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The sensitivity of landscape evolution models to spatial and temporal rainfall resolution

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Abstract

Climate is one of the main drivers for landscape evolution models (LEMs), yet its representation is often basic with values averaged over long time periods and frequently lumped to the same value for the whole basin. Clearly, this hides the heterogeneity of precipitation – but what impact does this averaging have on LEM outcomes? This paper examines the sensitivity of the CAESAR-Lisflood LEM to different spatial and temporal precipitation resolutions – as well as how this interacts with different size drainage basins over short and long time scales. A range of simulations were carried out varying rainfall from 0.25 hour, 5 km to 24 hour lumped resolution over three different sized basins for 30 year durations. Results showed that there was a sensitivity to temporal and spatial resolution, with the finest leading to > 100 % increases in basin sediment yields. To look at how these interactions manifested over longer time scales, several simulations were carried out to model a 1000 year period. These showed a systematic bias towards greater erosion in uplands and deposition in valley floors with the highest spatial and temporal resolution data. Further tests showed that this effect was due solely to the data resolution, not from other (e.g. orographic) factors. The implications of these findings are that past and present LEMs may be under-predicting basin sediment yields, as well upland erosion and downstream deposition - that may have significant impacts on the modelled basin profile and shape.

1 Introduction

Landscape Evolution Models (LEMs) have been extensively developed to understand how Earth surface processes influence drainage basin dynamics and morphology. One of the important forcings of erosion and morphodynamic change in these models is climate – usually in the form of precipitation. However, all LEMs use some degree of spatial and temporal averaging for their driving climate and/or precipitation data. Spatially, rainfall (or suitable climate parameters) are usually lumped over the whole basin and changed together. This clearly removes the effects of spatial heterogeneity in the rainfall that may be caused by atmospheric factors (i.e. convective vs frontal) or due to topography (orographic effects). Temporally, there is always some form of averaging, whether decadal, annual, daily or hourly, that conceals heterogeneity in the precipitation input. This averaging may be intentional to simplify or speed up the model or may be driven by the sampling

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frequency of field measurements of rainfall. However, the temporal resolution may be important with, for example, short intense periods of rainfall being capable of generating flooding that would not occur if it were averaged over a longer time period. An important practical reason for using coarse spatial and temporal resolution precipitation data is data availability, model parsimony and model efficiency. Using spatially lumped climate values makes models simpler to construct and coarse temporal resolutions can make them faster to run by enabling longer time steps. Furthermore, the availability of high temporal and spatial resolution precipitation data is often poor – especially if the quality and validity of the data is considered. Finally, many LEM studies run over tens to thousands of years where it is impossible to generate or reconstruct suitable records of precipitation of a high resolution.

There has been a limited exploration of precipitation resolution impacts in previous LEM studies (Sólyom and Tucker, 2007), where was argued that over the long time scales that LEMs are often applied spatial effects will become less important. For example, as the modelled period of a simulation increases the probability of a separate convective rainfall cells hitting all parts of the basin increases. Similarly, Sólyom and Tucker (2007) suggest that temporal effects become less important when the basin is of sufficient size that hydrological travel times from the top to the bottom of the basin are greater than the duration of precipitation events (Sólyom and Tucker, 2007). Looking at a wider literature, as morphodynamic changes within basins are heavily associated with basin hydrology, insights may be drawn from hydrological modelling studies - where the influence of the spatial and temporal resolution of rainfall inputs has been discussed for over three decades (Lobligeois et al., 2014). From the hydrology literature there is a general agreement that finer detail in the representation of spatial and temporal variability of rainfall in a hydrological model, will improve the outputs, especially when observing hydrographs from a single event (Beven and Hornberger, 1982; Bronstert and Bárdossy, 2003; Finnerty et al., 1997; Hearman and Hinz, 2007; Ogden and Julien, 1994; Wainwright, 2002; Wilson et al., 1979). Coarser resolutions will result in a long, low intensity prediction of the runoff, and finer resolutions result in shorter, higher intensity predictions (Hearman and Hinz, 2007). Several authors have suggested that finer spatial resolutions are required for smaller basin sizes (Andréassian et al., 2001; Gabellani et al., 2007; Lobligeois et al., 2014), as coarser spatial resolutions tend to incorporate a greater proportion of rainfall that did not fall within the basin. For example, Gabellani et al., (2007) found that to achieve a model performance of less than 5 % RMSE in the discharge, the spatial resolution of the rainfall is required to be no more than 20 % that of the basin size, and the temporal resolution no more than 20 % of the basin time of concentration. However, Lobligeois et al., (2014) argued that the appropriate resolution depends on the scale of the basin, the characteristics of the basin and the characteristics of individual rainfall events. Additionally, Krajewski et al., (1991) claimed that the temporal resolution had a greater impact than the spatial resolution.

It is important to also consider that the uncertainty within rainfall products increases with finer spatial and temporal resolutions (Mcmillan et al., 2012), meaning that improved model performance is tempered by increased uncertainty surrounding the precipitation data. Therefore, to reduce the propagation of rainfall uncertainties through a hydrological model, the spatial and temporal resolutions are often aggregated to coarser scales, such as a basin-average areal value, and daily, decadal, monthly or annual totals. In such cases, Segond et al., (2007) suggested that a reliable basin-average value is sufficient, provided that there is not enough rainfall variability to overcome any dampening effects of the basin. This is supported by Lobligeois et al., (2014), where results from modelling 181 basins in France across a range of hydro-climatic conditions with lumped and semi-distributed hydrological models found that in almost every case the performance of lumped and semi distributed models were very similar. Other studies have also observed that models utilising basin-averaged rainfall show similar performances to those utilising more detailed rainfall (Kouwen and Garland, 1989; Nicótina et al., 2008; Pessoa et al., 1993). The apparent lack of improved performance with finer spatial and temporal resolutions may also be explained by the ability to highly calibrate hydrological model outputs to field data. This has led to the development of parameter ensemble techniques, such as the Generalised Likelihood Uncertainty Estimate (GLUE) method (Beven and Binley, 1992; Beven, 2006).

In summary – the above studies show that for basin scale hydrological modelling, temporal and spatial resolution of rainfall can have an impact on model outputs, but the model calibration process can account for the impacts. It would seem sensible to apply this knowledge to LEMs, however, erosion and deposition processes within drainage basins does not linearly reflect the hydrology. For example, an LEM driven by hourly precipitation data (Coulthard et al., 2012b) has shown that erosion, deposition and sediment yields responded exponentially to flood size. Tucker and Hancock (2010) also identified this sensitivity of erosion and deposition to discharge in their review of LEMs. They examined research considering the role of discharge variability through time on erosion and landscape development. (e.g. Lague et al., 2005; Molnar et al., 2006; Tucker and Bras, 2000) and illustrated how precipitation variability can have an equal or greater erosive impact than precipitation amount (Tucker and Bras, 2000). Additionally, Tucker and Hancock (2010) noted that erosion and sediment transport rates will also tend to increase with greater flow variability – and flow variability may in turn be affected by the spatial and temporal resolution of precipitation.

Modelling studies have also shown that geomorphic responses can be chaotic and highly variable with similar size flood events delivering highly different volumes of sediment and producing significantly different patterns of erosion and deposition (Castelltort and Van Den Driessche, 2003; Coulthard and Van De Wiel, 2007; Coulthard et al., 1998, 2005; Simpson and Castelltort, 2012; Van De Wiel and Coulthard, 2010). Furthermore, (Coulthard et al., 2013a) showed that the timing and size of the flood wave generated by a hydrodynamic flow model in LEMs had an important impact on sediment yield. It is therefore reasonable to expect that whilst there is a relationship between hydrology and erosion and deposition – they may have different sensitivities to spatial and temporal resolutions of rainfall data.

An additional, yet important difference between hydrological and LEM studies are the metrics used for model assessment. Hydrological studies are frequently measured on the basin hydrograph – a spatially lumped metric of water delivered over

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time at the basin outlet. Whereas, landscape evolution models are assessed on the spatial patterns of erosion and deposition such as basin shape or hypsometry (Hancock et al., 2015; Tucker and Hancock, 2010). Furthermore, over longer time scales spatial patterns or erosion and deposition become more important, as positive feedbacks lead to streams/gulleys incising, growing and increasing their basin area. Therefore, the basin outlet metric used by most of the previously mentioned hydrological studies will be hiding evolving spatial heterogeneities within the basin that over time are important for LEM's.

This raises the research questions:

a. How does the spatial and temporal resolution of precipitation/climate data impact upon basin erosion and deposition patterns, and ultimately longer term landscape evolution?
b. As data resolution is often a compromise between availability and applicability, are there optimum, or ideal spatial and temporal resolutions? And how do these change for basins of different sizes and configurations, over different time scales?
c. Are the metrics and methods commonly used for assessing the performance of basin hydrological models appropriate for LEM and morphodynamic models?

This paper will address these three questions by developing the CAESAR-Lisflood LEM (Coulthard et al., 2013a) to incorporate spatially variable rainfall and use it to test the impacts of spatial and temporal precipitation resolution on basin geomorphology over a range of basin sizes.

2 Methods

2.1 CAESAR-Lisflood and model developments

CAESAR-Lisflood is a grid based LEM that uses a hydrological model to generate surface runoff, which is then routed using a separate scheme generating flow depths and velocities. These are then used to drive fluvial erosion over several grainsizes integrated within an active layer system. In addition, slope processes (mass movement and soil creep) are also simulated. Previous versions of CAESAR-Lisflood used a lumped hydrological model based on TOPMODEL driven by one precipitation time series for the whole basin. This study required the spatial and temporal resolution of the precipitation inputs to be altered, which led to some model adaptations. A detailed description of the revised hydrological components is provided below, but for elaboration on the hydraulic, fluvial erosion and slope model operation readers are referred to Coulthard et al., (2013a).

The hydrological model within CAESAR-Lisflood is based on an adaptation of TOPMODEL (Beven and Kirkby, 1979) based on an area lumped exponential store of water, where storage and release of water is controlled by the m parameter. m is responsible for controlling the rise and fall of the soil moisture deficit (Coulthard et al., 2002) and therefore influences the characteristics of the modelled flood hydrograph (Welsh et al., 2009). Higher values of m increase soil moisture storage leading to lower flood peaks and a slower rate of decline of the recession limb of the hydrograph, and therefore represent a well-vegetated basin (Welsh et al., 2009). Conversely, lower values of m represent more sparsely vegetated basins. If the local rainfall rate r (m.h^{-1}) specified by an input file is greater than 0, the total surface and subsurface discharge (Q_{tot}) is calculated using Equation (1).

$$Q_{tot} = \frac{m}{T}\log\left(\frac{(r-j_t)+j_t\exp\left(\frac{rT}{m}\right)}{r}\right)$$

$$j_t = \frac{r}{\left(\frac{r-j_{t-1}}{j_{t-1}}\exp\left(\left(\frac{(0-r)T}{m}\right)+1\right)\right)}$$

Here, T = time (seconds); j_t = soil moisture store; j_{t-1} = soil moisture store from the previous iteration. If the local rainfall rate r is zero (i.e. no precipitation during that iteration), equation (2) is used:

$$Q_{tot} = \frac{m}{T}\log\left(1+\left(\frac{j_t T}{m}\right)\right)$$

$$j_t = \frac{j_{t-1}}{1+\left(\frac{j_{t-1}T}{m}\right)}$$

Equations 1 and 2 calculate a combined surface and subsurface discharge, and these are separated prior to runoff flow routing. This is done using a simple runoff threshold, which is a balance of the hydraulic conductivity of the soil (K), the slope (S) and the grid cell size (Dx) (Coulthard et al., 2002) (equation 3).

$$Threshold = KS(Dx)^2$$

The volume of water above this threshold, or above a user-defined minimum value ($Q_{\min}$), is subsequently treated as surface runoff and routed using the hydraulic model.

The temporal resolution of precipitation data used in CAESAR-Lisflood could already be adjusted and for most previous applications has been hourly, though the model has also been run with daily (Coulthard et al., 2013b) and at ten minute resolutions (Coulthard et al., 2012a). To enable spatially variable precipitation inputs and hydrology, CAESAR-Lisflood was modified so that precipitation rates could be input via spatially fixed pre-defined areas. These areas are defined with a raster index file with numbers corresponding to the areas. In this study regular square areas of rainfall were used that corresponded with the available rainfall data, but any shape area can be used. For each area, a separate version of the hydrological model (equations 1-3) is run, enabling different levels of storage and runoff to be generated in different areas.

The volume of runoff in a cell (determined by the hydrological model above) is then treated as surface flow and routed across the DEM surface using the Lisflood-FP hydrodynamic flow model developed by Bates et al., (2010) described further in Coulthard et al., (2013a). This model is a 2D hydrodynamic model containing a simple expression for inertia. Flow is routed to a cell's four Manhattan neighbours using Equation (4)

$$q_{t+\Delta t} = \frac{q_t - gh_t\Delta t\dfrac{\partial(h_t + z)}{\partial x}}{\left(1 + gh_t\Delta t n^2 q_t / {h_t}^{10/3}\right)}$$

where Δt = length of time step (s); t and $t + \Delta t$ respectively denote the present time step and the next time step; q = flow per unit width ($m^2.s^{-1}$); g = gravitational acceleration ($m.s^{-2}$); h = flow depth (m); z = bed elevation (m); and x = grid cell size (m). $\frac{\partial(h_t+z)}{\partial x}$ = water surface slope.

Flow depths and velocities determined by the hydraulic model are then used to calculate a shear stress that is then fed into a sediment transport function to model fluvial erosion and deposition. CAESAR-Lisflood provides a choice of sediment transport function with the Einstein (1950) or Wilcock and Crowe (2003) methods. Sediment transport is then determined over (up to) nine different grainsize classes and these may be transported as bedload or suspended load. A distinction is made between the deposition of bed load and suspended load, where bedload is moved directly from cell to cell, whereas fall velocities and the concentration of sediment in within a cell determine suspended load deposition. Importantly, the incorporation of multiple grainsizes, selective erosion, transport and deposition of the different size allows a spatially variable sediment size distribution to be modelled. However, as this grainsize heterogeneity is expressed vertically as well as horizontally, a method for storing sub-surface sediment data is required. This is achieved by using a system of active layers comprising: a surface active layer (the stream bed); multiple buried layers (strata); and, if needed, an un-erodible bedrock layer (Van De Wiel et al., 2007). Slope processes are also simulated, with landslides occurring when a user defined slope threshold is exceeded and soil creep carried out as a function of slope.

2.2 Study area

The basin studied is the River Swale in Northern England. The mean basin relief is 357 m, ranging between 68-712 m with an average river gradient of 0.0064. The headwaters of the Swale are characterized by steep valleys and the geology is Carboniferous limestone and millstone grits (Bowes et al., 2003). Downstream, valleys are wider and less steep, with the underlying geology becoming Triassic mudstone and sandstones (Bowes et al., 2003). This basin has been extensively modelled in previous studies (Coulthard and Macklin, 2001; Coulthard and Van de Wiel, 2013; Coulthard et al., 2012b, 2013a), and a pre-calibrated version of the CAESAR-Lisflood model was readily available. The basin was sub-divided to provide test sub basins of various sizes giving three basin sizes – herein referred to as the Complete Swale, the Upper Swale and the Arkengarthdale tributary (Figure 1; Table 1).

2.3 Precipitation data, and model configuration

The rainfall data used was derived from NIMROD rainfall radar (Met Office, 2003) that has a native resolution of 5 km grid cells and 0.25 hour time steps with rainfall intensities in mm.hr^{-1}. A ten-year record was extracted from the period 2004 - 2014 for the 5 km cells lying over the Swale basin. The 0.25 hour - 5 km resolution were the finest scale data available and to provide a range of different resolutions these data were re-sampled to the scales detailed below (Table 2). When aggregating to coarser spatial scales, the relative contribution of each 5 km cell was weighted, equal to its relative contribution to the basin. Therefore, with each spatial resolution the same volume rain input is applied at each daily time step. Note, that this differs from some studies of the effect of spatial resolution where some of the variation can be explained by producing rainfall records from a domain that exceeds the bounds of the basin. Here, only the spatial representation of the same rainfall record was examined.

To study the impact of spatial and temporal precipitation data, a matrix of model runs was carried out as shown in Table 2. Spatially, rainfall was lumped into basin average (henceforth "Lump"), 20, 10 and 5 km cells, and temporally averaged into 24, 12, 8, 6, 4, 1 and 0.25 hour time steps. This matrix of runs was applied to all three basins (Complete Swale, Upper Swale and Arkengarthdale) though as the smallest basin (Arkengarthdale) is smaller than the 20 km resolution grid cell, it is run at 5 km, 10 km and Lump spatial resolutions.

To investigate any longer term impacts of precipitation resolution, two 1000 year simulations were carried out on the Upper Swale basin using the end members of our driving data, the 24 hour - Lump and 0.25 hour - 5 km resolution data. Both simulations used the 10 year precipitation record looped 100 times. However, this test would result in the same spatial patterns of rainfall being applied to the same area one hundred times that could bias areas of erosion and deposition to those receiving the most precipitation – rather than being a test of the spatial and temporal resolution. Therefore, two additional 1000 year simulations were carried out where after every simulated ten years, the locations of each rainfall pixels were randomly reassigned (called random 1 and random 2). Results from the two long term simulations where then compared against both of these random simulations.

All simulations were carried out over a 50 m resolution DEM, with no bedrock and vegetation parameters applied. Excluding the 1000 year simulations, all other runs shown in Table 2 were carried out for a 30 year period based on the 10 year rainfall record repeated three times. The initial simulation conditions were based on a 'spun up' DEM and grainsize distribution generated by a 30 year model run using the 24 hour - Lump rainfall. Apart from rainfall parameters and the basin DEM, all model parameters were kept constant, with one exception where the input/output difference allowed was set at 10 $m^3.s^{-1}$ for the Complete Swale, 5 $m^3.s^{-1}$ for the Upper Swale and 2.5 $m^3.s^{-1}$ for the Arkengarthdale. This ensured that the model ran efficiently, with each value appropriate for the respectively basin size, and the hydrological regime. A list of CAESAR-Lisflood parameter values used in the simulations is shown in Table 3.

For all simulations, water and sediment outputs were sampled from the model at 0.25 hour time steps and the DEM saved every 10 simulated years. From these data, mean annual output and values above the 95^{th} percentile (representing peaks) were calculated for both water (discharge rate $m^3.s^{-1}$) and sediment yield (volume). To allow better comparison between the basin sizes, the above metrics were calculated as a percentage deviation from the baseline, which was taken to be the 24 hour - Lump resolution. To assess the impact of different resolutions on the modelled basin hydrology, outputs were compared to discharge data at Catterick Bridge using RMSE and Nash-Sutcliffe metrics for the ten year record 2004 - 2014.

3 Results

3.1 Hydrology

The influence of the spatial and temporal resolution on the rainfall data is shown by the considerable differences in maximum rainfall rate values for the Complete Swale basin (Table 4). These changes are largely translated through to the basin hydrology (Tables 5 and 6) but with some changes. Looking at mean annual discharge (Table 5) there is a clear increase in water output with finer temporal and spatial resolution for the largest Complete Swale basin, though only an increase with finer temporal resolution for the smaller two basins. Looking at peak values (Table 6) these changes are even less apparent with most differences due to finer temporal resolution. However, overall these changes are relatively minor (c.4 % for mean annual discharge and 5-10 % for peak discharges) especially when compared to the difference in maximum rainfall intensity.

The change in resolution also influences the performance statistics for the hydrology with Table 7 showing an improvement in performance (RMSE and Nash-Sutcliffe) with finer temporal resolution with only very small improvements due to finer spatial resolutions (RMSE only). It should be noted that a direct comparison is not straightforward due to the location of the gauging station that is downstream from the outlet of our DEM and also drains an additional tributary.

3.2 Sediment outputs

Tables 8 and 9 describe how with changing temporal and spatial resolution there is a clear trend of increasing sediment yields with finer spatio-temporal resolutions. Compared to basin hydrology, the results show that the sediment yield is notably more sensitive, with the greatest deviation being 118.1 % in the mean annual volumes, with the corresponding hydrological deviation being 2.8 %. Each basin shows a sensitivity to spatial resolutions, which increases with the basin size though differences are reduced between the 1 hour and 0.25 hour temporal resolutions.

For the 1000 year simulations, there are clear differences in erosion and deposition patterns between the random 1 (with 0.25 hour 5km resolution data) and the 24 hour - Lump simulation (Figure 2). Notably there is more erosion in all headwater and first order streams and substantial amounts of deposition in the valley floors. The six cross sections (Figure 3, A to F) provide more detail on morphological changes at these sites with 3-5m additional incision at cross section B and 6m at cross section D, along with up to 3m of deposition at cross sections D and E. Interestingly these are not restricted to single channel threads, but in particular at E across some 350m of valley floor. We have chosen to present the results from the random 1 simulation, as firstly there is very little difference between the morphology generated by random 1 and random 2 (Figure 4) and secondly because there were notable differences between the 1000 year 0.25 hour 5km resolution simulation and the random runs. These differences are a facet of repeating the 10 year rainfall sequence 100 times and are presented in Figure 5, where the most notable difference is > 2.5m in the valley floor to the Western side of the basin along with smaller changes in the valley floor downstream.

4 Discussion

4.1 The impact of precipitation spatial and temporal resolution on sediment yield and longer term landscape evolution

Clearly both temporal and spatial resolution of precipitation has an important effect on both the amount of sediment coming from a basin, and where it is eroded and deposited (Tables 8 and 9; Figures 2 and 3). The effect of increasing the spatial and temporal resolution of the rainfall input is to increase significantly the local rainfall intensity over parts of the basin, whilst the overall rainfall volume remains the same. This leads to a slight increase in the basin water discharge (< 5 %), but a much greater increase in sediment yields - that are in some cases doubled. Looking at differences in spatial patterns of erosion and deposition (Figure 2), the impacts of different precipitation resolution is very apparent – where increased local rainfall intensities afforded by higher resolution data lead to increased local runoff and thus increase erosion in the smaller upland tributaries and headwaters. Further down the basin, these effects are lessened as flood peaks diffuse downstream, and due to this and the increased sediment loads from upstream there are increased volumes deposition in the valley floor sections (e.g. Figure 3, cross section E). The disproportionate relationship between changes in hydrology and erosion/deposition is highly important in this context, as small changes (here local and temporal) can clearly have a significant impact on basin sediment yield and local erosion/deposition patterns. This affirms the findings of (Coulthard et al., 2012b) where they noted the ‘geomorphic multiplier’ effect between rain, runoff and sediment yield.

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For the 1000 year simulations we used the results of the random 1 and random 2 simulations as there were notable impacts of repeating the same 10 year 0.25 hour 5km rainfall patterns. Here, one or two precipitation cells containing high amounts of rainfall lead to more erosion and deposition in certain locations, that was amplified over 100 repeats (1000 years). Clearly this is an unrealistic effect though comparing the random simulations to the 0.25 hour 5km simulation (Figure 5) only small parts of the basin were notably affected by this. However, if the heterogeneity of a real 1000 year rainfall record was used, we might expect orographic rainfall effects to generate a systematic increase in rainfall in higher areas. Indeed, Figure 6 shows a general, though not significant, orographic relationship for the Swale rainfall data we used. It is therefore, very important to disentangle whether any increased erosion totals, or changes in erosion patterns are due to the precipitation data resolution or orography. To test for this, we carried out a series of additional simulations using the 0.25 hour - 5 km data, where the 5 km rainfall grid cells were randomly re-distributed or 'jumbled' to produce 20 different records. These jumbled data were then averaged to each of the temporal resolutions and the 30 year simulations were re-run. These results are shown in Figure 7, where we have plotted the relationship between total discharge against the total sediment yield as reassigning the precipitation data area locations alters the total volume of rainfall into the basin. Figure 7 indicates that as the temporal resolution of the rainfall increases, so does the hydrological and sediment totals of the model from each run. Furthermore, the trend lines show a clear offset between the different resolutions. Therefore, this strongly indicates that it is the spatial and temporal resolution not any orographic effects within the data that are responsible for increased sediment yields previously described.

For existing and previous LEM studies these results suggest that there may have been a systematic under-representation of basin wide erosion by using lumped and coarse temporal resolution climate/precipitation data. Whilst this is a concern, many LEMs are constructed to explore relationships between processes, drivers and subsequent landscape change/development so a lumped/basin wide underestimation (even of > 100 % as indicated above) may not directly alter the findings of the studies. However, where LEMs are being used for engineering and landscape forecasting purposes (e.g. (Hancock et al., 2000, 2002, 2010) or where LEMs have been calibrated/validated (e.g. Coulthard et al., 2012a) this may be important. In addition, and possibly more importantly than basin wide sediment yield changes, the findings of this study show there are considerable differences in the spatial patterns of erosion and deposition between simulations with 24 hour - Lump and 0.25 hour – 5 km resolution precipitation data. Notably, there is increased erosion in upland and first order streams – that also leads to increased deposition and valley floor aggradation downstream. Over the thousand years we have simulated in this study, these differences can be several metres in elevation. This leads to a change in the shape of the basin long profile - and thus when projected over even longer time scales will lead to larger shifts in shapes of predicted basins, landscapes and landforms. It is important to remember that this is only to the precipitation data resolution. For many existing models, and for those dealing with very long time scale simulations (e.g. > 10 000 years) incorporating high resolution precipitation data is impractical – as is generating precipitation time series at such resolutions for millennia. Therefore, a practical next step for

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this research would be to determine if there is a compensatory factor or exponent that can be used to easily account for this effect.

4.2 The impact on different size basins

Considering the effect of different basin sizes, the largest, Complete Swale basin showed a greater sensitivity to the spatial resolution of the precipitation data. This was expected as there are more precipitation cells covering the basin, and therefore greater variation. This is clearest in Table 8, where the mean annual sediment yield varies by nearly 35 % between the Lump and 5 km resolutions for 24 hour rainfall for the Complete Swale, but less than 5 % for both the Upper Swale and Arkengarthdale basins. Looking at temporal variations alone, the smallest basin size, Arkengarthdale is the most sensitive, with the Upper Swale being the least – presenting no clear relationship. Overall, this indicates that the basin size relative to the precipitation data spatial resolution is an important consideration and to comprehensively answer the research question, more simulations with finer resolution precipitation data (or over a larger basin) would be required. It is an attractive assumption that there will be a 'sweet spot' of spatial and temporal rainfall data for a certain basin size, but our data does not support this. Furthermore, the nature of the precipitation (e.g. small footprint convective rain storms vs larger footprint frontal weather) could also affect this relationship.

4.3 Are hydrological basin wide metrics suitable for LEM/Morphodynamic models?

This study raises some interesting issues regarding the suitability of hydrological type metrics (e.g. basin discharge) for evaluating LEMs, morphodynamic or geomorphic models. Basin sediment yield may be a useful indicator of overall LEM performance, but will conceal much of the important geomorphic change within a basin. Therefore, a good hydrological and/or sediment yield prediction from a LEM does not necessarily translate to a good morphodynamic prediction. Similar hydrographs of water and sediment at a basin exit may come from completely different parts – and leave a very different geomorphic signature. Here is an important distinction between the hydrology and geomorphology – as different hydrological responses will not necessarily leave any sort of hydrological record in the system. But geomorphological changes in response to the hydrology will.

Largely model metrics are driven by the aims of the model. For example, a hydrograph may be a very useful output for a basin hydrological model (to feed in, for example, into a flood model). Whereas for a morphodynamic model we are interested in the changes occurring throughout the basin not just those reflected at the end. This is especially important for LEMs where patterns of erosion and deposition feedback to control the shape of basins and landscape development – and this effect increases with the duration of model study or simulation. This point is identified in recent work by (Hancock et al., 2015) showing that using the SIBERIA model, over 10 000 years different shape landscapes can evolve yet generate very similar sediment yields.

4.4 Limitations

It is important to consider that these findings are based on numerical simulations that contain many of simplifications and assumptions. CAESAR-Lisflood is driven by a hydrological model where changes in land-use are represented through altering model parameters (*m*) leading to flashier or more reduced hydrographs. This may prove to be a considerable sensitivity to precipitation temporal and spatial resolution and in these simulations we have deliberately used a moderate value for an *m* of 0.01 – which in previous CAESAR-Lisflood simulations has been used to represent natural scrubland. We would suggest that lower values for grassland (e.g. 0.005) would increase sensitivity and larger for forest/woodland (0.02) would reduce sensitivity, though further simulations would be required to show this. There may be issues with the DEM resolution (here 50 m) and how that interacts with different spatial precipitation resolutions with other workers showing that grid resolution in LEMs can have an impact (Hancock et al., 2015). Furthermore, there are uncertainties associated with the upscaling of the precipitation data and the transfer of rain radar data to actual values. However, notwithstanding the above limitations, our results provide very useful insight into how spatially and temporally changing precipitation can alter simulated basin geomorphology and sediment yields.

5 Conclusions

These findings show that whilst there is a relationship between hydrology and erosion and deposition, importantly they have different sensitivities to spatial and temporal resolutions of precipitation data. Compared to 24 hour - Lump data, using the highest resolution rainfall data can lead to a doubling in basin total sediment yields. This is linked to increased erosion in upland and first order streams with deposition and aggradation in valley floors that over longer term simulations leads to considerable changes in the basin evolution. Our findings are placed in the context of LEMs – but it should be considered that such issues of rainfall spatial and temporal resolution may be highly important to soil erosion models, and other basin based sediment models that may be missing the effects we have described here.

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Table 1. Basin areas and elevations for the three test basins used.

Catchment	**Area (km^3)**	**Minimum Elevation (m)**	**Maximum Elevation (m)**
Complete Swale	415	68	712
Upper Swale	181	182	712
Arkengarthdale	62	198	664

Table 2 Matrix of runs using different temporal (x) and spatial (y) resolutions.

	24 Hour	**12 Hour**	**8 Hour**	**4 Hour**	**1 Hour**	**0.25 Hour**
Lump	24 Hour - Lump	12 Hour - Lump	8 Hour - Lump	4 Hour - Lump	1 Hour - Lump	0.25 Hour - Lump
20 km	24 Hour- 20 km	12 Hour- 20 km	8 Hour - 20 km	4 Hour - 20 km	1 Hour - 20 km	0.25 Hour - 20 km
10 km	24 Hour- 10 km	12 Hour- 10 km	8 Hour - 10 km	4 Hour - 10 km	1 Hour - 10 km	0.25 Hour - 10 km
5 km	24 Hour- 5 km	12 Hour- 5 km	8 Hour - 5 km	4 Hour - 5 km	1 Hour - 5 km	0.25 Hour - 5 km

Table 3. CAESAR-Lisflood model parameters used.

CAESAR-Lisflood Parameter	**Values**
Grainsizes (m)	0.0005, 0.001, 0.002, 0.004, 0.008, 0.016, 0.032, 0.064, 0.128
Grainsize proportions (total 1)	0.144, 0.022, 0.019, 0.029, 0.068, 0.146, 0.220, 0.231, 0.121
Sediment transport law	Wilcock & Crowe
Max erode limit (m)	0.002
Active layer thickness (m)	0.01
Lateral erosion rate	0.0000005
Lateral edge smoothing passes	40
m value	0.01
Soil creep/diffusion value	0.0025
Slope failure threshold	45 degrees
Evaporation rate (m/day)	0
Courant number	0.7
Mannings n	0.04

Table 4. Maximum rainfall intensities from the ten year record for each resolution, taken from the domain for the Complete Swale catchment.

Maximum Rate ($mm.hr^{-1}$)	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Lump	2.87	4.08	5.90	5.96	7.83	17.30	37.74
20 km	3.29	5.03	7.10	8.21	10.54	18.66	70.63
10 km	3.29	5.03	7.10	8.21	10.54	19.06	70.63
5 km	4.06	5.77	7.58	8.70	11.24	25.23	76.75

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Table 5. The percentage deviations of the mean annual hydrological outputs using different spatio-temporal resolutions, for each catchment.

	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Complete Swale							
Lump	0.00	1.19	1.61	1.54	1.68	1.63	1.66
20 km	0.80	1.62	1.90	2.11	2.36	2.53	2.49
10 km	0.74	1.72	2.15	2.38	2.55	2.58	2.61
5 km	0.76	1.96	2.35	2.52	2.68	2.81	2.82
Upper Swale							
Lump	0.00	1.05	1.40	1.61	1.71	1.90	1.97
20 km	-0.08	0.93	1.38	1.50	1.74	1.88	1.91
10 km	0.21	0.96	1.57	1.65	1.81	2.00	2.05
5 km	0.22	1.13	1.69	1.67	1.85	2.01	2.00
Arkengarthdale							
Lump	0.00	2.27	2.88	3.26	3.76	4.33	4.32
10 km	-0.78	2.28	2.67	3.12	3.74	4.27	4.26
5 km	-0.94	2.26	2.26	3.07	3.44	4.21	4.29

Table 6. The percentage deviations of the volume of hydrological outputs above the 95th percentile using different spatio-temporal resolutions, for each catchment.

	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Complete Swale							
Lump	0.00	3.72	4.19	4.65	4.96	5.16	5.15
20 km	0.32	4.05	4.53	5.14	5.50	5.76	5.75
10 km	0.46	4.25	4.76	5.38	5.74	5.99	6.00
5 km	0.16	3.96	4.49	5.16	5.51	5.72	5.75
Upper Swale							
Lump	0.00	3.61	4.82	5.27	5.58	6.05	6.08
20 km	-0.06	3.51	4.69	5.14	5.45	5.89	5.93
10 km	-0.02	3.58	4.78	5.25	5.57	6.05	6.09
5 km	-0.24	3.41	4.47	4.97	5.31	5.77	5.72
Arkengarthdale							
Lump	0.00	6.75	7.26	8.33	8.94	9.64	9.78
10 km	-0.05	8.38	7.27	8.31	8.89	9.56	9.70
5 km	-0.12	6.56	7.15	8.35	8.86	9.64	9.70

Table 7. Hydrological performance statistics from the Upper Swale catchment, comparing daily discharges from the CAESAR-Lisflood model and observed daily discharges recorded from Catterick Bridge. Red shading indicates the worst performance statistics, and the green the best performance statistics.

RMSE ($m^3.s^{-1}$)	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Lump	20.58	19.37	18.61	18.05	17.54	16.72	16.50
20 km	20.59	19.46	18.68	18.13	17.61	16.72	16.52
10 km	20.57	19.47	18.69	18.14	17.59	16.70	16.50
5 km	20.55	19.50	18.74	18.19	17.64	16.74	16.53

Nash-Sutcliffe	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Lump	0.24	0.33	0.38	0.42	0.45	0.50	0.51
20 km	0.24	0.32	0.38	0.41	0.45	0.50	0.51
10 km	0.24	0.32	0.38	0.41	0.45	0.50	0.51
5 km	0.25	0.32	0.37	0.41	0.45	0.50	0.51

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Table 8. The percentage deviations of the mean annual sediment yield outputs using different spatio-temporal resolutions, for each catchment.

Complete Swale	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Lump	0.00	44.04	51.96	48.54	53.50	66.50	66.18
20 km	27.78	63.16	72.56	73.12	83.15	91.09	91.74
10 km	30.99	64.85	78.46	72.59	87.91	98.71	100.54
5 km	34.72	67.94	90.64	84.03	101.28	115.00	118.10
Upper Swale							
Lump	0.00	16.14	22.77	22.39	29.88	35.02	40.25
20 km	-2.45	14.18	15.28	20.36	26.06	34.00	37.49
10 km	-4.19	14.68	20.45	23.21	28.81	38.02	38.85
5 km	3.02	22.70	29.75	37.81	41.30	52.93	52.56
Arkengarthdale							
Lump	0.00	30.06	42.76	54.01	58.83	75.95	77.44
10 km	-1.15	37.84	49.28	53.23	61.45	75.01	74.75
5 km	-4.20	50.49	50.49	61.63	67.36	87.34	80.74

Table 9. The percentage deviations of the volume of sediment yield outputs above the 95th percentile using different spatio-temporal resolutions, for each catchment.

Complete Swale	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
Lump	0.00	44.54	49.62	48.47	54.83	63.76	63.50
20 km	17.81	53.18	66.84	62.02	72.51	79.50	82.67
10 km	23.26	51.26	69.28	56.03	72.42	84.76	84.67
5 km	25.28	54.26	78.76	70.22	85.10	96.84	99.21
Upper Swale							
Lump	0.00	20.08	26.65	27.70	34.05	39.88	43.84
20 km	-2.57	18.03	20.03	24.82	30.96	38.02	40.99
10 km	-3.85	17.94	23.75	26.99	32.98	41.57	42.02
5 km	0.31	23.35	29.55	37.00	41.46	50.90	51.20
Arkengarthdale							
Lump	0.00	32.27	43.35	55.16	59.67	73.18	76.78
10 km	0.04	39.32	51.18	51.31	59.64	71.47	71.93
5 km	-4.28	39.25	51.48	61.22	65.81	82.59	75.84

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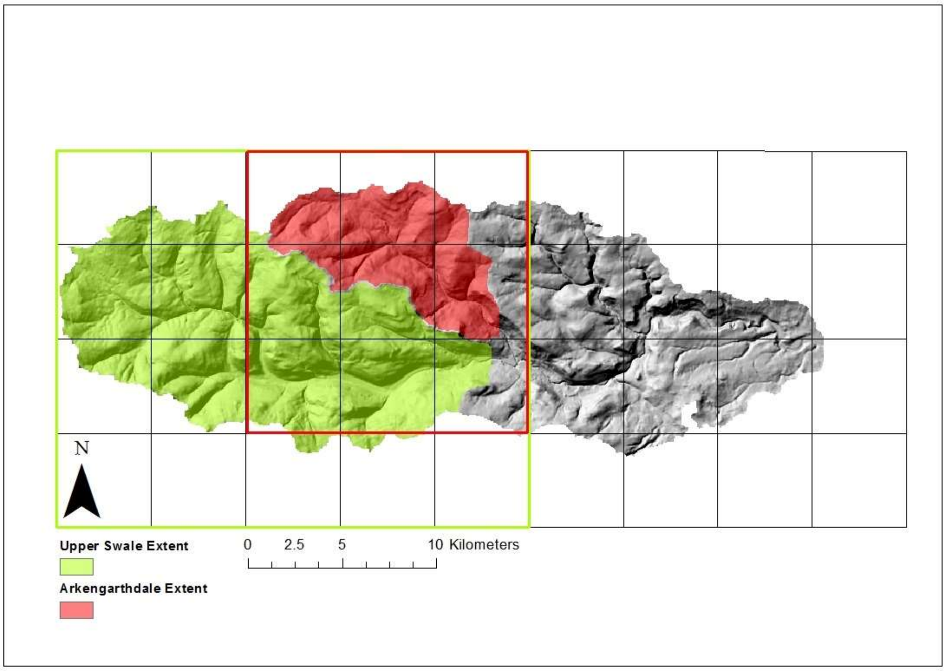

Figure 1. Map showing the extents of the three test basins with the Upper Swale in green, and the Arkengarthdale extent in red. Additionally the 5 km rain radar grid cells overlaying the three basins are shown – coloured according to the basins they cover.

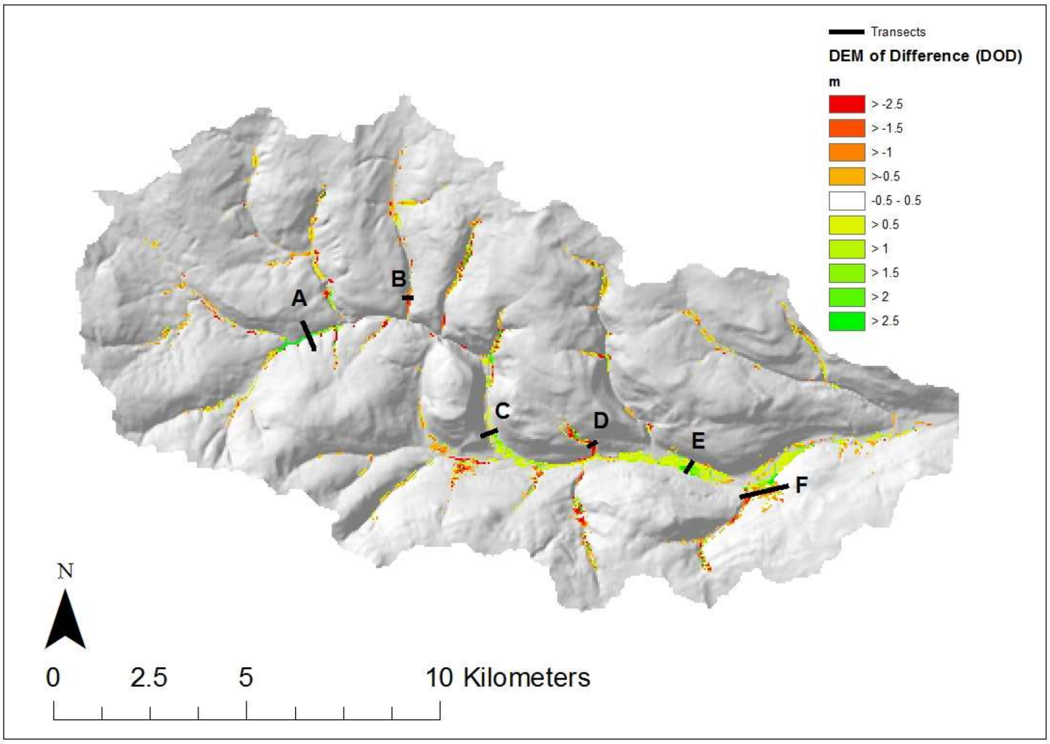

Figure 2. DEM of Difference for the 1000 Year Swale Test. The differences shown are elevations from the random 1 simulation minus the elevations from the 24hour-Lump simulation. Cross sections (Figure 3) are marked A-F.

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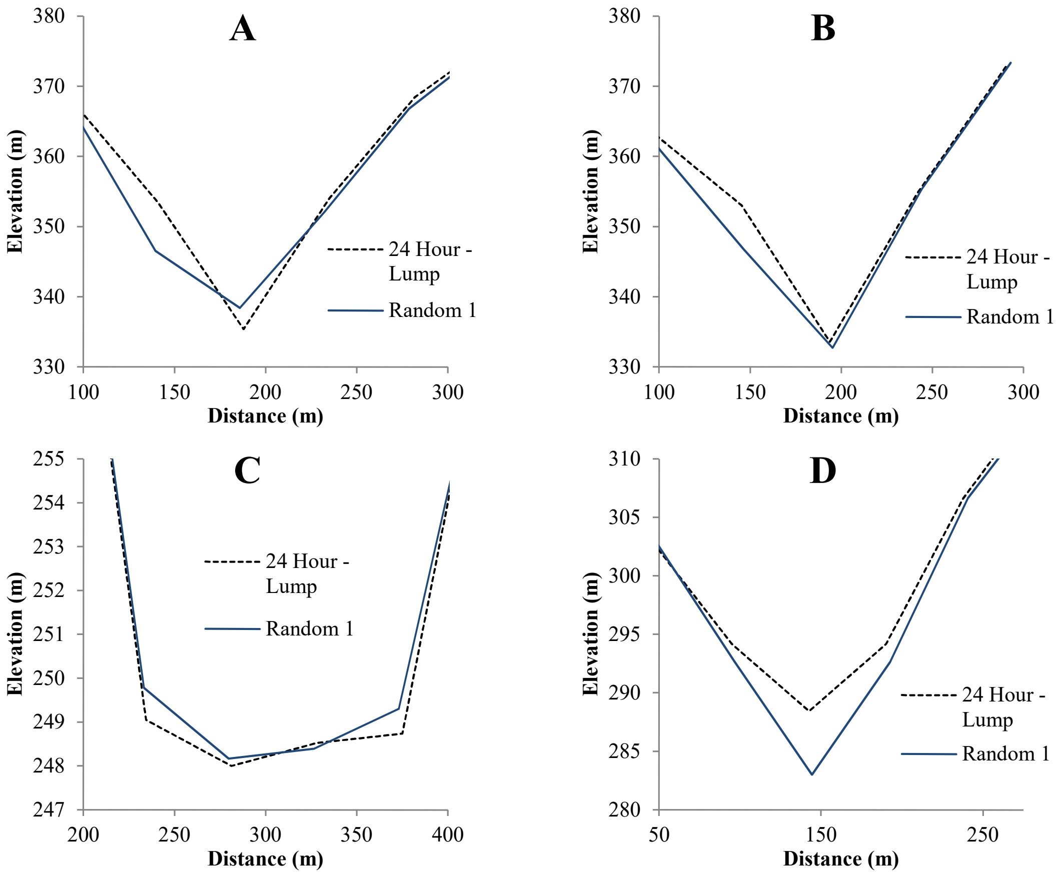

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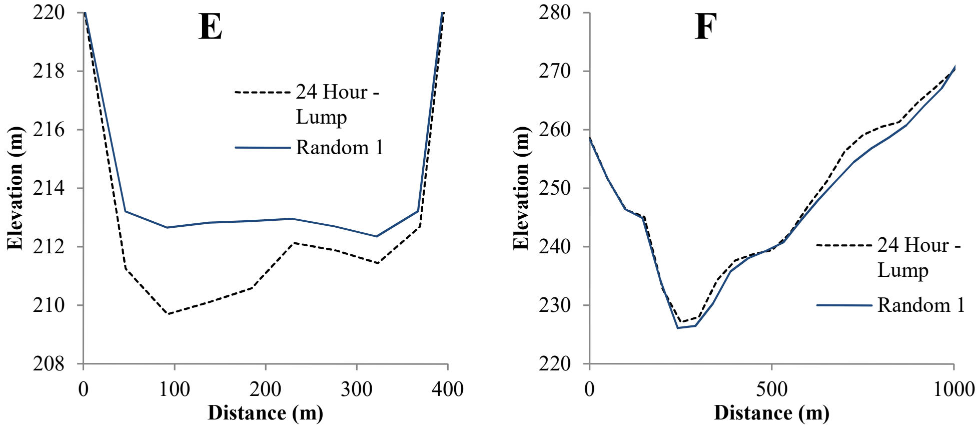

Figure 3. Cross sections identified in Figure 2.

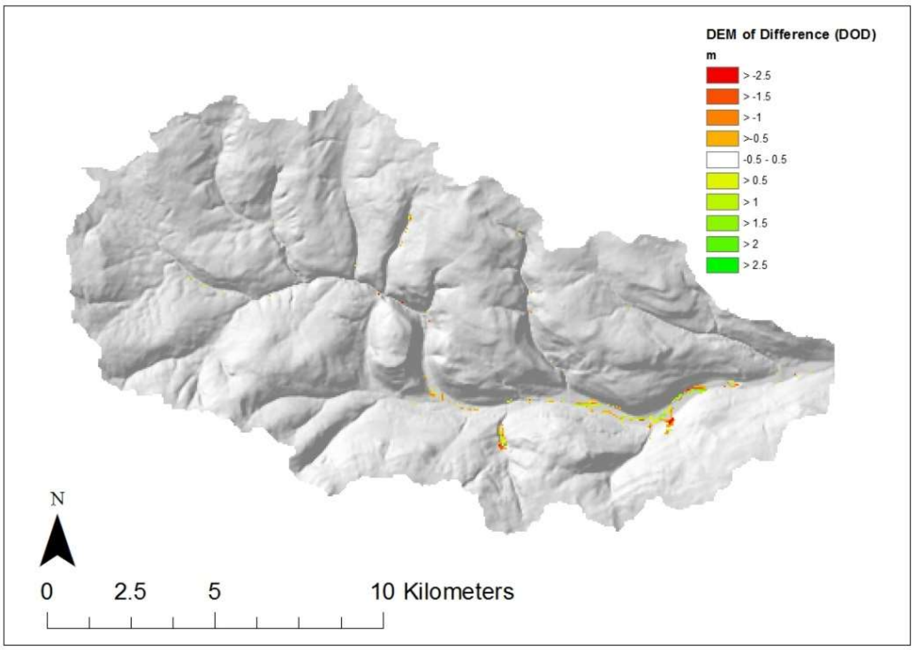

Figure 4. DEM of difference between 1000 year random runs 1 and 2.

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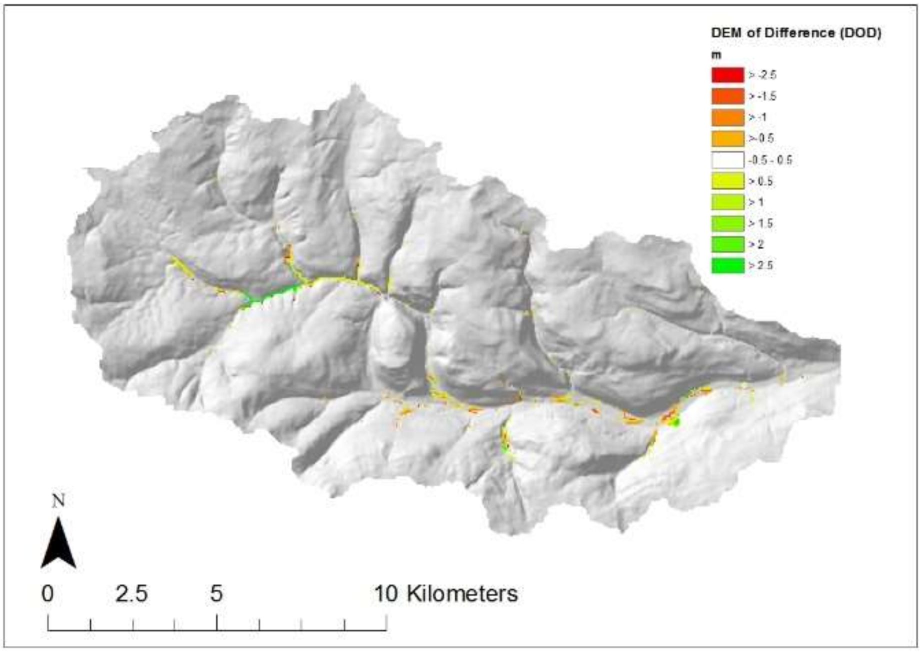

Figure 5. DEM's of Difference (DOD) between 1000 year random 1 and the 0.25 hour 5km resolution simulation.

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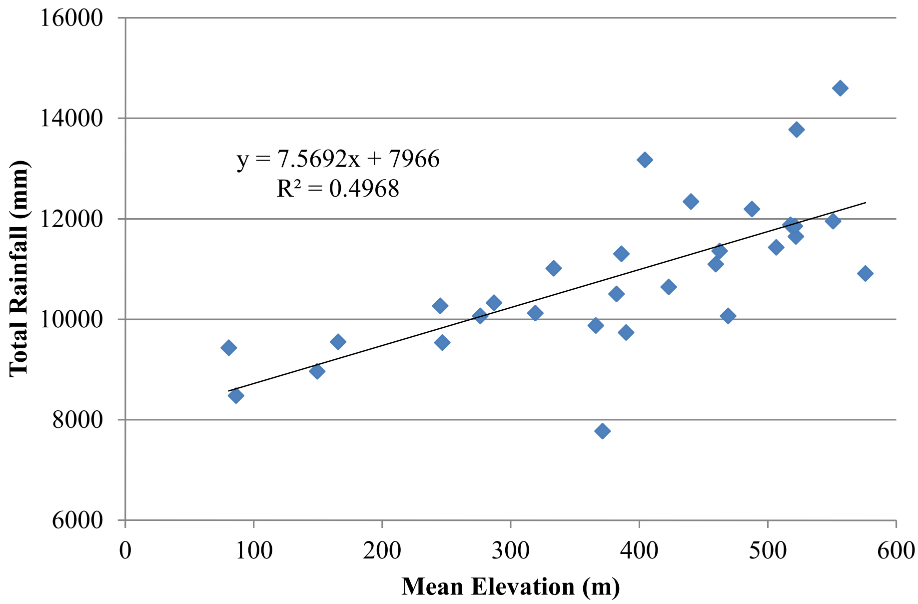

Figure 6. Relationship between the total rainfall and mean elevation for each 5 km pixel within the Complete Swale basin.

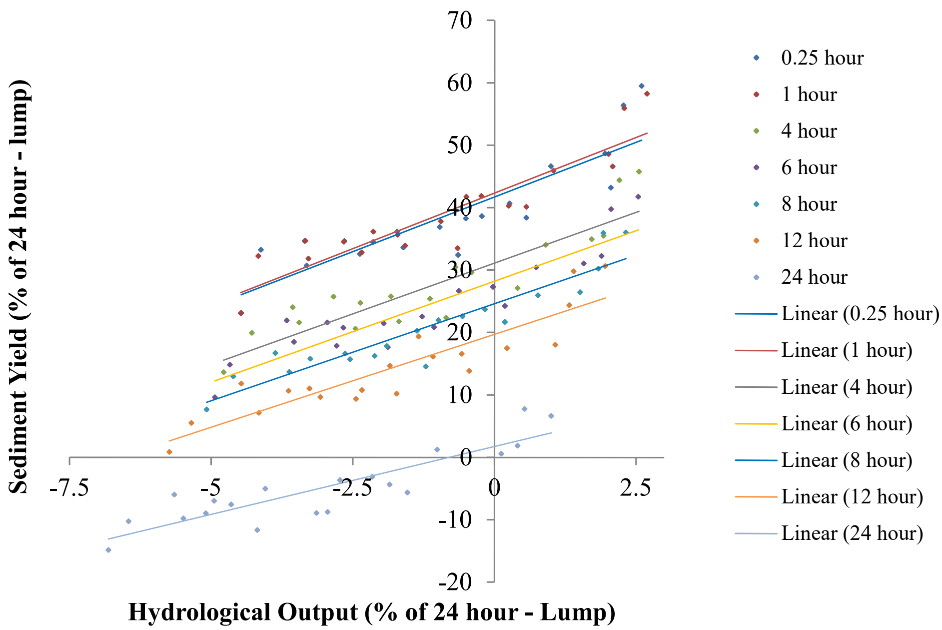

Figure 7. The relationship between hydrological output and sediment yield from each temporal resolution, based on outputs of the 20 jumble ensembles of the Upper Swale catchment.