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Interactive comment on "HyLands 1.0: a Hybrid Landscape evolution model to simulate the impact of landslides and landslide-derived sediment on landscape evolution" *by* Benjamin Campforts et al.

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Reviewer 1

See AC1

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Reviewer 2

Alexander Densmore

Summary: This is a very well-written manuscript that makes a clear contribution to knowledge.The authors have combined an elegant new fluvial landscape evolution model with an existing approach to modelling bedrock landslides. The result is, to my knowledge, the only modern landscape evolution model that explicitly accounts for bedrock landslides,and that will therefore allow a number of new problems to be addressed. The authors have done a very good job of summarising both the model and some of these potential applications. I have made some comments and suggestions on the manuscript PDF, which I will paper not repeat here. Most of these are minor and relate to clarification of a few points or requests for a little more information. These should be straightforward for the authors to address. The only more substantive questions relate mostly to the figures,especially Figs 7-10. The text and captions don't fully explain what these figures are showing, making it hard for the reader to fully understand the results. The text describes changes in the lateral position of the river system due to landsliding, but I really don't think that Figs 9-10 show this clearly or effectively. As this seems to be one of their main take-home messages about the impact of landsliding on these landscapes, I think that they could perhaps do more to show these changes to the reader. Once these relatively minor issues are addressed, however, then the revised manuscript should be ready for publication.

Reply: We explicitly want to thank the reviewer, Alexander Densmore, to review our manuscript in such a short period, given the challenging times. We are pleased that the reviewer appreciates our work. Minor comments regarding typos and text edits are addressed directly in the updated version of the manuscript.

Reviewer Point 2.1 — Line 6 - remove earth

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Reply: Fixed.

Reviewer Point 2.2 — Line 64 - This isn't actually the case - I had to go back and check! We used the lowest point on a hillslope that fit the failure criteria, but that point did not need to be in the channel. As stated on p. 15,208, 'This ensures that landslides begin near the toes of hillslopes', but not necessarily at the toe. Line 66 - As above, this isn't what was done in that paper, so I suggest cutting this. You're absolutely right that sediment is spread at a constant slope and that there's absolutely nothing mechanistic about the approach, however.

Reply: Thanks for clarifying this and apologies for misinterpreting this. We removed this sentence and rephrased to: (i) all hillslopes behave as Mohr-Coulomb materials (Taylor et al. 1948), (ii) landslides initialize near the toes of hillslopes and (iii) landslide-derived sediment is spread under a constant slope, following the steepest downslope path.

Reviewer Point 2.3 — LLine 76 - The wording here is a little confusing - it sounds like the processes aren't available at large scales, which isn't what you mean. I suggest rewording as something like '...processes, and require input parameters which may not be adequately known at large spatial scales.'

Reply: Good suggestion, we rephrased accordingly.

Reviewer Point 2.4 — Line 81 - While the text above is very clear on what has been done to date, I feel like there is a sentence missing that just puts those pieces together into a single statement that motivates your work. In other words: what's the specific gap that you will now be able to fill?

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Reply: We added the following sentence: Notwithstanding the prominent role of landslides in shaping the earth surface and controlling sediment supply and transport, few efforts have been made to actively simulate the impact of stochastic landsliding on landscape evolution and sediment dynamics over large spatial and temporal scales.

Reviewer Point 2.5 — Line 107 - due to landsliding

Reply: Fixed.

Reviewer Point 2.6 — Line 112 - This was already defined on line 58

Reply: Fixed.

Reviewer Point 2.7 — Line 116 - OK... with the caveat that this is also going to depend upon the spatial resolution of the model and the way in which rivers are modelled in the grid - i.e., whether or not they are treated as a single thread of cells, or whether the equations are applied to the whole landscape. I presume it's the latter although this isn't explicitly stated

Reply: We added two sentences to the previous paragraph for clarification: Note that HyLands does not explicitly distinguish between river or hillslope cells: all equations are applied to the entire landscape. Processes affecting sediment thickness and bedrock elevation in each cell can be either fluvial dynamics (SPACE), landslides, or a combination of both, hence the hybrid nature of HyLands. Moreover, as suggested by A. Densmore, we moved the following sentence from the discussion to this point in the manuscript: Note that this approach implies that all river cells in the landscape are assumed to occupy 1 grid cell with distance dx, that channel width may be less

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than, equal to, or greater than dx, and that river width is only a function of contributing drainage area.

Reviewer Point 2.8 — Line 135 - the

Reply: Fixed.

Reviewer Point 2.9 — Line 155 - Can you remind us (briefly) how this is determined?

Reply: We added the following sentences to clarify: V is the net effective settling velocity, which represents the still-water particle settling velocity corrected for the upward effects of turbulence and the vertical gradient in sediment concentration through the water column (Davy and Lague, 2009). HyLands enables spatially variable values for V to distinguish between settling velocities over flooded versus non-flooded nodes.

Reviewer Point 2.10 — Figure 2: There is a slight mismatch with the text here, given that the text doesn't refer to f at all, but simply builds negative exponential functions of H/H* into eqns 3 and 4. I wonder, therefore, if it's more straightforward to flip this by 90 deg and to relate this more clearly to eqns 3 and 4. I get the echoes here of the tools/cover effect plots, but I think it's potentially a bit confusing as currently designed. Just a thought.

Reply: Good point. We flipped the axes as suggested, and defined $f\,(H/H_*)$ in the figure caption. We also referenced the relevant erosion/entrainment equations in the caption to make the function notation less confusing.

Reviewer Point 2.11 — Line 207 - plane

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Reply: Fixed.

Reviewer Point 2.12 — Line 208 You use both node and pixel in this section - are they equivalent? If so then I suggest using one term or the other; if not then please explain the distinction.

Reply: Good point. We use the term 'cell' now throughout the text

Reviewer Point 2.13 — Line 217 - Suspended sediment makes sense here - I'm struggling to envision a situation, however, where a measurable volumetric fraction of hillslope sediment contributes instantly to the dissolved load of the river. Perhaps cut, unless I'm missing something?

Reply: We dropped dissolved

Reviewer Point 2.14 — Line 222 - True - and also doesn't account for different depositional slopes for different landslide bulk rheologies or grain size distributions...

Reply: Thanks for clarifying

Reviewer Point 2.15 — Line 230 - an approach

Reply: Fixed.

Reviewer Point 2.16 — Line 232 - landslide-derived

Reply: Fixed.

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Reviewer Point 2.17 — Line 245 - ... and there is no deposition at that cell?

Reply: We added these words for clarification.

Reviewer Point 2.18 — Line 246 - Is this the angle of the surface of the resulting deposit? If so, then maybe call it a minimal deposit surface angle. 'Spreading angle' could be confused with spreading across multiple flow directions.

Reply: Good suggestion. We adjusted the text accordingly throughout the manuscript

Reviewer Point 2.19 — Line 249 – Should this be changed to 'over the landscape'? Presumably the spreading algorithm distributes sediment downslope, whether or not the target cell is a hillslope or channel cell. This comes back to an earlier question - is there any distinction made between hillslope and channel cells, or are the model equations applied to the whole landscape? The previous text suggests the latter, but this sentence might imply that there is a difference. It would be great if you could clarify this.

Reply: Good that you point us to this. We added a couple of sentences right after the GMB equation (Eq. 5) to clarify. See also reply to earlier comment (2.7)

Reviewer Point 2.20 — cfr. == cf. ?

Reply: Fixed

Reviewer Point 2.21 — Line 251 - Again - are nodes and cells the same thing? If so then it would be good to use a consistent term.

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Reply: Good point. We use the term 'cell' now throughout the text

Reviewer Point 2.22 — Line - 272 conditions?

Reply: Fixed

Reviewer Point 2.23 — Table 1 - It took me awhile to realise that (a) referred to a note at the bottom of the table - perhaps make this superscript to match the others?

Reply: Fixed

Reviewer Point 2.24 — Table 1 - I suggest inserting a space (m yr^{-1}), to avoid confusion.

Reply: Fixed

Reviewer Point 2.25 — Table 1 - This should be mentioned explicitly in section 2, rather than defined in the table notes

Reply: We added this information in the main text of the manuscript, after introducing Eq. 5, see also reply to earlier comment (2.9)

Reviewer Point 2.26 — Line 310 - Applying HyLands to the Namche Barwa-Gyala Peri massif I don't have any issue with this application... but I find it a slightly odd choice, not least because of the very limited field data available to ground-truth the Larsen and Montgomery landslide inventory. Given the rapidly-growing number of

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well-constrained inventories out there, why did you choose this particular one? The pre-1974 inventory is particularly poorly constrained in terms of the time scale that it covers, and both inventories suffer from extreme orthorectification issues caused by the steep topography. There's also nothing known about the history of either rainfall or earthquake landslide triggers in that area, other than the big 1950 event which almost certainly triggered some of the events in the inventory. It's not a bad choice to evaluate the model, but it just seems like there are other inventories out there that fit your requirements better. I'd be curious to see an additional line in the text that gives the reason why this was chosen.

Reply: Again, a very insightful comment. We agree with the reviewer that if the aim of this exercise would be to exactly reconstruct an observed LS inventory, other regions would probably make up for a better application for reasons given by the reviewer. However, our intention is not to calibrate HyLands to a specific study area, neither to reproduce exact magnitude frequency distributions because these would indeed require detailed information on earthquake and storm histories. Rather we were interested if we could reproduce the general shape of the empirical and universally observed magnitude frequency and area-volume relationships. The question remains as to why we selected the Namche Barwa-Gyala Peri massif as an area to test HyLands. We now address this issue in the manuscript by adding the following lines of text:
We selected the Namche Barwa-Gyala Peri massif to evaluate the performance of HyLands given its unique geomorphologic configuration featuring amongst the highest globally documented river stream power in combination with very active hillslope processes (Larsen, 2012). With HyLands being designed to couple the role of fluvial and hillslope processes, this region makes up for a good test environment. Note however that we do not intent to calibrate neither validate the model but run it using fixed, theoretical model parameters (section 3.2.3). Applications of HyLands aiming to constrain the model through parameter calibration and validation (section 4.3) would require additional data to ground-truth landslide inventories and to provide detailed records on

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landslide triggers such as earthquakes and storms.
Also note the reply to Reviewer 1, which is related to this comment (see AC1 RC 1.2)

Reviewer Point 2.27 — Line 320 - Out of curiosity, why would you do this?

Reply: We address this question in the manuscript now: We resampled the DEM to a resolution of 20 m in order to evaluate the capacity of HyLands to reproduce the rollover in the magnitude frequency distribution, often reported to occur for landslide areas < 900 m^2, which would be the minimum landslide area when using the original SRTM data.

Reviewer Point 2.28 — Line 342 - It's not clear what this text is doing within the citation - perhaps rework this into the sentence.

Reply: Fixed

Reviewer Point 2.29 — Figure 7 - It's quite hard to see the detail in this figure without zooming way in - I wonder if you can make more efficient use of the space by increasing the size of the panels. Given that the colorbars for each row are almost identical, do they need to be shown 4 times?

Reply: Good suggestion, we remade the figure.

Reviewer Point 2.30 — Figure 7 - I might be missing something, but the left-hand column just seems to show landslide locations - I can't see anything that follows the red-to-blue color scale indicated. The other two colorbars seem to fit with the middle

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and right-hand columns, but what are the colors meant to indicate on the left-hand column?

Reply: Good point. Actually in the left hand column of the previous figure, you can see the landslides if you would zoom in closely. However, as this is very difficult to see, we removed the colorbar for these figures.

Reviewer Point 2.31 — Figure 7 - It's not very clear what you're plotting. All of your model parameters relating to erosion and deposition are represented as rates, with units of L/T. So it's not obvious why you've taken the square root of those quantities and how you've kept units of meters. I understand that this won't affect the patterns that you show, but I think this could be more clear to the reader.

Reply: This remark is similar to the one made by reviewer 1. We corrected the units to $\sqrt{m}$. See also see also AC1 SP1.14

Reviewer Point 2.32 — Figure 7 - Rather than referring to this as 'SED' in the figure, it would be better to relate this back to the parameters that you have already defined and used throughout the manuscript so far. Is this the same as H in equation 1?

Reply: Yes, this is H, we changed the label of the colorbar.

Reviewer Point 2.33 — Line - 360 I'm not sure where that can be seen on Fig 7 - perhaps point it out?

Reply: Good suggestion. We now point it out explicitly: e.g., the deposition pattern in Fig. 7.h reflects the shape of erosion patterns resulting from previous landslide activity

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Reviewer Point 2.34 — Figure 8 - Rather than 'PDF', it might be better to label this for what it is, which is the spatial frequency density of landsliding per unit area

Reply: Good suggestion, we will adjust

Reviewer Point 2.35 — Figure 8 - This may be a problem with the PDF conversion, but the symbol for this zone seems to be missing from the legend on the figure, along with the best-fit regression line

Reply: Sorry for that. We messed up the legend of the figure, this is fixed now

Reviewer Point 2.36 — Figure 9 - The caption for this figure is a little bit lacking, in that it's not clear what is being plotted. What's the difference between the top-left and top-right subfigure in each panel? What does the blue line in each panel represent? Why is the brown line labelled 'Current Topo' in the left-hand column, but seems to correspond to 'Sediment' on the right-hand y-axis? The brown lines seem to show different things in the two columns, so I'd suggest making these distinct. Also, confusingly, blue areas seem to denote sediment on the profiles in the left-hand column, but water in the profiles on the right - I didn't realise that this was the case until I got to Fig. 10 a couple of pages later. This is a really interesting figure - a little more care with the colors, labels, and caption would really help the reader to get the most out of it.

Reply: Thanks a lot for these very useful recommendations. We adjusted the labels on the figure and changed the figure caption as follows: **(a-d)** Time slices showing evolution of the landscape to steady state, before the landslide period. The upper left subplots show the evolution of topography through time. The upper right subplots show the evolution of of sediment thickness (H) through time. On both subplots, the blue line represents the location of the river, plotted in the lower subplots. These lower

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subplots show the topographic and bedrock elevation (red and black line respectively). The difference between the topographic elevation and the elevation of the bedrock represents the sediment thickness. With respect to total elevation, sediment thickness is small, which is why sediment thickness (orange line) is also plotted against a separate right-hand y-axis. The gray shaded area represents bedrock underlying the river profile. **(e-h)** Time slices showing the landslide period where intense landsliding is occurring over a period of 100 years. The upper left subplots show the landslide activity. The location of landslides is indicated with black diamonds. The colors represent the square root of the landslide erosion (-) and deposition (+) during the presented time step. The upper right subplots show the evolution of of sediment thickness (H) through time. On both subplots, the blue line represents the location of the river, plotted in the lower subplots. These lower subplots show the topographic and bedrock elevation (red and black line respectively) as well as the volume occupied by sediments and water (orange and blue shaded area respectively). Note that, during landsliding, both pure landslide dams arise as well as irregularities in the bedrock profile (the grey bumps). The latter originate from the river being redirected after landsliding forming epigenetic gorges (see text). We adjusted Figure 10 accordingly.

Reviewer Point 2.37 — Line 402 - I don't understand - does this mean that the profile is always taken in the same place, but that in some places that profile corresponds to the active channel and in other places it doesn't (when the channel has been diverted to a different location)? Or are those bumps areas where bedrock incision and lowering of the channel bed has been inhibited by the addition of large volumes of sediment?

Reply: We agree that this was a confusing sentence and removed it from the manuscript. Instead, we now elaborate on this issue in the next paragraph by extending our explanation on the formation of epigenitic gorges. This comment is similar to the remark of reviewer 1, addressed in AC1 RC1.3 and one of the following remarks (PT 2.39)

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Reviewer Point 2.38 — Line 407 - Just to clarify, landslide sediment has the same transport coefficient as any other sediment in the model, right? So there is no 'immobile debris'?

Reply: Correct, we removed immobile

Reviewer Point 2.39 — Line 412 - I'm not sure that I would call that 'drainage re-routing', as that implies a lateral shift in the position of the active channel. Is that what you mean?

Reply: We actually mean to describe such a lateral shift. We rephrased the corresponding paragraph in the text as:
The drainage re-routing mechanism dominates in the simulations presented here and results in the formation of epigenetic river gorges (Fig. 10). Epigenetic river gorges are characterized by rivers incising into the bedrock of former valley walls due to the blockage of the formal channel by landslide derived sediment (Ouimet et al. 2008).

Reviewer Point 2.40 — Line 457 - See my earlier queries on section 2 - this information could usefully be included there.

Reply: Good suggestion, we move this sentence to section 2. See also reply SP 2.7 .

Reviewer Point 2.41 — Line 494 - True... or even with medium-complexity approaches such as RAMMS or Flow-R...

Reply: Indeed, we added those and corresponding references

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Reviewer Point 2.42 — Line 509 - True. You could cite Fan et al. (2018) Landslides as an example where this has been done, or Fan et al. (2019) Rev of Geophys as a good review of the problem.

Reply: Absolutely, a reference to the review of Fan et al. was intended here, good that you point us this

Reviewer Point 2.43 — Line 519 - them: Not sure what you're referring to here.

Reply: We adjusted the sentence

Reviewer Point 2.44 — Line 526 - OK - so, given the results of those studies, as well as the recent work by Thomas Croissant as well as some of the authors, what are the most pressing remaining questions or issues?

Reply: One example of a pressing remaining question has been suggested by reviewer 1 and is now added as a potential application to this paragraph (see also AC1 RC1.5): A particular question which remains open for debate is the way in which landslides influence the evolution of a landscape to steady state. Albeit the stochastic nature of landslides will prevent landscapes to evolve towards time and space invariant topographies, even with landslides, landscapes will evolve towards a quasi steady sate if external drivers such as climate and tectonics remain constant. Although our mechanistic understanding of landscapes strongly improved by studying steady state landscapes, an even more interesting and challenging question would be to study the impact of landslides on the dynamic evolution of a landscape towards such a steady state. The latter being more relevant for most real-world landscapes which are known to be rather in transient than a steady state (Mudd et al. 2017).

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Reviewer Point 2.45 — Line 530 - ... or to a major landslide triggering event. See, for example, some of the work after the 2015 Gorkha earthquake that speculated on this exact point.

Reply: Good suggestion. We rephrased and inserted some additional references as: Second, HyLands can be used to evaluate the response time of a landscape to a major landslide triggering event and to understand the timescales over which landslide-derived sediments are exported from the landscape (Wang et al., 2015; Li et al.,2016; Schwanghart et al., 2016; Robinson et al., 2017; Roback et al., 2018)

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