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 Some of the comments by the reviewer refer to unpublished research examining the role of temporal rainfall resolution – and make complete sense as does the thought experiment outlined in the review. However, it is difficult to reference unpublished findings, but we have looked in some detail at the SIBERIA literature, finding a relevant section in a user manual and used this accordingly in the revised MS.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.