Dear authors,

My apologies that it took a while to post this which is due to a misunderstanding. I think you have received two insightful reviews of the manuscript that you submitted. In my view the paper can be published in ESurf if these remarks (and the ones suggested by Declan Valters) are accounted for in a revised version. The main comment of ref. 1 relates to the potential interaction of soil properties and resolution. I most certainly agree with the fact that this is a valid point that should be dealt with in a revised manuscript. However, it is in my view not necessary to carry out a large number of additional simulations to investigate this as this would be a different research topic altogether. I do think though that you should discuss this issue (and its potential implications) in a revised version of the MS. You already addressed the issue along those lines in an author comment that can form the basis for the rewriting of this part of the MS

Reviewer #2 has concerns with the way you deal with increased temporal rainfall resolution. As erosion is indeed a non-linear function of discharge/rainfall intensity nonlinear effects are indeed to be expected. Reading your MS I do feel these remarks are important but may partially be caused by a misunderstanding of the procedure you used and of the aims of your study, which focuses on spatial patterns rather than total erosion amounts. Please clarify this in a revised manuscript: I am sure that this will also be of great help to other researchers who want to better understand your research.

Kind regards,

Gerard Govers, Associate Editor

Thank you for the comments and guidance. We apologise for the delay in the response – the questions posed and additional work carried out proved quite complex to blend with the original manuscript resulting in many changes – that we think improve the paper considerably.

We have added text and references to acknowledge the points made by Reviewer 1 – which are important, but we feel beyond the scope of this paper. In line with Reviewer 1 we have made some major changes removing the section on basin size comparison and shifting the orographic effects section to the methods/results rather than being in the discussion.

For Reviewer 2 we carried out a number of additional simulations to address the question as to whether or not any differences in sediment yield could be calibrated or adjusted for. This was indeed possible, but showed interesting, and important spatial changes in erosion and deposition patterns that were due to this adjustment/calibration process. We felt these were both important and built upon the aims and objectives of the paper. All changes are described fully in the responses to the reviewers and highlighted in the tracked changes MS submitted.

Best wishes, Tom Coulthard and Chris Skinner

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

Reviewer 1 Comments

This paper deals with a very interesting and relevant question for the scientific community working on sediment transfers in mesoscale river basins: how do the spatial and temporal resolution of the meteorological forcing impact modelled sediment yields? While this issue has already been addressed from a purely hydrological standpoint, it remains understudied in modelling approach dealing with landscape evolution and soil erosion. However it seems to me that the conclusions raised by the authors are not supported by enough simulations. My main concern is about the potential effect of changes in soil hydrological properties (spatially and temporally) as the spatiotemporal resolution of rainfall is changed. This is not at all considered by the authors in their simulations while they recognise at the end of the discussion that it may change considerably the sensitivity of landscape evolution models to rainfall resolution. As hydrological properties might be scale-dependant, changing only the spatiotemporal resolution of rainfall between runs without considering potential scale interactions between rainfall and soil behaviour may lead to erroneous conclusions on the sensitivity of landscape models. I know that adding runs in which the soil properties are randomly changed (m and K parameters) will need considerable additional computation time but the conclusions of the paper would be more supported and strengthened.

We would like to thank the reviewer for their comments and thorough review. Aside from typo's and other minor points/clarifications, the main point the reviewer asks us to address is the interaction with soil properties and the balance between precipitation (P) and infiltration (I).

We agree completely with the reviewer that soil and land use properties might influence our results. However, the focus of this study is to examine just the impact of spatial and temporal rainfall resolution. In our parameterisation, hydrological factors that will change spatially are deliberately treated globally so we can look solely at the role of rainfall resolution. The experimental set up (e.g. having different hydrological areas defined by the rainfall grid resolution) is contingent upon the deliberately limited research questions we are asking – and to look at both soil properties and rainfall resolution would, we suggest, require a completely different model set up.

We believe that it is important to consider that basin hydrology – both in terms of soil properties – and the driving precipitation – is often dealt with incredibly simplistically in LEM's, if at all! Therefore, our motivation is to explore not just the sensitivity to resolution – but to show the difference between having no representation and some representation of a distributed hydrology in LEM's.

Since this paper was first submitted – we have also submitted (and now published in early view) an article that takes a tightly constrained look at the impact of spatial changes in the TOPMODEL m value on the geomorphic outputs over longer time scales (Coulthard & Van De Wiel, 2016). *There is certainly a place for a study looking at both together. This could be* *looking at a combination of the two approaches opens up the CAESAR-Lisflood model to a framework of modelling using Hydrological Response Units (HRU), a common approach in semi-distributed hydrological models, such as Dynamic-TOPMODEL and SWAT. This allows rainfall, land cover and soil properties to be represented at higher resolution than a global lumped estimate, but divided into broadly hydrologically homogenous regions.*

Whilst we have not carried out any additional research to answer the points raised by the reviewer above and below, we certainly accept their validity – and have added a section to the discussion/limitations section

Coulthard, T. J., & Van De Wiel, M. J. (2016). Modelling long term basin scale sediment connectivity, driven by spatial land use changes. Geomorphology. http://doi.org/10.1016/j.geomorph.2016.05.027

Concerning the structure of the manuscript, the result section is very short and could be expanded, particularly if additional simulations are presented. The discussion section is rather heterogeneous in answering the 3 research questions written in the introduction. Section 4.2, addressing question 2, is very short and does not fully address it, as the authors recognise that more simulations would be required. Also Section 4.3, addressing question 3, is not supported by the data (no reference to them). I would suggest focusing the results and the discussion on question 1.

We have changed the research questions – and dropped number 2.

If this question is fully addressed according to the above mentioned issues dealing with the hydrological basin properties, this would represent a substantial contribution to earth surface mass transfers. For those reasons, I do not recommend acceptance of the manuscript in its present form.
Specific remarks:
P2 L31-33: “Improved model performance” is not only “tempered by increased uncertainty surrounding precipitation data”, but by the uncertainty in the budget of precipitation (P) versus infiltration (I) or storage in the soil.
P3 L8-9: I fully agree with the authors here. This also refers to the ability to simulate correctly P-I budgets, spatially and temporally. As argued in the general comments, the authors should try to address that issue in their numerical sensitivity analysis.

See first comment. There is of course a need to look at the sensitivity of models to both spatial and temporal changes in precipitation AND land use – but in this paper we have focused on just one. This is to (a) make the experimental design simpler and (b) because spatial changes in land cover is really a different research/science question that we have answered in a subsequent paper.

P4 L30: I found the description of the model spatial discretisation quite confusing (not sure to have completely understood yet), mentioning here "area lumped parameters" and later (P5 L18) "grid cell size Dx" without giving any typical size for Dx. Is it the DEM resolution (50m) mentioned

Changed to say 50m.

P7 L31? Could the authors try to be more specific on spatial discretisation and if possible limit the reference to previous papers to very specific model details that are not essential for that study?

There are no references in this paragraph, the three before or the two

P6 L1-3: As far as I understand, the hydrological model is adapted to the rainfall grid. Thus I agree with the authors that it enables having different levels of storage and runoff in each cell, but only due to rainfall variations. Varying also m and K would also create variations (i.e. P-I budget), but the authors kept constant those parameters (P8 L3).

This is true - but the cells do not cover hydrologically homogenous areas and values of m and k would be difficult to determine. m and k are not scale dependent, therefore the use of global values here is justified, yet we acknowledge that adjusting these values to local conditions will change the outputs - this is beyond the scope of this study (which is motivated only by rainfall resolution).

P7 L29: How can the authors be confident in their conclusions with only 2 additional long term random simulations?

In each random scenario the rainfall distribution was reshuffled every ten years, producing a significant element of randomness to the full 1000 year record simulated. However, both these two random runs produced similar results to each other. Additional random scenarios could be run, yet this is computationally expensive and would yield similar results. The random runs were motivated by wanting to disrupt the spatial pattern in the ten year record, which is repeated 100 times in the long term runs - in reality, we could have been confident with just one test as this achieved this, but the only very minor variations between the two reinforce this further.

We can see that this may not be clear from the text – so this has been clarified in the methods section. Part of this is trying to explain how methods evolved in response to results – but within the methods section!

P8 L1 : Which initial grainsize distribution was used to run the 30 year model used as an initial condition? Which grain sizes are given in Table 3?

The grainsizes in Table 3 are those used to initialise the model with a global distribution, which was then spun up using a thirty year simulation. The spun-up grain size distribution was used for the tests. Text has been added to make this much clearer.

P8 L16: “considerable differences”: this is not new and references should be given to situate these data.

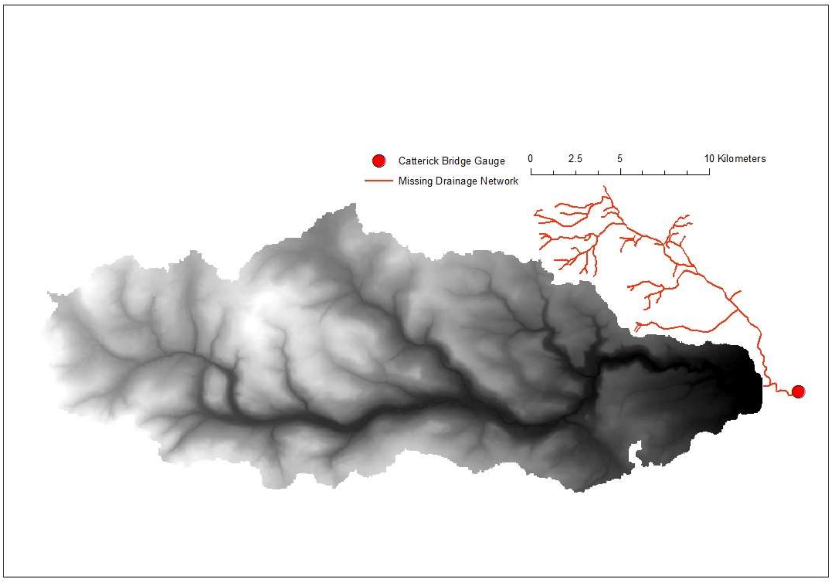
Yes - this well established and long been understood. Line 16 has been altered in the manuscript to make this clearer.

P8 L21-23: I agree that these changes are minor. Could they be significantly different if m and K parameters were also randomly changed from one run to another?

Possibly, but as previously mentioned that is not the aim of this study.

P8 L28: “also drains an additional tributary”. This may be critical. What is the drainage area of this tributary? How are the authors confident with that comparison between model and measurements?

The purpose of the hydrology tests was not to assess the model's performance and skill at estimating the hydrological conditions, but to demonstrate the effects on the hydrology when driving the model with different resolutions of input data. We believe that the data presented do this effectively.



The image above shows the full extent of the Swale catchment we have used, plus the location of the Catterick Bridge gauge station and the missing drainage network. The system is predominantly Gilling Beck , which becomes Skeeby Beck before entering the River Swale. The information for the Catterick Bridge Gauge station (http://nrfa.ceh.ac.uk/data/station/info/27090) states it has a draingage area of 499.4km^2 - of which, the Complete Swale DEM is 415km^2 - so the missing area covers 17% of the drainage area. It's overall contribution to the discharge of the River Swale is not known.

P9 L11 : Very little difference is observed between random 1 and 2. This relates to a previous comment. Are 2 random simulations enough? Why not having done more, as presented later with the jumbled runs (P10 L9) for answering another question. Could these differences be more important if additional random simulations were performed? Otherwise this result (little difference) contradicts somehow with the results in Figure 7 showing a great dependence of the sediment yield to the rainfall allocation. Overall, it seems to me that the authors tried to address too many questions in the paper without running enough simulations to address each of them.

The jumble runs involve the shuffling of the rainfall distribution just the once. Random 1 and 2 each involve 100 reshuffles of the rainfall distribution and therefore include a higher degree of randomness. They are akin to carrying out 100 10 year re-shuffled simulations. So we were happy with their results – and the simple comparison of Random 1 and 2 showed they were performing correctly. If these runs had involved a single shuffling at the beginning of the 1000 year then we would expect that each run would show much greater difference in the erosion patterns seen.

P10 L8-9: if this issue is so important, it should be introduced as an objective of the paper. As written it appears like an additional side issue. The description of these jumbled runs should be added in the method section and removed from the discussion.

This has been changed. Moved to methods/results and removed from discussion.

P10 L5-10: I fully agree with the authors that it is a major limitation to this study. Thus I recommend the authors to try to assess how m and Ks variations could impact the sensitivity analysis as it will help to generalize their findings.
We believe that Reviewer 1 is referring to Page 12 here. The CAESAR-Lisflood model does not presently allow for a variable K value. This study looks solely at the influence of the rainfall input resolution on the modelled sediment yields and geomorphology of the catchment. By allowing for spatial variation of m and K as suggested, this would add a further variable from the standard approach of using a global value for these parameters. It is our belief that, although it would be an interesting avenue of investigation (indeed, similar work by one of the authors has recently been published in this area), it would only confuse the purpose of the investigation in this manuscript.

P10 L10: Why 20 different records? Does this number has an impact on the range covered in Figure 7 (i.e. from -7 to 2,5% for X-axis and from -15 to 60% for Y-axis)?

Twenty was chose as there are 20 rain cells in this domain -and this showed a clear pattern, as would have with ten. Running for 100 tests might extend the range covered in Figure 7, but not the step difference between the temporal resolutions which was the point of the Jumble tests.

P18 Table 3: Evaporation was set to 0. How does it impact the conclusions? K is missing in this table.

K is not a variable parameter in C-L - Evaporation was set to 0, yet this was constant throughout the tests. It will make a small difference, as would including the vegetation parameters or a bedrock layer making the region transport limited. This needs to be viewed as a conceptual sensitivity test into rainfall resolution alone. Varying other factors is beyond the scope of this study.

P27 Figure 6: Total rainfall : The authors should specify over how many years.

Over the available NIMROD record (ten years).

P28 Figure 7: Why was this analysis done on the upper Swale only? The complete basin is characterised by more rainfall cells and would have probably exhibited more variations in the random redistribution of rainfall (see author's comment in section 4.2, line 5). I find this figure very interesting in addition to the results from Table 8 for example, as it clearly shows the impact of the jumbled runs. This sensitivity of the sediment yield to different spatial and temporal distribution of the rainfall raises again the question : would this sensitivity be the same if also m and K parameters were included in a wider jumbled run numerical analysis.

Computational efficiency was the main reason. This involved 160 tests - each taking roughly 8 hours for the upper Swale, and 2 - 3 days for the Complete Swale. Also consistency - the majority of the additional tests (1000 year, Random 1 and 2) were conducted using the Upper Swale. We have added a note to indicate that long model run times restricted how many simulations we could carry out.

Again, we feel the global values for m and K are justified for this study for reasons stated previously throughout the response. By varying the values in each cell, it would make it difficult to disentangle the influence of the rainfall resolution, and the influence of varying these values.

Technical correction:
P2 L15 : delete reference at the end of the sentence
Done
P3 L19-20 : can not find those three references in the reference list
Thank you – they had been manually added not in the referencing SW!
P3 L28 : Coulthard et al. (2013a)
this reference seems correct ?
P5 L4 : Add units for Qtot P6 L11-13 : n (Manning) is missing in the list
Added.
P7 L29: were then compared
Thank you.
P28 Figure 7: homogenize the colors for 6 hour (yellow and purple)
Changed.

The sensitivity of landscape evolution models to spatial and temporal rainfall resolution:
Reviewer 2 Comments

We have made considerable changes to the MS based on this review – both including a number of additional references and in a series of new simulations to address the final point made by the reviewer. These are detailed below and in the revised MS.

This paper examines the effect of temporal and spatial resolution has the erosion and landform evolution predictions of a LEM. The broad conclusions of the paper are a worthwhile contribution but the discussion misses some important points and previous work, and misrepresents previous work by other authors.

We would like to thank the reviewer for their comments and to apologise for completely missing developments made by previous authors. Some of the comments by the reviewer refer to unpublished research examining the role of temporal rainfall resolution – and make complete sense as does the thought experiment outlined in the review. However, it is difficult to reference unpublished findings, but we have looked in some detail at the SIBERIA literature, finding a relevant section in a user manual and used this accordingly in the revised MS. The calibration process outlined in the Willgoose and Riley (1998) paper makes no direct reference to rainfall resolution – but having read the reviewers comments – and re-read the paper sections it is clear that this is part of the calibration process. We have added sections and re-worked parts of the paper to clearly acknowledge this. Our findings (with regard to temporal rainfall precipitation) certainly agree with those mentioned above – and this is duly noted.

We considered removing the temporal component of the model comparison and focusing on the spatial in the revised MS, but thought that our experiments still contained an important contribution as it looked at how the relationship changed through different resolutions as well as over different basins. Additionally it also allowed the combination of spatial and temporal rainfall resolution to be examined. Therefore, it represents a systematic investigation into rainfall spatial and temporal resolution.

First looking at the question of spatial resolution. It's rather hard to judge the results without some idea of what the spatial pattern of rainfall is in the 10 year record and how persistent this pattern is over the 10 year period. A couple of thought experiments will clarify my concerns.

1. Imagine now that the pattern remains exactly the same over the 10 year period (i.e. the amount of rainfall over the catchment changes from year to year, but the pattern of this rainfall is exactly the same form year to year). Then the random redistribution of rainfall in space will be completely invalid since what is required a random resampling of the rainfall in each year. This is an extreme case of orographic rainfall.

2. Imagine now that the pattern is completely uncorrelated from year to year and from 5km pixel to 5km pixel. In this case the random redistribution will be OK and any changes will simply result in random noise in the erosion and landform results. The authors have failed to justify that the differences they observe are anything other than random effects.

We have to be careful to consider that in reality rainfall is not random. It does have patterns (spatial and temporal) – and some of these temporal patterns should be retained otherwise the resampled/ chopped record is meaningless. Therefore, we have not randomly re-sampled during the year – as the rainfall is made of 'events' – here largely associated with frontal rainfall. It would be unrealistic to distintangle these events – so you would (for example) have one pixel of heavy rain pop up in the middle of a dry spell. We have done this to a degree by spatially 'mixing' every 10 years – but the mixed pixels are still in temporal sync with each other. This could be broken down into annual mixing – but over a 1000 year simulation would that really give a different solution from our one? As figure 4 shows, there is relatively little difference between two of our random 1000 year simulations.

What we have done by spatially mixing the rain cells every 10 years in a 1000 year run, is to show the aggregate of 100 mixed up, 10 year simulations (its an easier way than showing an average if you like). By having different mixed up runs that give very similar results spatially and in bulk yields (Figure 4) – yet clearly different from the non mixed up results (figure 5) - we show that we can remove any spatial bias in the patterns of rainfall we are using in these 1000 year simulations. This means that we can compare 5km spatially distributed (randomly mixed spatially every 10 years) to lumped rainfall simulations over the same period.

A neater solution to this issue would be to use a synthetic rainfall generator that also simulates spatial patterns of rainfall. These exist, though are relatively new and less tested than non spatial rainfall generation methods (e.g. Peleg & Morin 2014)*. Here, this would significantly expand the work required, scope and aims of the paper (in effect, it is another paper).*

Peleg, N. & Morin, E., 2014. Stochastic convective rain-field simulation using a high-resolution synoptically conditioned weather generator (HiReS-WG). Water Resources Research, 50(3), pp.2124–2139. Available at: http://doi.wiley.com/10.1002/2013WR014836 [Accessed June 17, 2016].

The way the question about time resolution is posed shows a misunderstanding of some of the solutions that other workers have used to address the problems highlighted of differences in mean erosion rate observed by the authors. There is no question that high time resolution runoff series results in significantly increased in erosion rates. The reviewer has also seen this in his our erosion computations and the 100% increase from daily to 0.25 hour accords with our own, unpublished, experience. This is because of the nonlinear dependence of the erosion time series on the runoff time series. A simple first order second moment analysis of the erosion time series shows this.

Consider an erosion equation that is dependent on the square of discharge (approximately the dependency of Einstein-Brown sediment transport equation)

E=bQˆ2 (1)

If Q is now a random value with mean Q* and variance SQ. A second order first moment analysis of this equation yields

E=b(Q*ˆ2+SQ) (2)

So that the erosion is higher than that where there is no variation in Q by a factor

(1+SQ/Q*ˆ2) (3)

This analysis shows that the erosion rate when you allow for randomness versus where you average out the variability will always be higher and the percentage increase is a function of the coefficient if variation of the runoff series.

My own observation is that this factor can easily by a factor 2 going from a daily runoff series to a 15 minute runoff series for a small catchment (i.e. the erosion will increase by 100%). The appearance of variance in equation (2) comes solely from the square dependence in equation (1). If equation (1) were a power of 1 (i.e. linear) then the variance term does not appear and the sub-daily variability would have no impact on the mean erosion rate.

This is a really interesting way of breaking down the issue for temporal rainfall – in our representation, erosion (with the addition of various parameters) is roughly the square of the velocity – so a similar relationship. We would have liked to include a similar breakdown in the revised MS – but would not want to make this look like our thoughts (and we cannot readily cite reviews). Hopefully, the quote from the SIBERIA manual we have included covers part of this (certainly the last para above).

Finally, the authors quote Hancock papers (2000,2002,2010) as examples where the long time resolution of the timesteps in the landform evolution model will yield significant underestimates of the erosion. This assertion is categorically incorrect and reflects a lack of understanding of how the model parameters were developed for these papers. I'm surprised at this because the first author has been collaborating for some time with Hancock. The parameters used in the Hancock papers are based on a calibration procedure described in Willgoose and Riley (1993,1998) Willgoose, G. R., and S. J. Riley (1993), Application of a catchment evolution model to the prediction of long-term erosion on the spoil heap at Ranger Uranium MineRep. Open File Report 107, The Office of the Supervising Scientist, Jabiru. Willgoose, G. R., and S. J. Riley (1998), An assessment of the long-term erosional stability of a proposed mine rehabilitation, Earth Surface Processes and Landforms, 23, 237-259.

In brief this process was 1. A conceptual rainfall-runoff model (with much the same capability as LISFLOOD) was calibrated to rainfall-runoff-erosion plot studies at the time and space resolution of the data (minutes and 100 sq metres) 2. A multiple regression was developed between sediment load, discharge and slope from the plot studies. 3. The rainfall-runoff model was then scaled up to the landform using a low resolution DEM of the site (about 1000 nodes) and 30 years of pluviograph data at 15 minute resolution was used to generate a 30 year runoff time series. 4. This 15 minute resolution time series was then used to generate a 15 minute sediment transport series using the regression. 5. This 15 minute erosion series was then lumped up to the annual level and "effective" parameters where developed that gave the same average and area and slope dependence at the yearly time step as the 15 minutes erosion time series. These are the parameters that are used in the annual time steps.

Now there is no doubt this was an extremely compute intensive task. In 1992 when this work was done it took about 4 weeks of CPU time on a high end workstation to generate the time series in step 3. This calibration has been used as the basis for other sites studied by Hancock.

The key difference between what was done by Willgoose and Riley (1998) (hereafter W&R) and in this paper is that the authors have explicitly included the randomness of the hydrology timeseries within the LEM, while in W&R this has been averaged out in the derivation of the effective parameters.
Finally on bottom of p10 and top of p11 the author contemplates whether there is a "compensatory factor or exponent". Indeed this is what the "effective parameters" in the approach of W&R do.
So in conclusion if we go to the plots of changes when using different averaging periods, the lower erosion rate observed by the author for low resolution rainfall is to be expected. But this can be adjusted by the use of "effective parameters" as done in W&R.

The more interesting question, but unfortunately not addressed by the authors, is if the average erosion rate for all the different time resolutions were adjusted to give the same annual erosion are the landforms generated significantly different (i.e. does the higher rainfall resolution and explicit modelling of runoff events lead to fundamental differences beyond a general change in the calculated mean erosion rate).

This *is* a really interesting question – and we are grateful for the reviewer for suggesting this. In the revised MS we have now done just this – to adjust model runs (via a compensation factor in the sediment transport law) so very similar sediment yields (erosion rates) are generated over 1000 year simulations. Rather than try and tune all our simulations to the same erosion rate (and therefore to reduce the number of simulations needed) we adjusted some simulations (e.g. 15 min lumped) too match existing results (e.g. 24 hour lumped). This required an additional 30 simulations – each taking 4-8 weeks. This generated some really interesting findings – and as the reviewer suggested – does lead to considerable differences in the spatial patterns of erosion and deposition found within the basin.

These simulations and research, have resulted (in the paper) in additional sections in the methods, results, discussion and conclusions – and we think they significantly enhance the paper and its findings.

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

T. J. Coulthard[1] and C. J. Skinner[1]

[1]Department of Geography, Environment and Earth Sciences, University of Hull, U.K.

Correspondence to: Tom Coulthard (T.Coulthard@hull.ac.uk)

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 erosion and deposition, topography and the final shape of LEM landscapes? This paper presents results from the first systematic investigation into how the spatial and temporal resolution of precipitation affects LEM simulations of sediment yields and patterns of erosion and deposition. This is carried out by assessing~~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 - Lump~~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 finest~~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. Additional research indicated that these differences in sediment yield could be accounted for by adding a compensation factor to the model sediment transport law. However, this resulted in notable differences in the topographies generated, especially in third order and higher streams. The implications of these findings are that uncalibrated past and present LEMs using lumped and time averaged climate inputs may be under-predicting basin sediment yields, under-predicting ~~as well upland~~ erosion in first order streams but over predicting erosion in second, third order streams and valley floor areas. Calibrated LEMs may give correct sediment yields but patterns of erosion and~~and downstream~~ deposition will be different and the calibration may not be correct for changing climates. This~~- that~~ may have significant impacts on the modelled basin profile and shape from long time scale simulations.

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 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. For the SIBERIA LEM, Willgoose and Riley (1998) and Willgoose (2005) use a scaling approach to calibrate the ‘effective parameters’ for SIBERIA, where they measure runoff and sediment erosion at a high temporal resolution in test plots and use this to calibrate a relationship to mean annual sediment transport. Though not explicitly stated, this method accounts for changes in sediment yield due to temporal precipitation resolution, though measures and accounts for this only in terms of bulk basin sediment yields. Nonetheless, the impact of finer temporal resolution data is important as Willgoose (2005; page 84) states *“"It is possible for this temporal resolution error in the simulated erosion record to be as much as an order of magnitude in size".*

~~(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)~~(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 do~~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 – basin *morphodynamics*~~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 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., 2016; 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.

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This raises the following~~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. Can any differences in sediment yield~~As data resolution is often a compromise between availability~~ and erosion and deposition patterns due to~~applicability, are there optimum, or ideal~~ spatial and temporal precipitation resolution be accounted~~resolutions? And how do these change~~ for via adjustment or calibration~~basins~~ of model parameters~~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} in m^3.s^{-1}); ~~)~~ 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:

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

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

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 that here is 50m (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 can~~could~~ already use precipitation data over a range of temporal resolutions~~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). Though 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 and n is Manning roughness coefficient.

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)~~Einstein (1950)~~ or as here used Wilcock and Crowe (2003) methods.~~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 the UK Composite NIMROD rainfall radar (Met Office, 2003)~~(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}. The maximum available~~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 absolute role~~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, as 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, to disrupt any spatial pattern legacies, 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). Only two random simulations were carried out, due to long model run times and as these random runs gave very similar results. Results from the two long term simulations were~~where~~ then compared against both of these random simulations.

One aim of this research is to see whether any changes in sediment yields and erosion and deposition patterns due to the spatial or temporal resolution of the precipitation could be accounted for by adjusting model parameters. To investigate this three series of comparison runs were carried out – where a factor was added to the sediment transport model to allow erosion totals to be adjusted to match. This allowed us to normalise the sediment yields from the simulations being compared, with the aim of observing any differences in spatial patterns of erosion and deposition in the DEMs. The following three sets of comparisons were carried out: to compare patterns of erosion and deposition for temporal resolution changes 0.25 hour - Lump vs 0.25 hour - 5 km); spatial resolution changes (24 hour - Lump vs 0.25 hour - Lump); and temporal and spatial resolutions (24 hour - Lump vs 0.25 hour - 5 km).

In order to adjust the sediment output, an additional term or compensation factor C was added to the Wilcock and Crowe, (2003) sediment transport formula used here, as shown in equation 5 below (as fully described in Van De Wiel et al., (2007) . Here, q_i is the sediment transport rate in m^{3}s^{-1}, g is gravitational acceleration (m s^{-2}), ρ_s and ρ are the density of sediment and water respectively, F_i is the fractional volume of the i-th sediment in the top active layer, U_* is the shear velocity ($U_* = [\tau/\rho]^{0.5}$) and W_i^* is a function that relates the fractional transport rate to the total transport rate.

$$q_i = C \frac{F_i U_*^3 W_i^*}{((\rho_s - \rho) - 1)g}$$

For each of the three comparisons identified above (e.g. 24 hour - Lump, 0.25 hour - 5 km and 0.25 hour - Lump) runs were carried out varying C from 1 to 2.5 in increments of 0.1, resulting in an additional thirty 1000 year simulations. After this, the closest matching sediment yields over the 1000 years were used to compare differences in spatial patterns of erosion and deposition.

A final test, was to determine whether or changes in erosion and deposition were due to orographic effects. Previous research indicates a geomorphic sensitivity in the CAESAR model to rainfall magnitudes (Coulthard et al., 2012b) so it is therefore important to disentangle whether any increased erosion totals were 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.

All simulations were carried out over a 50 m resolution DEM, with no bedrock representation and no 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 pre-conditioned ‘spun up’ DEM ~~and grainsize distribution~~ generated by a 30 year model run using the 24 hour - Lump rainfall. This ‘spinning up’ process removes sharp gradient changes in the DEM that may be a legacy of its generation and also allows the model to evolve a surface channel grainsize distribution from the initial global distribution described in Table 3. 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. The 1000 year simulations were carried out for the upper Swale only, as the longest run times here were 4 weeks, compared to 8+ weeks for the whole Swale.

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 95th percentile (representing peaks) were calculated for both water (discharge rate $m^3.s^{-1}$) and sediment yield (m^3~~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 well understood (e.g. Tustison et al., 2001) and shown here~~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 differences~~changes~~. Looking at mean annual discharge (Table 5) there is an~~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 linked~~due~~ to finer temporal resolutions~~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 (Table 4).~~.~~

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 - these figures are not presented here as an assessment of the model's performance, but as an indication of the relative differences using different rainfall input resolutions.~~.~~

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 - 5 km~~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 3-5 m~~5m~~ additional incision at cross section B and 6m at cross section D, along with up to 3 m~~3m~~ of deposition at cross sections D and E. Interestingly these are not restricted to single channel threads, ~~but in particular~~ at E this occurs across some 350 m~~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 > 2.5 m~~5m~~ in the valley floor to the Western side of the basin along with smaller changes in the valley floor downstream.

For the 1000 year comparison runs, with the *temporal* comparison 24 hour - Lump simulations with a compensation factor of 2.0 gave sediment yields that were within 3 % of the 0.25 hour - Lump simulation. For *spatial*, 0.25 hour - Lump with a compensation factor of 1.1 gave yields within 4 % of 0.25 hour - 5 km simulations and for *spatial and temporal*, 24 hour - Lump with a compensation factor of 2.2 was within 5 % of the 0.25 hour - 5 km simulation. Figures 6, 7 and 8 describe the spatial patterns of the differences between the two final DEMs from these simulations. These show areas of greater difference in the lower half of the basin for different temporal resolution data, in the upper half of the basin for spatial resolution data and in both upper and lower for changes in spatial and temporal resolution. In each Figure a series of cross sections are highlighted to illustrate vertical changes.

For the simulations to test the impact of orography, Figure 9 shows there is a general, though not significant orographic relationship for rainfall intensity in the Swale. To indicate whether this has any effect on basin sediment yield, the results of the jumbled runs (Figure 10) show that as the temporal resolution of the rainfall increases, so does the hydrological and sediment totals 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 described previously.

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). Finer resolution (~~The effect of increasing the~~ spatial and temporal) ~~resolution of the~~ rainfall inputs can~~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 (Tables 8 and 9). Changes in rainfall resolution also alter~~. Looking at differences in~~ spatial patterns of erosion and deposition (Figures 2 and 3) with~~Figure 2), the impacts of different precipitation resolution is very apparent – where~~ increased local rainfall intensities (from finer~~afforded by higher~~ resolution data) leading ~~lead~~ to increased local runoff and thus increased~~increase~~ erosion in the smaller first and second order streams (Figure 2, cross sections B, D, F). Contrastingly, the lump simulations contain~~upland tributaries and headwaters. Further down~~ the cumulative of the spatially distributed rainfall and ~~basin, these effects are lessened as flood peaks diffuse downstream, and due to~~ this leads to greater amounts of erosion (and less~~and the increased sediment loads from upstream there are increased volumes~~ deposition) in 3rd order streams and the valley floor sections (e.g. Figure 3, cross sections A and~~section~~ E). The disproportionate relationship between changes in hydrology and erosion/deposition is highly important in this context, as small changes in hydrology (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.

~~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~~ For existing and previous LEM studies these results suggest that there may have been a systematic under-representation of basin wide sediment yields by using lumped and coarse temporal resolution climate/precipitation data. These is may not be of concern to many LEM studies, that are interested in exploring general relationships between processes, drivers and subsequent landscape change. However the spatial changes in erosion and deposition patterns generated by the different resolution rainfall data will affect results and findings. Over the 1000 years we have simulated in this study, the coarser resolution data leads to more incision/erosion in 3rd order and higher streams, with less in 1st and second. This has led to a change in the shape of the basin long profile - and thus when projected over even longer time scales will lead to changes in the shapes of predicted basins, landscapes and landforms. Resolving this is troublesome as for many existing models, especially those dealing with longer time scale simulations (e.g. > 10 000 years), incorporating high resolution precipitation data is impractical. The data is simply not available and generating synthetic rainfall complex. Therefore, can these changes in erosion and deposition patterns (and sediment yields) be compensated for via model adjustment rather than calibration?

4.2 Adjusting to compensate for spatial and temporal rainfall resolution effects

In our final set of 1000 year comparison runs, erosion and deposition totals were adjusted so simulations with different spatial and temporal rainfall resolutions could be compared. Sediment yields could easily be matched, however there were differences in erosion and deposition patterns produced by different temporal (Figure 6) and spatial resolutions (Figure 7). This indicates that such adjustment (similar to that carried out by Willgoose and Riley, 1998) can be carried out, but with some notable effects and possible limitations.

Adjusting for temporal changes in rainfall resolution led to good results in the upland, Western side of the basin, with very few areas where there were differences in erosion and deposition patterns greater than 0.5 m (Figure 6, cross section A). But with greater changes in the valley floor sections lower down, with more erosion/less deposition generated by the adjusted 24 hour resolution simulation (Figure 6 cross sections B and C). In the steeper upland areas a larger compensation factor (2.0) is required for the 24 hour rainfall to generate similar amounts of erosion as the more intense, flashier events from the 0.25 hour data. As the 2.0 compensation factor is applied globally, in the lower parts of the basin where there is less difference in flow magnitudes generated by the 0.25 and 24 hour runs, this leads to more erosion or less deposition.

Conversely, adjusting for spatial resolution leads to very small differences in the lower, Eastern sections (Figure 7, cross sections B and C) but major changes in the upland area with 8 m more erosion/less deposition from the adjusted lump simulation at Figure 7 cross section A. As for Figure 2, by lumping local rainfall heterogeneity there are smaller flows in first and second order streams, but greater in 3rd – leading to the incision at cross section A. Here the incision at A is greater than values shown in Figure 2 as the temporal resolution of the data is 0.25 hour rather than 24 hour. There are very few differences in the lower sections of the basin (Figure 7, cross sections B and C) as for both simulations here the flows will be the cumulative of the total basin rainfall (as rain cells are switched every 10 years in the 0.25 5km random simulation).

Adjusting for both (Figure 8) best represents how most LEMs may be adjusted for using coarser spatial and temporal resolution data. This comparison required our largest compensation factor (2.2) and generated patterns that could be described as a merging of Figures 6 and 7 – with more erosion/less deposition in cross sections A, B and C. As per the discussion for Figure 2, the coarser resolution data drives more erosion/less deposition in 3rd order streams and the valley floor – if continued for more thousands of years this would result in a considerably different long profile, which would change the morphometry of the basin.

However, there are further difficulties associated with adjusting models to compensate for different resolution data. For example, if we have a convective 4 hour event of 6 $\mathrm{mm.hr^{-1}}$ and a synoptic 24 hour event of 2$\mathrm{mm.hr^{-1}}$ then adjusting erosion rates for 24 hour resolution data would scale erosion from the convective storm down and the synoptic event up. This adjustment, however, would assume the same erosion/deposition relationship between our synoptic and convective event and in the context of climate change it is highly likely that this will change. For example, climate changes may lead to more or less rainfall as well as greater or lesser rainfall durations and intensities. In other words, the relationship between mean annual erosion rates and mean annual rainfall is non-stationary, yet here any adjustment or scaling factor is fixed. This could readily lead to "over-calibration", a phenomena noted by the hydrological community (Andréassian et al., 2012), where the parameters in hydrological models are adjusted too tightly based on too few observations. The issue of non-stationary calibration of parameters is also widely acknowledged in the hydrological modelling literature (for example, Beven, 2006) where the period simulated is far shorter, and therefore possibly less varied, than the longer time scales over which LEMs may operate.

In summary – the adjustment of model parameters can be used to compensate basin sediment yields for different resolution rainfall data, but there is an impact on patterns of erosion and deposition within the basin. Using such adjustments is likely to be basin specific and the correction will not be correct over changing climates. Calibration, the adjustment of sediment yields to match field data, will likely encounter the same issues. ~~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 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., 2016~~2015~~) showing that using the SIBERIA model, over 10 000 years different shape landscapes can evolve yet generate very similar sediment yields.

Field Code Changed

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. Basin hydrology is a balance between precipitation, evaporation, infiltration and groundwater effects. These processes are all spatially and temporally variable but we have quite deliberately only altered the rainfall to determine model sensitivity to just this parameter. Within CAESAR-Lisflood the TOPMODEL *m* parameter is used to account for evaporation, infiltration and groundwater effects and can also be changed spatially and temporally (Coulthard and Van De Wiel, 2016). Examining model sensitivity to both may be useful future research.

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., 2016).~~(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 simulated basin sediment yields~~whilst there is a relationship between hydrology~~ and spatial patterns of erosion and deposition are sensitive to the~~, importantly they have different sensitivities to~~ spatial and temporal resolutions of precipitation data used~~. Compared~~ to drive models. The impact of temporal changes is greater than spatial, though~~24 hour - Lump data,~~ using finer~~the highest~~ resolution data for both leads to significant increases in sediment outputs, with 0.25 hour - 5 km resolution~~rainfall~~ data leading~~can lead~~ to a doubling in basin ~~total~~ sediment yields over with the 24 hour - Lump data. These changes are due~~. This is linked~~ to finer resolution data generating increased erosion in upland and first order streams with increased deposition and aggradation in valley floors. Further~~ that over longer term~~ simulations indicated that these differences in sediment yield could be removed with a compensation/adjustment factor inserted in the sediment transport law. However, using such a factor resulted in notable differences in the topographies generated, especially in third order and higher streams. Overall, the implications of these findings are that uncalibrated past and present LEMs using coarse spatial and temporal resolution precipitation drivers may be under-predicting basin sediment yields, under-predicting erosion in first order streams but over predicting erosion in third order streams and valley floor areas. Calibrated LEMs may give correct sediment yields but patterns of erosion and deposition will be different and the calibration may not be correct for changing climates. It is highly likely this will have significant impacts on the modelled basin profile and shape from long time scale 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 using coarser resolution precipitation data.~~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

Table 5. The percentage deviations of the mean annual hydrological 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	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.

Complete Swale	24 hour	12 hour	8 hour	6 hour	4 hour	1 hour	0.25 hour
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

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

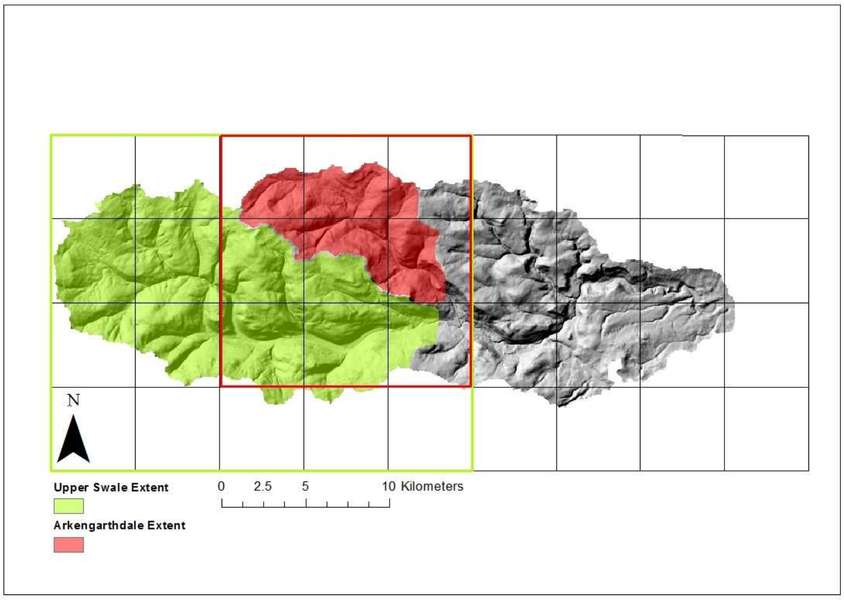
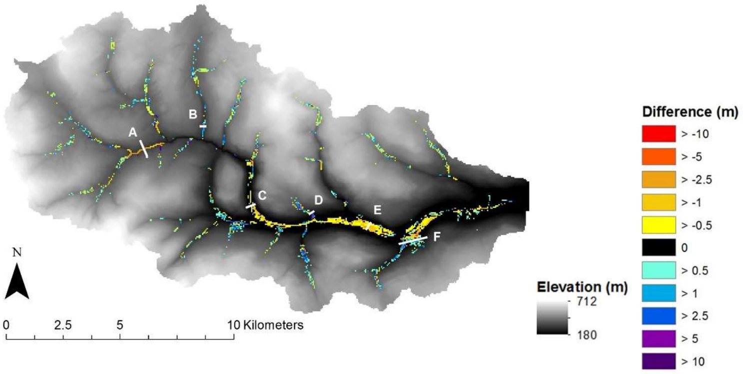


Figure 1. Map showing the extents of the three test basins with the Upper Swale in green, and the Arkengarthdale extent in red. Additionally the 5 km rain radar grid cells overlaying the three basins are shown – coloured according to the basins they cover.


A
B
C
D
E
F
N
0
2.5
5
10 Kilometers
Elevation (m)
712
180
Difference (m)
> -10
> -5
> -2.5
> -1
> -0.5
0
> 0.5
> 1
> 2.5
> 5
> 10

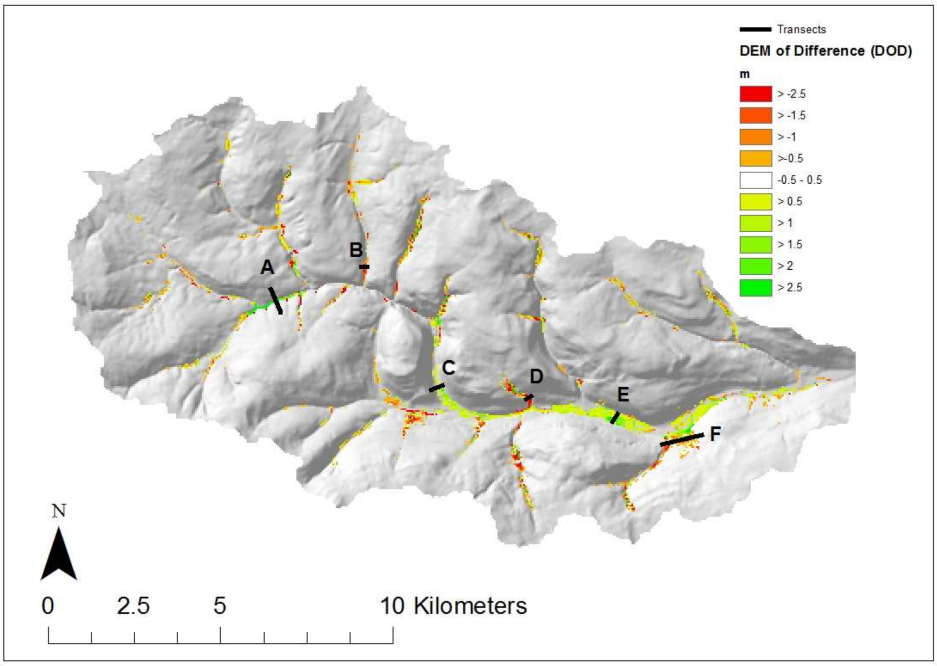
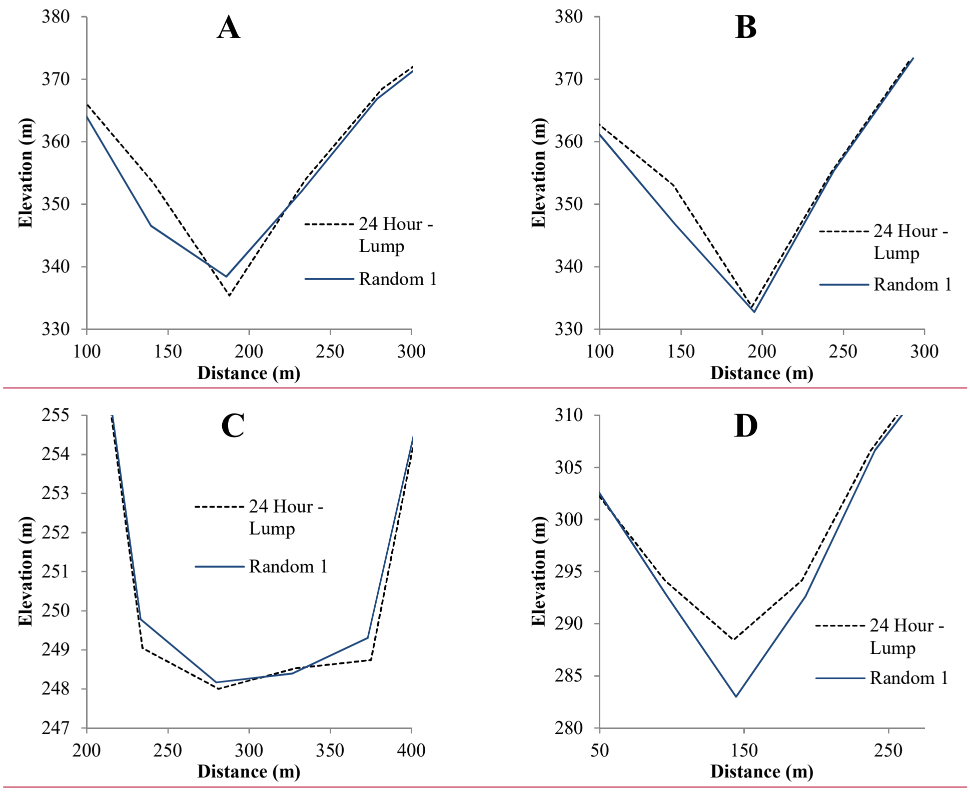
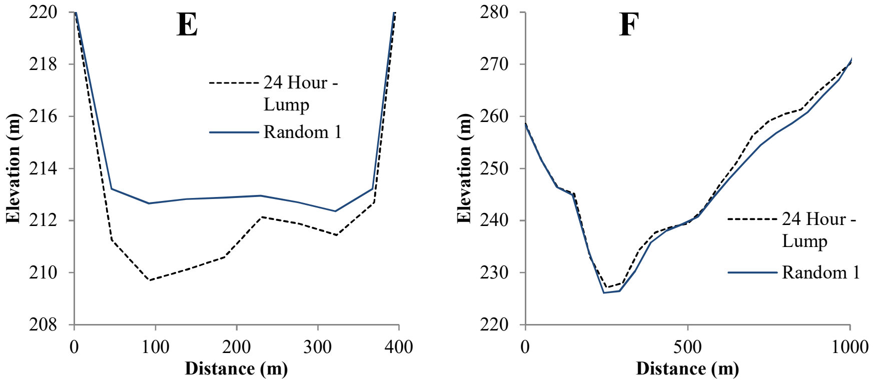
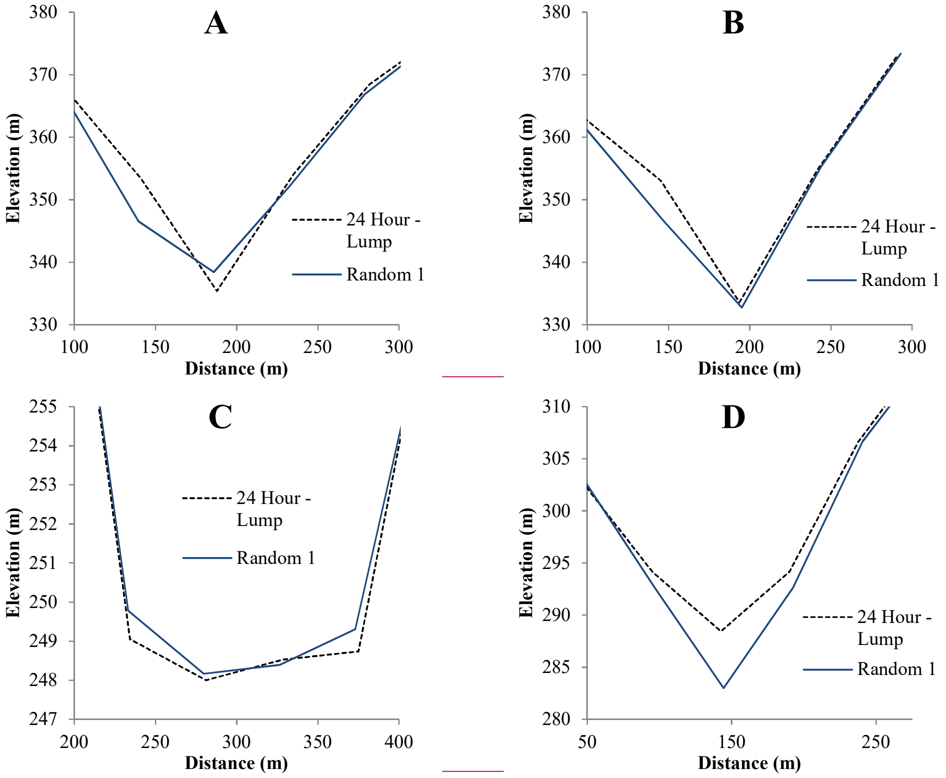


Figure 2. DEM of Difference for the 1000 Year Swale Test. The differences shown are elevations from the 24hour - Lump~~random 1~~ simulation minus the elevations from the random 1 0.25 hour - 5km.~~24hour-Lump simulation.~~ Cross sections (Figure 3) are marked A-F. Yellows to reds indicate where the first (24 hour – Lump) simulation has eroded more/deposited less than the second (random 1) simulation. Blues indicate more deposition/less erosion.


A
B
C
D
Elevation (m)
Distance (m)
380
370
360
350
340
330
100
150
200
250
300
255
254
253
252
251
250
249
248
247
400
310
305
300
295
290
285
280
50
24 Hour - Lump
Random 1


E
220
218
216
214
212
210
208
Elevation (m)
0
100
200
300
400
Distance (m)
24 Hour - Lump
Random 1
F
280
270
260
250
240
230
220
Elevation (m)
0
500
1000
Distance (m)
24 Hour - Lump
Random 1


A
B
C
D
Elevation (m)
Distance (m)
380
370
360
350
340
330
100
150
200
250
300
255
254
253
252
251
250
249
248
247
400
310
305
300
295
290
285
280
50
24 Hour - Lump
Random 1

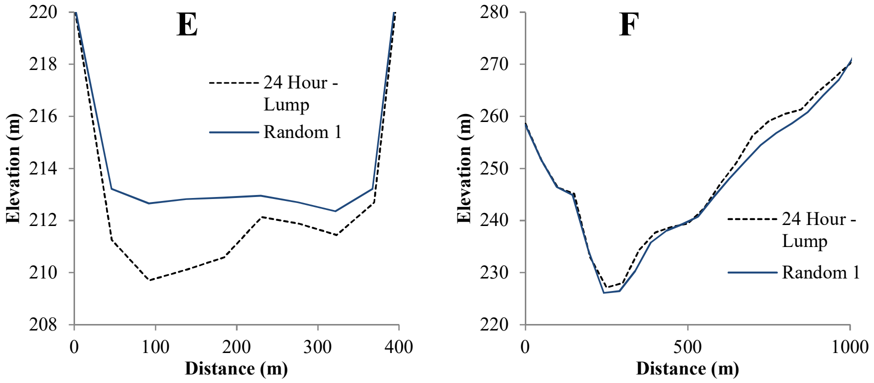
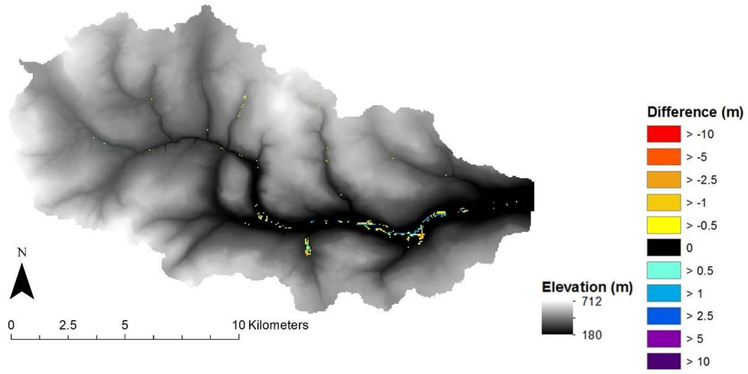


Figure 3. Cross sections identified in Figure 2.



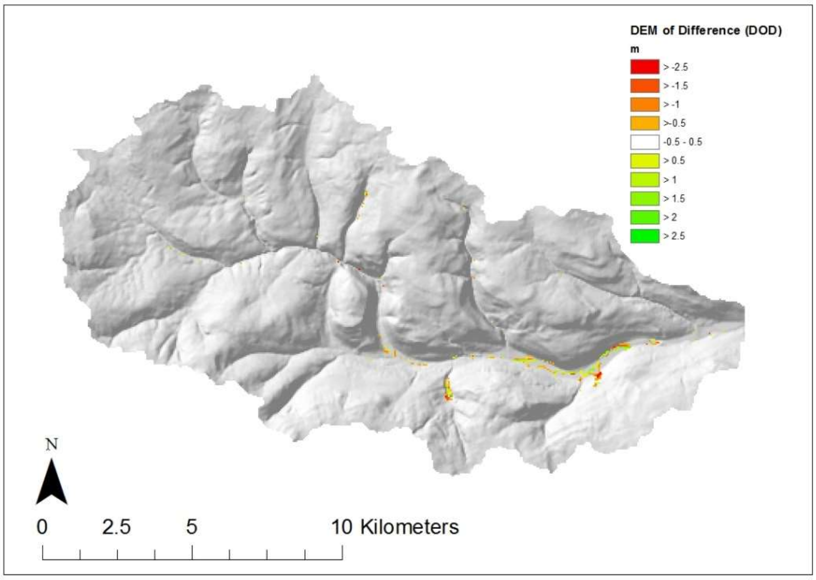
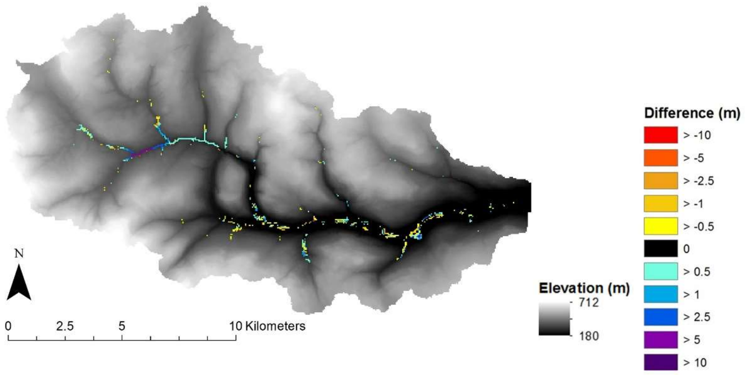


Figure 4. DEM of difference between 1000 year random runs 1 and 2.


Difference (m)
> -10
> -5
> -2.5
> -1
> -0.5
0
> 0.5
> 1
> 2.5
> 5
> 10
Elevation (m)
712
180
N
0
2.5
5
10 Kilometers

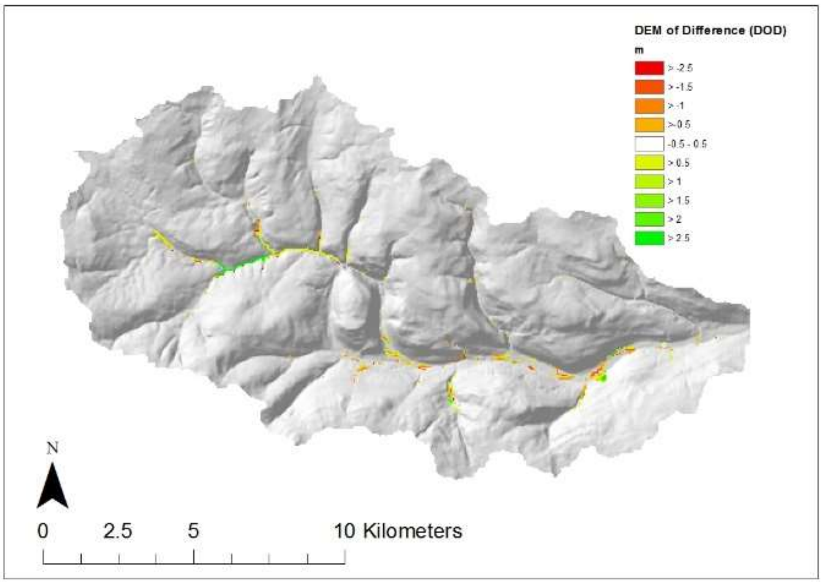


Figure 5. DEM~~DEM's~~ of Difference (DOD) between 1000 year random 1 and the 0.25 hour - 5km resolution simulation.

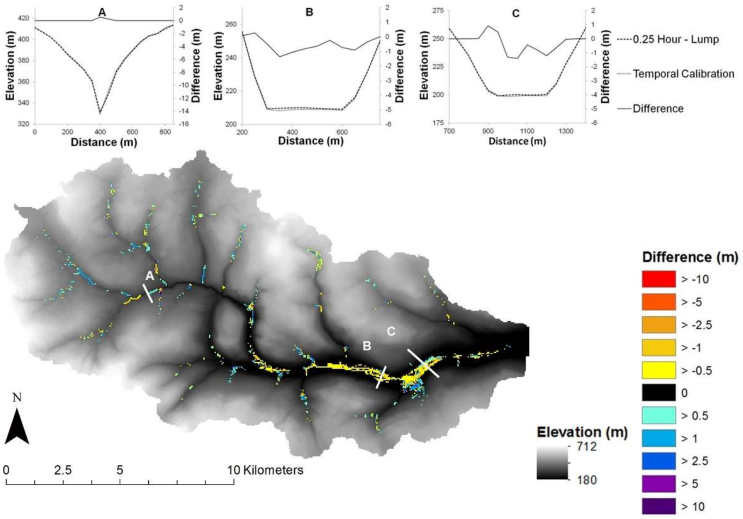


Figure 6. DEM of Difference for the adjusted temporal resolution comparison. The differences shown are elevations from the 24 hour - Lump (2.0 factor) simulation minus the elevations from the 0.25 hour - Lump. Yellows to reds indicate where the first (24 hour – Lump 2.0) simulation has eroded more/deposited less than the second (0.25 hour - lump) simulation. Blues indicate more deposition/less erosion.

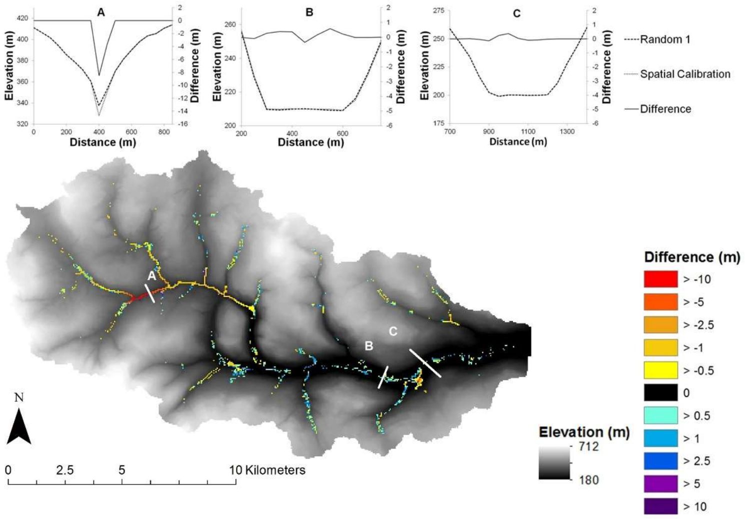


Figure 7. DEM of Difference for the adjusted spatial resolution comparison. The differences shown are elevations from the 0.25 hour – Lump (1.1 factor) simulation minus the elevations from the 0.25 hour – 5 km. Yellows to reds indicate where the first (0.25 hour – Lump 1.1) simulation has eroded more/deposited less than the second (0.25 hour – 5 km) simulation. Blues indicate more deposition/less erosion.

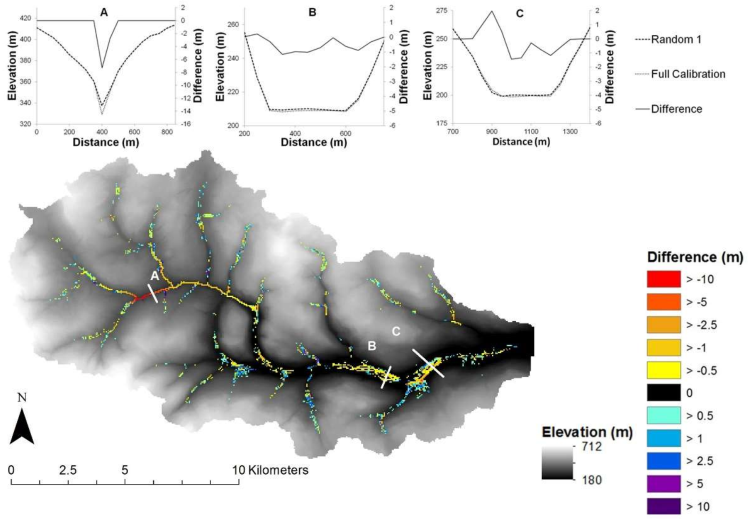
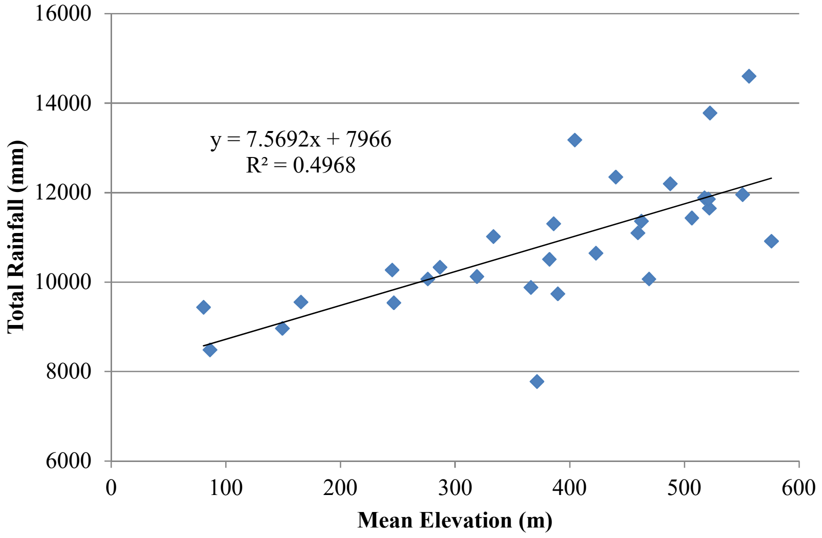


Figure 8. DEM of Difference for the adjusted temporal and spatial resolution comparison. The differences shown are elevations from the 24 hour - Lump (2.2 factor) simulation minus the elevations from the 0.25 hour – 5 km. Yellows to reds indicate where the first (24 hour – Lump 2.2) simulation has eroded more/deposited less than the second (0.25 hour-5 km) simulation. Blues indicate more deposition/less erosion.


16000
14000
12000
10000
8000
6000
0
100
200
300
400
500
600
y = 7.5692x + 7966
R² = 0.4968
Total Rainfall (mm)
Mean Elevation (m)

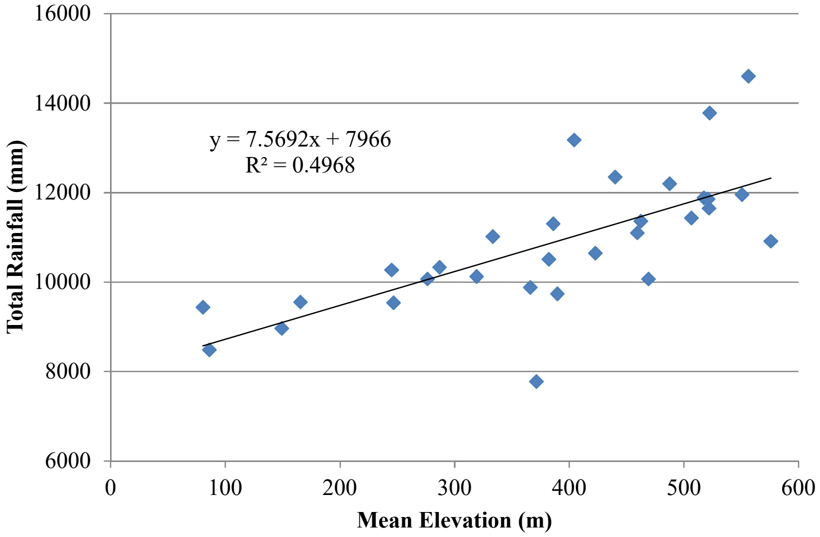
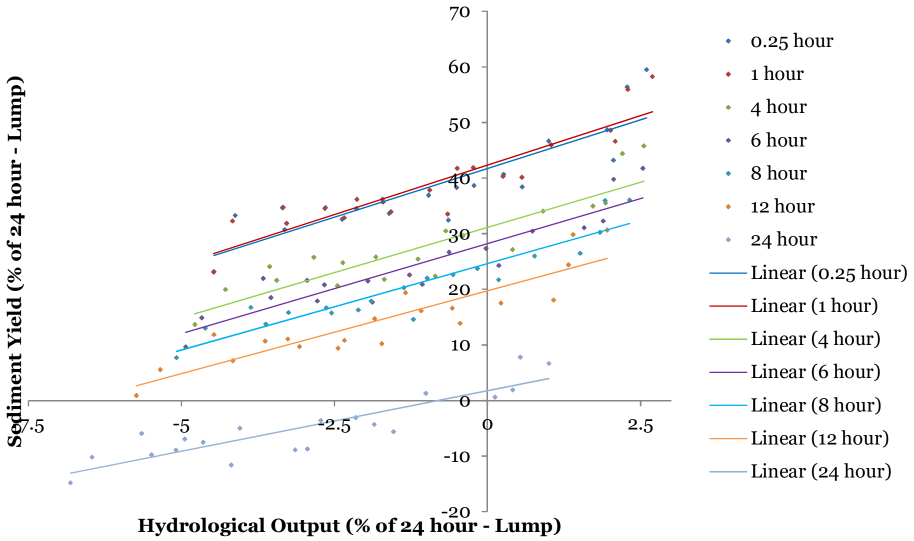


Figure 9.

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

5


70
60
50
40
30
20
10
0
-10
-20
-7.5
-5
-2.5
0
2.5
Sediment Yield (% of 24 hour - Lump)
Hydrological Output (% of 24 hour - Lump)
0.25 hour
1 hour
4 hour
6 hour
8 hour
12 hour
24 hour
Linear (0.25 hour)
Linear (1 hour)
Linear (4 hour)
Linear (6 hour)
Linear (8 hour)
Linear (12 hour)
Linear (24 hour)

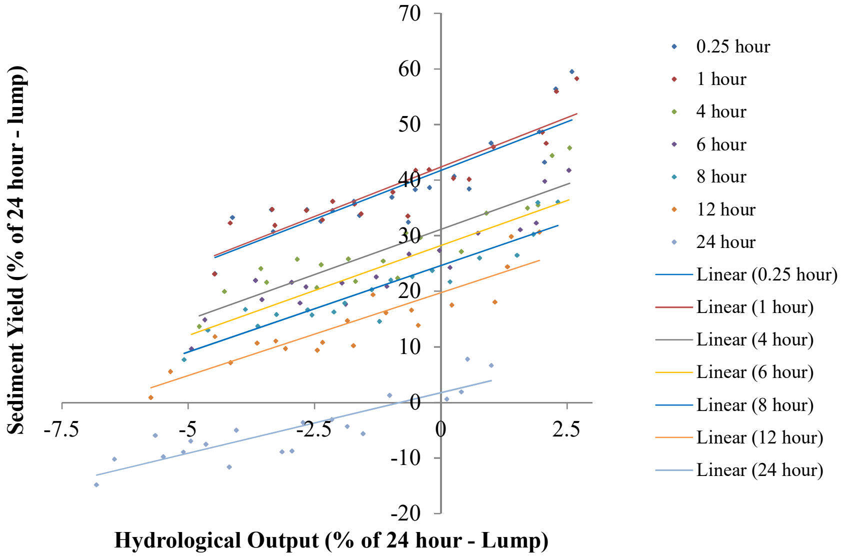


Figure 10~~7~~. The relationship between hydrological output and sediment yield from each temporal resolution, based on outputs of the 20 jumble ensembles of the Upper Swale catchment.