

Dear editor,

Thank you and the two anonymous reviewers for the second round of feedback on the manuscript. The comments were helpful in clarifying the manuscript, particularly in the methods, and in refining the focus to earthflow influence on the landscape rather than on habitat. Below, we have detailed our response to the referee comments.

Sincerely,
Sarah Schanz, on behalf of the authors

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*As mentioned I found the introduction quite confusing as it focuses on the impact of earthflows on salmon habitat rather than earthflows themselves. As the primary outcome of the paper is a tool which describes the activity of the earthflows and identifies their distinctive features I feel the introduction needs more reference to the earthflow literature.*

The reference to salmon habitat unfortunately lingered after the first revision. We revised the first paragraph of the introduction, where habitat was mostly mentioned, to focus more on geomorphic impacts. We tried to maintain a balance in which habitat was still mentioned as a motivating factor for research into earthflows – even if we can't concretely address it here. To that end, we made habitat a vaguer implication. We added more background information on earthflow response to climate.

Clean doc: Lines 23-324, 43-45.

Track changes doc: 23-44, 55-57.

*The study area section is very focused on the geology of the region rather than any known impacts of the earthflows (or other landslides) on the landscape. I would also expect a bit more discussion on the human impact of the area if known i.e. how much of the region was logged? What is the coverage these days? I would also expect some discussion of whether salmon spawn in the region if most of the study is focused on the impact of earthflows on salmon habitat.*

In the first paragraph of the study area, the logging history is discussed. We expanded this to state the impact of logging on rivers, and that all forests are <100 years old in the study area. Widespread logging practices ceased in the 1940s, though patchwork logging does occur. We retained the geology focus because the geology controls where earthflows occur, and so is important to understand. Since we have revised the introductions to de-emphasize salmon habitat, at the suggestion of the first round of reviews and the above comment, we don't include a discussion of whether salmon spawn in the region.

We don't know of any studies detailing the impacts of earthflows and other landslides on this particular landscape, and have made that clear in the last paragraph of the study area section. The North Fork Teanaway Watershed Analysis did examine shallow landslides near stream banks, but only with the aim of roughly estimating potential habitat threats to fish. No impacts were quantified or mapped.

Clean doc: Lines 79-81, 106, 110-111.

Track changes doc: Lines 105-107, 132, 137.

*The current structure of the results section is a bit confusing as it jumps between subjects. I would suggest that the mapping results should be followed by a discussion of the MADstd trends, then the Maximum ages (radio carbon dating) and then the relative dating and verification of the dates. This will help the reader to follow the logic of the MADstd metric and its use in relative dating a little easier.*

We appreciate the referee’s suggestion. However, we prefer to keep the earthflow verification section before relative activity results, so that the relative activity results are based on a MADstd system that is shown to work. We do recognize that the apparent subject jumps are confusing, particularly without any overarching logic laid out. To that end, we have added an introduction/roadmap paragraph to the results that explains why the results are ordered the way they are.

Clean doc: Lines 220-223

Track changes doc: Lines 322-325

*In the methods section, I think the expected power law scaling should be presented. See two recent Esurf preprints about valley width for good examples - one by Clubb et al. and one by Harel et al. In the results section, I think you should fit power laws to the data and show the best-fit equations on figure 4 (even if they are bad fits, which is expected given the influence of earthflows).*

We added text about the expected power law scaling, including an example from similar lithologies in the Pacific Northwest, USA, and the suggested example from Clubb et al in the Appalachian Mountains, USA. Both examples have a power law exponent of 0.3, and we added this regression line to the background of Figure 4 for reference. Interestingly, the non-landslide points do match this regression exponent, though the earthflows clearly do not.

Clean doc: Lines 198-204, Figure 4 and caption

Track changes doc: Lines 270-275, Figure 4 and caption

*Figure 7 is a bit confusing at first. I didn’t notice that the outlines of B, C, and D were colored at first and I wasn’t sure what the colors of the earthflows meant. I think you need a MADstd color bar and I think you should explain in the caption what B, C, and D are examples of. The caption is short now so I think you have room to spell it out clearly. Also, D looks like an example of a case where MADstd and topography match?*

Taking into account both referees’ comments to Figure 7, we revised panels B-D to be clearer. First, we added a line to clearly connect each panel to the associated bar in Panel A. We added MADstd labels to each earthflow and clarified the color scheme in the caption. For panel D, we zoomed in to show this better. None of the examples of MADstd and topography NOT matching are very clear, and this is the best example we could show. We expanded the figure caption to explain B-D, and to point the reader to the toe of the landslide in D that is overlapping a higher MADstd earthflow.

Tracked changes and clean doc: Figure 7 and caption.

| Reviewer comment                                                                                                     | Line change (clean) | Line change (tracked) | Author comment                                                                                                                                                                                                    |
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| Line 46: It is currently not clear where the Eel River Basin is or how any study there may relate to the study area. | 50                  | 62                    | We clarified that the Eel River is in California, USA, and that it is used here as an example of how earthflows can influence landscape evolution.                                                                |
| Line 48-49: This sentence is confusing and hard to follow                                                            | 52-54               | 64-66                 | Revised to:<br>“ <b>Additionally</b> , in-stream sediment production <b>from earthflows</b> is unsteady <b>because</b> annual to decadal precipitation conditions cause intermittent movement over the decades to |

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|                                                                                                                                                                                                                                                             |              |              | centuries that the earthflow is active.”                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Line 51: Again, the Eel River is referenced as if the reader should know where it is or why it is an important reference for this study. It is also not clear how earthflows produce topographic highs from this sentence.                                  | 55-58        | 67-69        | Added ‘California, USA’ after Eel River to give location, and restructured the sentence to both clarify that this is an example of where earthflows influence topography and clarify how topographic highs are produced from differential erosion:<br><br>“Differential erosion by earthflows results in valley-scale topographic patterns: lithologic controls on earthflow location in the Eel River basin, California, USA, concentrates erosion in the melange units, and lowers that landscape relative to isolated resistant sandstone outcrops.” |
| Figure 1: The regional bedding information should be included on the map as it is relevant to the results of the study.                                                                                                                                     | Fig 1        | Figure 1     | We’ve added the regional bedding in the form of strike and dip symbols; we did not include dip angle because it made the map unreadable.                                                                                                                                                                                                                                                                                                                                                                                                                |
| Line 114: How were the landslides mapped? Was this done by hand? How were the edges of the earthflows delineated? Typically, landslides are identified from satellite images by changes of colour but it is not clear how this is done with the Lidar data. | 123, 126-127 | 151, 154-155 | We clarified that earthflows were mapped in ArcGIS and edges were identified by the morphologic shear zones, depositional toes, or erosional scarps.<br><br>“We mapped the edges of earthflows as the edge of shear zones next to undisturbed hillslopes, and used scarps and toe deposits to delineate the top and bottom of earthflows from surrounding hillslopes.”                                                                                                                                                                                  |
| Line 115: What is meant by hourglass shape? Does this mean the scar and toe of the landslide are wider than the centre?                                                                                                                                     | 124          | 152          | Yes, it does mean that. We clarified for others unfamiliar with the term (which we realize now is probably used mostly in US-centric textbooks and is not globally common):<br><br>“..hourglass shape with a wide head scarp and toe compared to a narrow transport zone..”                                                                                                                                                                                                                                                                             |

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| Line 116-117: Are these older earthflows undistinguishable from the rest of the landscape or from other mass movements?                                                                                                         | 127-130 | 156-158 | <p>It is both, but the latter point is important as we want to focus only on earthflows.<br/>Added/edited text:</p> <p>“These morphologic clues degrade over time and it becomes harder to distinguish earthflows from other mass movements. Therefore, we focus our analysis on Holocene earthflow activity when it is still possible to distinguish the characteristic earthflow morphologies.”</p> |
| Line 120: How were the dated earthflows selected?                                                                                                                                                                               | 136-138 | 164-166 | <p>This is detailed in the middle of the paragraph. The existing line was edited to clarify what a visual estimate of roughness is:</p> <p>“Sampled earthflows were selected based on potential for a fresh exposure via road or stream erosion and to capture a range of activity, which we estimated by the prominence of levees and shear zones in the bare earth lidar”</p>                       |
| Line 123: Maximum earthflow activity does this refer to the duration of the earthflow activity? Activity and age seem to be used interchangeably throughout the manuscript but they may mean different things to other readers. | 135-136 | 163-164 | <p>We added a sentence to clarify that this is when earthflow activity started.</p> <p>“Maximum earthflow activity refers to a maximum estimate of how long since an individual earthflow first became active.”</p>                                                                                                                                                                                   |
| Line 124: What is a visual estimate of roughness?                                                                                                                                                                               | 136-138 | 164-166 | <p>Clarified to be specific:</p> <p>“Sampled earthflows were selected based on potential for a fresh exposure via road or stream erosion and to capture a range of activity, which we estimated by the prominence of levees and shear zones in the bare earth lidar”</p>                                                                                                                              |
| Line 133: As this methodology and the ages of the lakes are an important constraint on the aging of the                                                                                                                         | 145-150 | 181-184 | <p>In addition to the reference to the methods outlined in Struble et al (2020), we summarized their methods to extract volume</p>                                                                                                                                                                                                                                                                    |

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| <p>earthflows this methodology needs to be explained.</p>                                                                               |                |                | <p>in two new sentences and an edited existing sentence:</p> <p>“We estimated the valley bottom elevation under the lakes using the average valley slope of surrounding un-dammed valleys. This valley floor estimate is interpolated in GIS with the lake perimeter elevation to form an estimated lake bottom topography. The bottom topography is subtracted from the lidar surface elevation to estimate the sedimentation volume post-earthflow.”</p>                                              |
| <p>Line 135: What does similar mean here? Are these basins in the same region as the study area? How were these rates produced?</p>     | <p>150-151</p> | <p>184-185</p> | <p>We specified that the basins are neighboring and added that the rates are produced by beryllium 10 erosion dating. We suggest Moon et al. (2011) for further details on how the rates were produced, but re-arranged this reference to make it clear that denudation rates come from Moon et al.</p> <p>“We used nearby mid-Holocene <sup>10</sup>Be denudation rates of 0.08 and 0.17 mm/yr (Moon et al., 2011) from neighbouring basins with similar mean annual precipitation and glaciation”</p> |
| <p>Lines 135 – 138: Include the equation and calculations to produce these dates. Currently it is not very clear what is happening.</p> | <p>151-154</p> | <p>185-188</p> | <p>We added/ revised the prior section to step through our calculations.</p> <p>“We multiplied the denudation rates by upstream contributing area for each lake to give a volumetric estimate of sediment delivery per year. The lake sedimentation volume is divided by this rate to estimate the years necessary to fill each lake. We repeat this process with the upper and lower denudation bounds to give a range of plausible sedimentation ages, which</p>                                      |

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|                                                                                                                                                                                                                        |                                 |                                 | approximate when the earthflow dammed the creek.”                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Line 142: A figure (maybe in the supplemental) of what an earthflow looks like in Lidar would be helpful. Could also be part of a multi-panel showing the different steps used to produce the MADstd of the earthflow. | Supplement Figures 2, 3         | Supplement Figures 2, 3         | Created two diagrams showing how MADstd was produced. Includes figures of an earthflow as it goes through the process. This figure is included as Supplemental Figures 2 and 3.                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Lines 144 – 146: It is not clear what MAD is a measure of. The referenced paper and the given description are too specialist for your typical reader.                                                                  | 162-164                         | 196-198                         | <p>We added more to the description, both in the section pasted below but also in our description of flow direction that can help the reader understand MAD. The referenced paper (Trevisani and Cavalli, 2016) does give good visual examples of MAD in hillslope and valley terrains, though their equations are very technical.</p> <p>“MAD is a bivariate geostatistical index that analyzes residual elevations between paired locations in a Digital Elevation Model (DEMs) (Trevisani and Cavalli, 2016). MAD results in a roughness index for each direction (N-S, E-W, NE-SW, and NW-SE) across each raster cell in the study area.”</p> |
| Lines 146-147: How is MAD combined with flow direction?                                                                                                                                                                | 164-166, Supplement figures 2-3 | 198-200, Supplement figures 2-3 | <p>We have added a sentence describing this:</p> <p>“Using surface flow directions derived from the DEM surface, these directional roughnesses are filtered to correspond to the flow direction; e.g., if the surface flow direction is N-S, then only the N-S roughness is used (Trevisani and Cavalli, 2016).”</p>                                                                                                                                                                                                                                                                                                                              |
| Line 150: In line 140 MAD is said to be a measure of earthflow activity and now we are looking at the relationship                                                                                                     | 179-181                         | 259-262                         | Thank you for catching that error. Age should be activity, and we’ve edited to say activity.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |

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| between age and MAD. Are activity and age being used interchangeably?                                                                                                                                   |                     |                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| Lines 150 – 165: It is not clear why these models are being applied to the DEM.                                                                                                                         | 118-119,<br>179-181 | 146-147,<br>259-262 | The models are being applied so that we can test the assumption that MADstd decreases with time since last earthflow activity. Diffusion in the model helps us simulate this.<br><br>We added lines to clarify.<br><br>“The MADstd relative dating method rests on the assumption that earthflow MADstd will decrease with time since last earthflow activity due to soil diffusion. In order to test this assumption, we simulated landscape diffusion on a recent earthflow and calculated MADstd through time; if our assumption is correct, MADstd should decrease with simulation time.” |
| Line 153: Why does it matter that the stream is not permanently dammed?                                                                                                                                 | 184                 | 264                 | It does not matter, and we have removed this phrase.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Lines 167 – 174: This paragraph should be higher up in the section before the discussion of diffusion models. We also need a clear definition of what directional roughness is.                         | 169-177             | 203-257             | Paragraph has been moved up, and directional roughness has been explained in response to an earlier comment by the referee.                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Line 180: How is width measured? It is not clear from the current description.                                                                                                                          | 211-212             | 313-314             | Width is measured as the length of the transect within the defined valley bottom. We added a phrase to clarify:<br><br>“..measure valley width as the width of the transect line within the 5% valley slope.”                                                                                                                                                                                                                                                                                                                                                                                 |
| Line 189: Were only earthflows mapped? If so this section could be called earthflow mapping to avoid confusion. Reporting the basic statistics of earthflows would be useful, i.e. smallest and largest | 224, 225-<br>226    | 326, 327-<br>328    | We changed the section name to 4.1 Earthflow mapping.<br><br>We added a sentence with earthflow statistics:<br>“Earthflows range in size from 1076 m <sup>2</sup> to earthflow complexes                                                                                                                                                                                                                                                                                                                                                                                                      |

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| earthflows (area or length), average size etc.                                                                                                  |              |              | 4e6 m <sup>2</sup> in area with a median area of 28,547 m <sup>2</sup> .”                                                                                                                                                                                                                                                                                                         |
| Line 219: If possible an extra panel showing how the width of tributaries unaffected by earthflows changes with drainage area would be helpful. | Figure 4     | Figure 4     | We added a regression line in each panel that shows the drainage area-valley width relationship for valleys unaffected by landsliding (Schanz and Montgomery, 2016; Clubb et al., 2022)                                                                                                                                                                                           |
| Figure 5: Unclear what Inset is meant to be showing. There needs to be a color bar and a label or legend highlighting the lake.                 | Figure 5     | Figure 5     | We have added a label to the lake as well as a color bar for the 5m MADstd.                                                                                                                                                                                                                                                                                                       |
| Line 247: The earthflow could have taken some time to dam the channel                                                                           | 285          | 391          | This is a good point. We have added clarification that this may not be exactly a maximum age estimate.<br><br>“..represents a maximum age – or a near maximum age if earthflow velocity was slower and did not immediately dam the channel.”                                                                                                                                      |
| Line 252 – 257: How can the residence time of carbon in earthflows be 4000 years when no other landslide comes close to that in terms of age?   | --           | --           | We state that the residence time can be upwards of 4000 years; we don’t expect all radiocarbon samples to have this large of residence time. And as explained in the text (line 274 clean), residence time can come from inherited time in the charcoal, not from earthflow movement/storage. And we do have two of our six samples that are greater than 4000 radiocarbon years. |
| Lines 268-272: This hypothesis was not stated earlier in the manuscript.                                                                        | 179-181, 306 | 259-262, 414 | We clarified. This is the assumption that underlies the roughness-age correlation. This is made clearer in the methods and is also restated here:<br><br>“Simulated diffusion verified our assumption that MADstd decreases with time since earthflow activity.”                                                                                                                  |



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| Lines 265 – 272: It still isn't clear why this experiment and model was done.                                                                                                                      | 118-119, 179-181, 306 | 146-147, 259-262, 414 | We have edited the methods to clarify this, and added a line to remind the reader of why the simulation was done (see comment just above this).                                                                                                                                                                                                            |
| Line 275: The properties of the earthflow could also affect the metric, slower flows may have lower MADstd values                                                                                  | 316-317               | 425-426               | This is a good point, and would affect the relative degree of diffusive and advective processes. We added a phrase to show that this is another way in which we do not understand the diffusive history:<br><br>“..the soil diffusion value, and on earthflow velocity, which would affect the relative strength of diffusive versus advective processes.” |
| Line 280: Is it possible to assume a K value from the dated earthflows? If an initial roughness is assumed a trend can be found and perhaps the modelling can provide an estimate for the K value. | --                    | --                    | Through inverse modeling, we could try to estimate K from the earthflows where we have a good age control. However, as the referee pointed out earlier, the morphology of the earthflow can also be affected by the velocity of the earthflow so initial roughness wouldn't be the same across all earthflows.                                             |
| Line 285: This isn't quite clear, do the flows being cut have lower MADstd values?                                                                                                                 | 326                   | 435                   | We added a clarification that the cut flows have lower MADstd values.<br><br>“Of these, 16 had MADstd values consistent with the cross-cutting relationship where the on-lapping earthflow had higher MADstd values than the underlying earthflow.”                                                                                                        |
| Figure 7 B-D. it is unclear what is happening in these panels. The polygons could be labelled with their MADstd values and the cross-cutting relationships can be made more obvious.               | Figure 7              | Figure 7              | Polygons have been labelled with MADstd values to make the relationships more obvious, and lines now link each panel to the category in panel A that they represent. Figure caption is expanded.                                                                                                                                                           |
| Lines 294-299: This is only true if there is clear evidence of erosion of the toes of the older flows                                                                                              | 343-344               | 456-57                | That is true, and we see evidence for erosion back to the valley walls in Figure 4, where low MADstd earthflows (light pink colors) fall along the                                                                                                                                                                                                         |

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|                                                                                                                                                    |                     |                     | regression line of non-landslide terrain. We added a sentence: “Earthflows with low MADstd values are near the regression line for non-landslide terrain, suggesting their toes have been eroded to the valley walls (Figure 4).” |
| Figure 8: Could have activity threshold marked on the histograms                                                                                   | Figure 8            | Figure 8            | Added a grey bar to the background of the histograms that shows the 0.13-0.15 MADstd activity level.                                                                                                                              |
| Line 350: Is there a preferential rainfall or wind direction?                                                                                      | --                  | --                  | We could not find this data. In the field, we don’t see a strong aspect dependence for vegetation, which we would expect to see if there is a preferential rainfall direction or even wind direction.                             |
| Line 398 – 400: Is there a photo of the field observations?                                                                                        | Supplement Figure 1 | Supplement Figure 1 | Images of the toes of earthflows are now included in the supplemental information as Supplemental Figure 1.                                                                                                                       |
| 322 typo - primarily should be primary                                                                                                             | 372                 | 487                 | Corrected to primary.                                                                                                                                                                                                             |
| 365 the extent of earthflow activity?                                                                                                              | 417                 | 534                 | Replaced ‘glaciation’ with ‘earthflow activity’                                                                                                                                                                                   |
| 373 Probably add Bennett 2016 to this sentence somewhere - <a href="https://doi.org/10.1002/2016GL068378">https://doi.org/10.1002/2016GL068378</a> | 43-45, 116, 425     | 55-57, 144, 542     | Added Bennett 2016 reference w/regards to climate correlation, and added to the introduction.                                                                                                                                     |
| 404 change ‘slopes’ to ‘channel slopes’                                                                                                            | 457                 | 575                 | Inserted ‘channel’ before ‘slopes’                                                                                                                                                                                                |