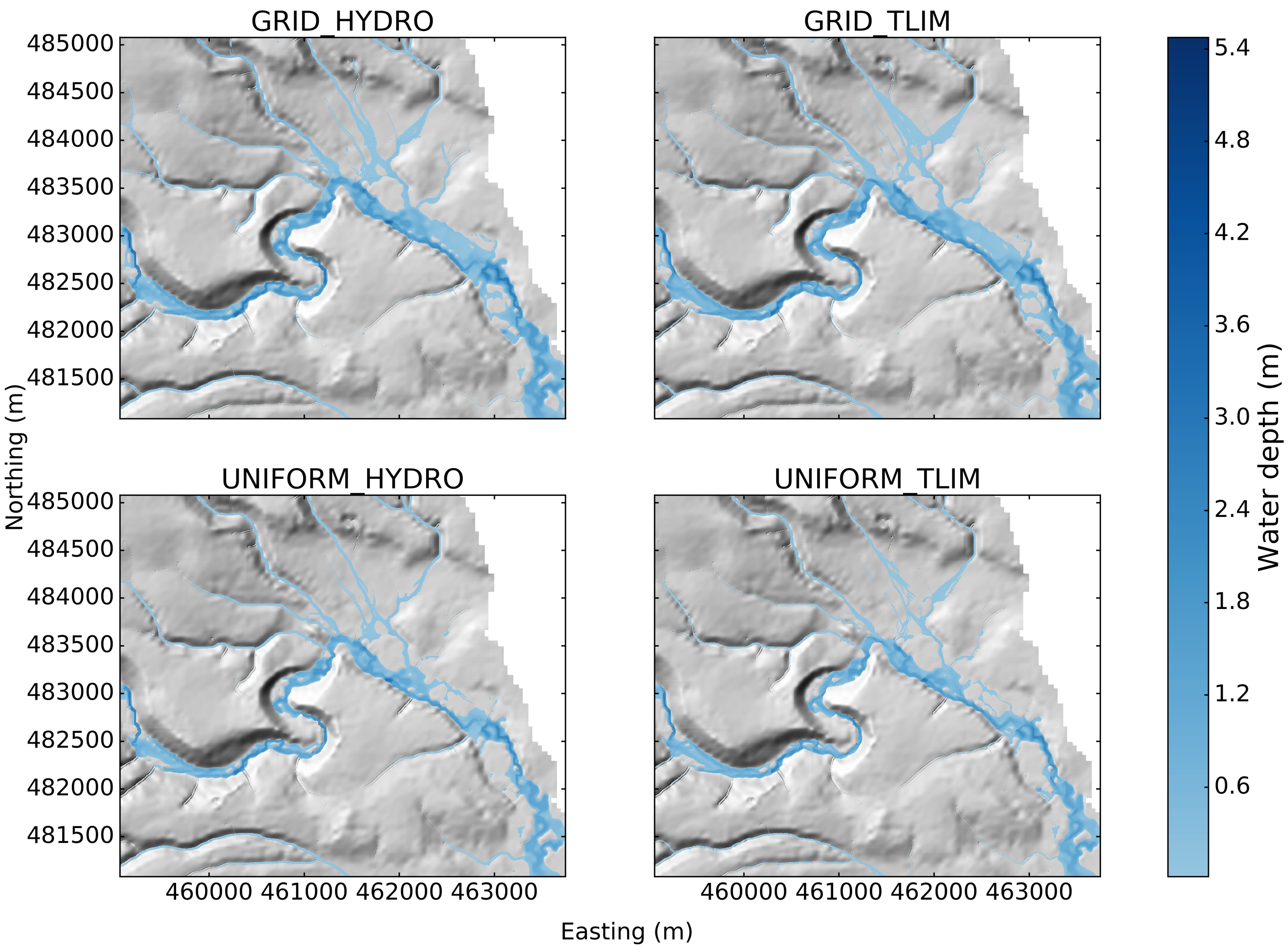

Figure 6.7: Flood extents in the Ryedale catchment at the time of maximum river discharge for each simulation.

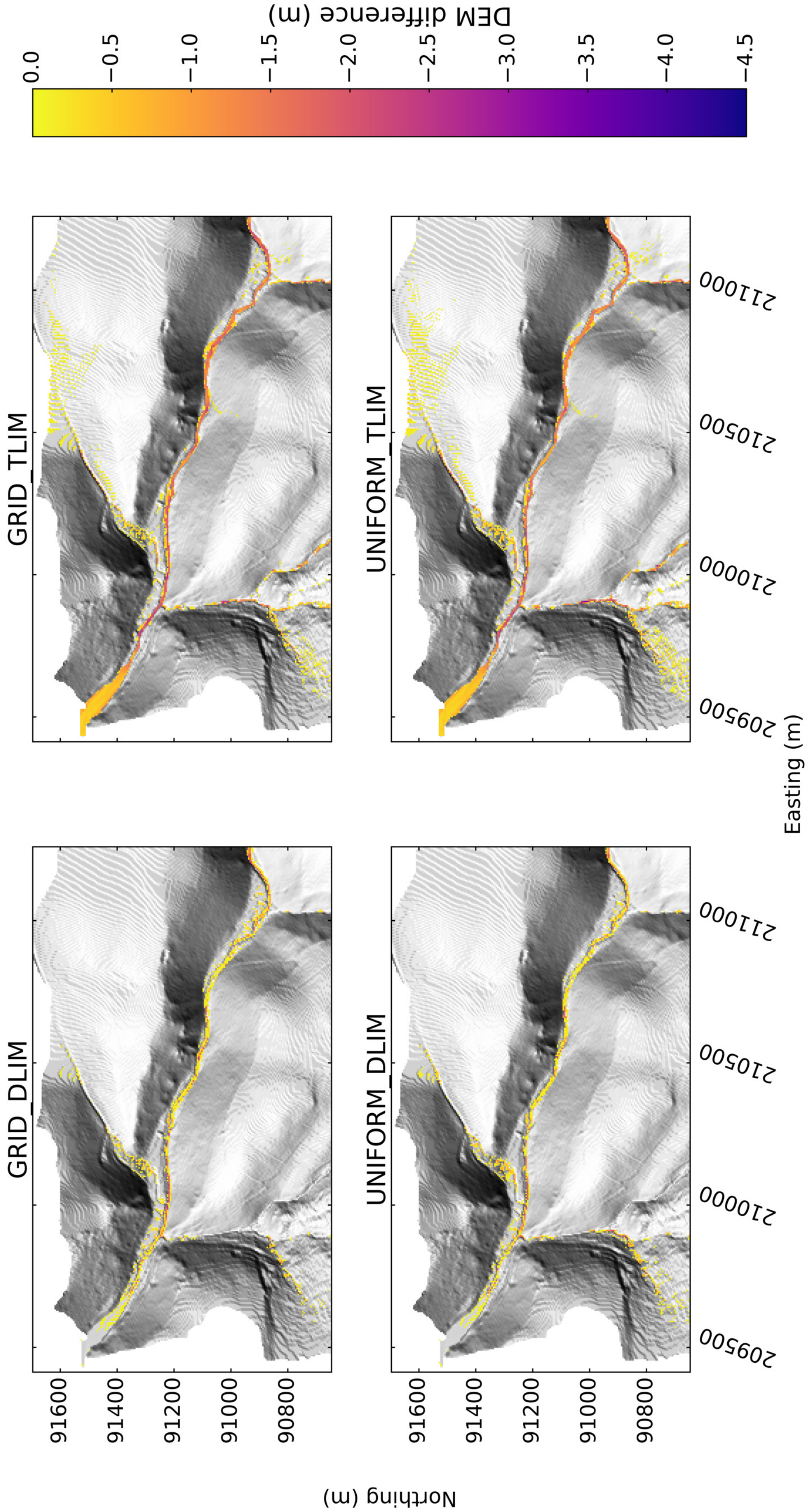

Figure 6.8: Boscastle. Erosion.

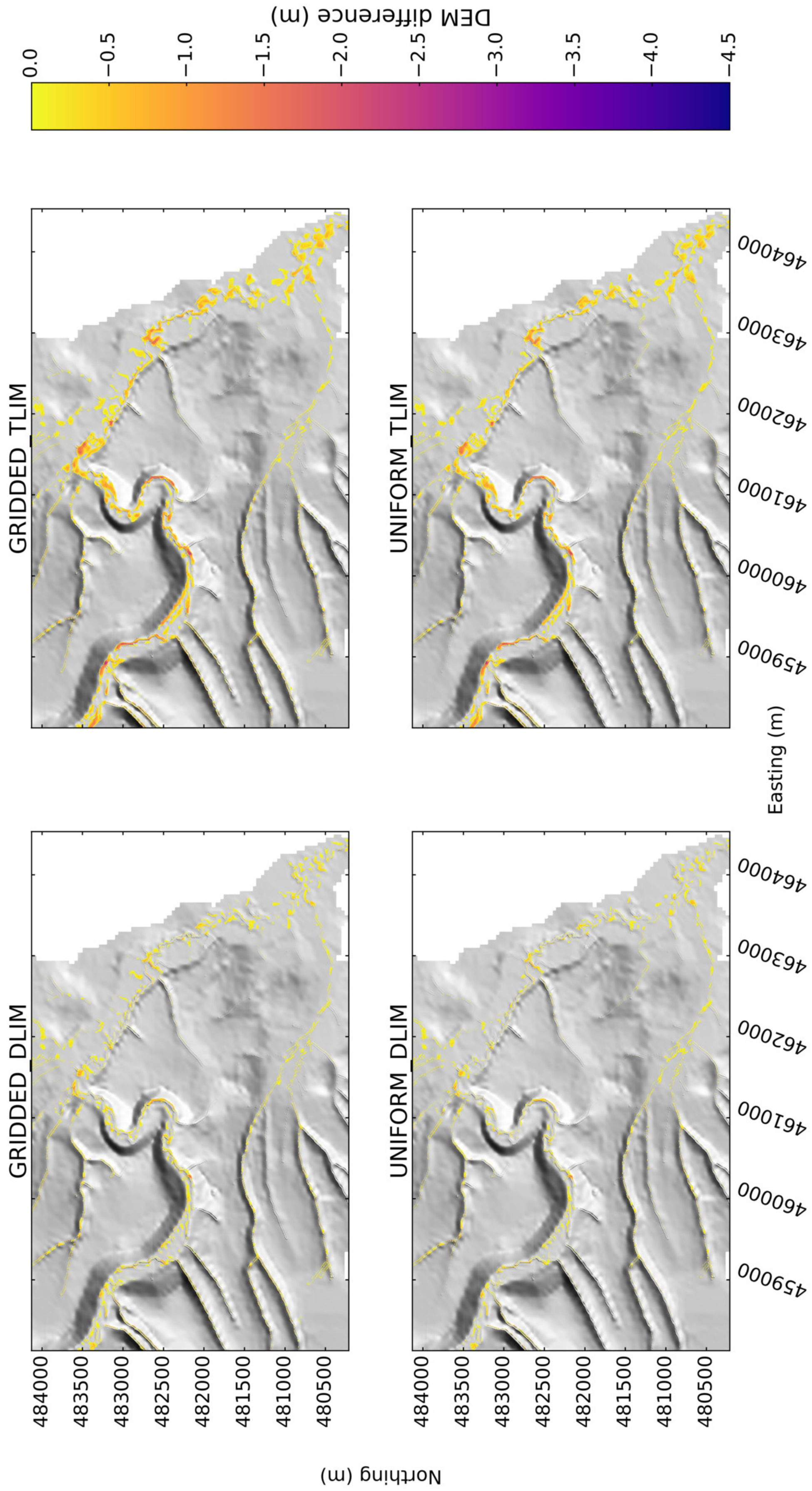

Figure 6.9: Ryedale. Erosion.

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