Authors' Response to Reviews of

"Controls on the formation and size of potential landslide dams and dammed lakes in the Austrian Alps"

Anne-Laure Argentin et al.
Natural Hazards and Earth System Sciences, https://doi.org/10.5194/nhess-2020-326

RC: ***Reviewers' Comment***, AR: Authors' Response

AR: Dear Andreas Günther,

We resubmit a revised version of our manuscript "Controls on the formation and size of potential landslide dams and dammed lakes in the Austrian Alps" to consider for publication in Natural Hazards and Earth System Sciences. First, we want to thank the two reviewers for their detailed and very constructive reviews. We appreciate their effort, which helped us to strongly improve our manuscript. We addressed almost all raised issues and revised our manuscript according to the reviewers' suggestions. Both reviewers considered our manuscript as an interesting contribution to the landslide dam community and we are confident that the revised version of this manuscript meets the high-quality standards of this journal. Before going into the details of the point by point response, we would like to emphasize the main modifications of the revised manuscript.

• As suggested by the anonymous reviewer #1, we now dedicate a whole section to each of the main limitations of the study (uniform slope thresholds, rheological model) in the Discussion. We also furthered our analysis of the impact of rheology on the landslide dam and lake geometry (Supplementary Fig. A1).

• We added a paragraph on the Austrian Alps in the Introduction as requested by the anonymous reviewer #2 and reformulated all unclear sentences and paragraphs.

• We also took into account the new work from Fan et al. (2020), which provides a new and extensive landslide dam database that we use for comparison in Figure 5. This new validation dataset fits well with our results.

As requested by both reviewers, we further performed slight modifications to the text for enhanced clarity and style.

The changes made in the manuscript can be visualized thanks to the Latex package TrackChanges. The modifications suggested by reviewer #1 and reviewer #2 are written in Blue and Green, respectively. The changes linked to the new dataset from Fan et al. (2020) are displayed in Purple while English corrections are made in Turquoise.

Thank you very much for the editorial handling.

1. Anonymous Referee #1, Received and published: 23 February 2021

RC: ***Anne-Laure Argentin et al. entitled "Controls on the formation of potential landslide dams and dammed lakes in the Austrian Alps", present a process-based modeling approach to envision susceptibility of land-slide damming and lake formation by individually simulating the process chain from the initiation probability of landslides, land-slide runout, river obstruction and damming. The concept and the methods employed by the authors are thought-provoking and progressive and this manuscript would be significant***

for the engineering geological and natural hazard community. The idea to conceptualize the landslide dam hazard chain through a process-based modeling is appreciable. Nevertheless, the study may still need some additional elements or factors that can be considered, warranting a minor to moderate revisions to the manuscript paper to be accepted and this reviewer see the following suggestions shall be followed.

AR: We thank the reviewer for the thorough review of our manuscript and the pertinent comments formulated. We are very glad that the reviewer finds our article a significant addition to the scientific community and are confident that we addressed the issues raised in this revised version of the article. In this response we reply line by line to the suggestions made:

1.1. Major comment #1: Modeling the landslide release areas

RC: ***The authors adopted a slope-based criterion following Hergarten et al. 2012 to determine the probability of landslide release areas. The authors do mention the reason for their choice "The approach proposed by Hergarten (2012) still seems to be the only model in this context which is able to predict the observed power-law distribution of rockfall and rockslide volumes". However, the performance of the model in a terrain with lithological variations need to be questioned. Different rocks would have different thresholds with regards to slope angle and stability.***

AR: The first method used from Hergarten (2012) is an empirical method, which is not physically process-based. Although it seems intuitive that different rocks would have different thresholds with regards to slope angle and stability, as formulated for soil-mantled slopes and bedrock slopes (Montgomery, 2001), it has seldom been tested with bedrock slopes (Goudie, 2016) and does not explain some "over-steepened" slopes (Fernández et al., 2008). Furthermore, rock mass strength is a variable that is controlled by a large set of parameters (e.g. lithology, structural discontinuities etc.), and, to our knowledge, no thresholds are available based on rock mass strength for our study area.

RC: ***In addition, rockfalls possess strong sensitivity towards discontinuities. I would request the authors to perform a validation of their analysis of landslide probability.***

RC: ***Is it possible to compare the landslide probability estimated by the Hergarten et al. 2012 to actual events of landslides within different geological units of the study area? It would be nice to see the performance of the model for past cases at first and then use it to predict the future.***

AR: The reviewer is right to mention the influence of lithology and discontinuities on landslide triggering. Our method uses a statistical approach that only holds for extended regions, does not take into account lithological variations and structural discontinuities, and thus cannot be applied to reproduce case studies. Moreover, we assume that the different stability thresholds lead to an equafinality of results. Taking the same thresholds for the whole mountain range allows for a simple model. The topography is the main control of landsliding here. Furthermore, no temporal constraints are applied to our model, and we do not investigate any triggering return periods or landslide frequency. We thus call "density" and not "frequency" the number of landslide simulated per km^2. This density is closer to a landsliding potential, with high densities where not much landsliding has already occurred (i.e. in steep terrains).

We validated our model by visually comparing the landslides created with a landslide database over the Austrian Alps. However, to provide a better overview of the difference between landslide densities per tectonic unit, created a histogram of the landsliding frequency in each lithological unit for both our model and the database:

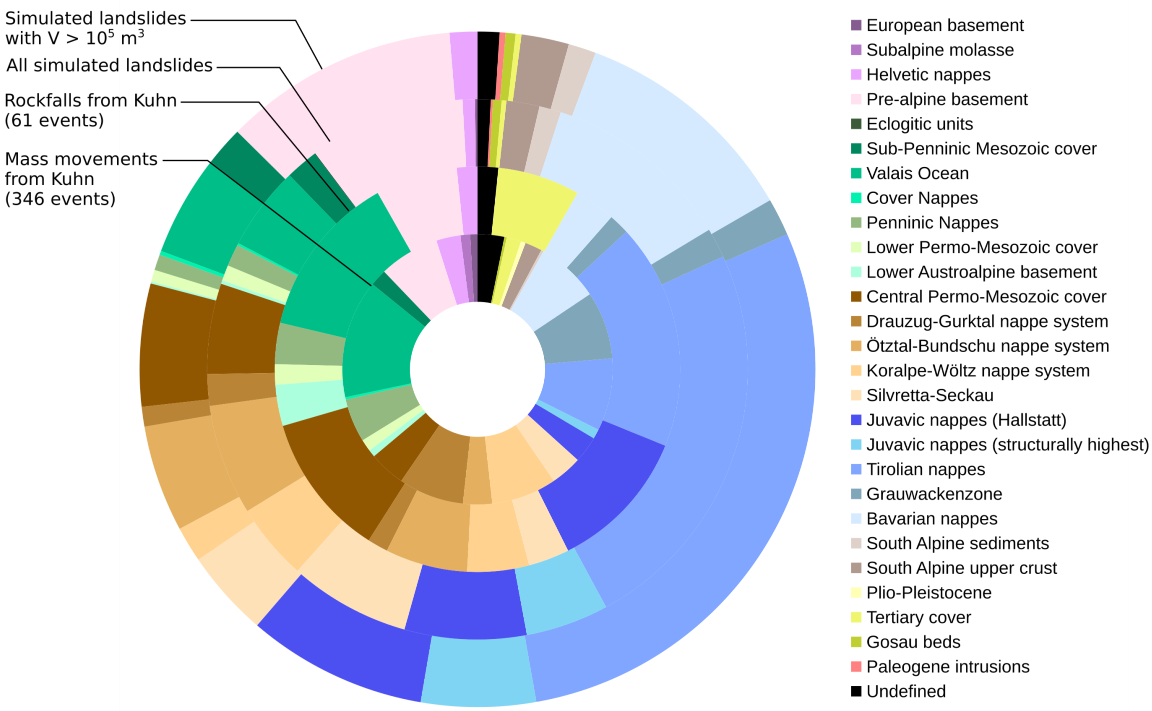

Figure 1: Comparison of landslide density depending on the Alpine tectonic unit. Each ring corresponds to a different dataset and the arcs length represents the landslide frequency for every tectonic unit.

The Tirolian nappes show a higher density of landslides in our model than in the datasets from Kuhn (visited 2020.07.27) (Fig. 1), which is logical since the time range investigated by the database is restrained. We notice that 1) the (computationally-driven) decision to choose landslides with $V > 10^5$ m^3 exacerbates differences with landslide database densities, 2) landslide densities are overestimated in steep terrains (e.g. calcareous nappes).

However, this model recreates the typical power-law scaling of landslides (Fig. 2, Tebbens, 2020), and changing the thresholds do not change the size distribution of landslides by much (Hergarten, 2012).

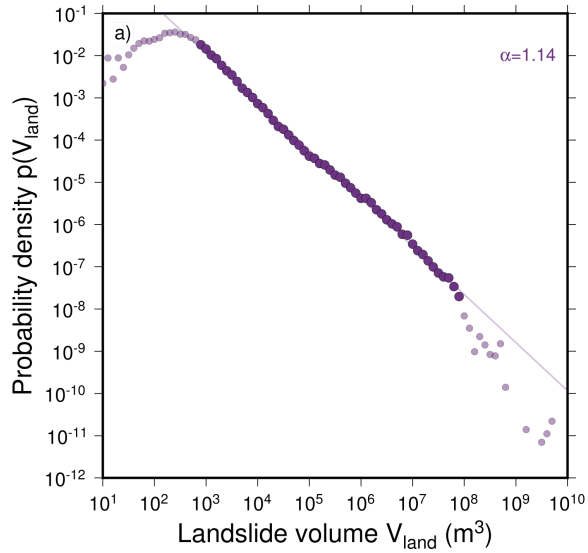

Figure 2: The landslide scaling of the landslides simulated in the model.

We clarified the aforementioned points in a new section of the Discussion. We expanded our paragraph to fully cover the limits of the method the reviewer signaled.

l. 441:

~~Simulations, however, tend to oversimplify reality and are based on various assumptions. We introduce simplifications in determining landslide release volumes and modeling fluid flow. These assumptions influence the shape and size of the deposits and their location relative to the river bed, which further controls the amount of impounded water. However, we use approaches and spatially uniform parameters validated in other studies (Hergarten, 2012; Hergarten, 2015; Hergarten, 2015). Further, we assume that lakes are filled to the brim, which might not always happen in reality, due to loss of water via groundwater flow through the landslide deposits or river bed substrate (Snyder and Brownell, 1996).~~
~~In our model to determine landslide release areas, we applied uniform stability thresholds, which are generally not well constrained and may also differ for different rock types. Thus, our model may not be able to reproduce the spatial distribution of landsliding. However, landslide inventories indicate that this is not the case for large, rapid mass movements on which we focus in this study, as large rock avalanches predominantly occur in steep landscapes with excessive relief made of strong rocks (Fig. 3). We thus conclude that our approach is suitable to qualitatively reproduce the distribution of potential large landslides and impounded lakes in a steep mountain range and to derive relationships between dam and lake size, the drainage system and valley morphology.~~

4.6.2 Uniform slope stability threshold

The determination of landslide release areas is crucial for our study. We employ an empirical model (Hergarten, 2012) that relies on the assumption of spatially uniform slope stability thresholds. We use the same slope stability thresholds for the entire Austrian Alps, which represents a distinct simplification. The study area hosts rocks that form differently steep landscapes, are characterized by potentially different rock mass strengths and therefore are likely to resist differently to erosive surface processes.

It is generally assumed that rock mass strength exerts some control on slope stability thresholds on bedrock slopes (Montgomery, 2001), which host the landslide release areas of the study region. However, this assumption has rarely been tested (Goudie, 2016) and can hardly explain the persistence of "over-steepened" valley flanks (Fernández et al., 2008) abundantly observed in glacially imprinted mid-latitude mountain ranges such as the Austrian Alps. In addition to rock type, a variety of other parameters, including weathering, tectonic stresses, type and orientation of discontinuities at different scales, influence rock mass strength (Augustinus, 1995).

However, this study focuses on regional patterns of landslide dams and lakes, and to our knowledge, no stability thresholds based on lithology or rock mass strength are available at this scale. Moreover, the model used here to determine landslide release areas (Hergarten, 2012) is so far the only model which is able to reproduce the typical power-law scaling of landslides (Supplementary Fig. E1; Tebbens, 2020). This scaling is not altered much by shifting the stability thresholds within a realistic slope range where rapid mass movements originate in mountainous areas (Hergarten, 2012). Furthermore, the power-law scaling applies to rockfalls but also to slides (Brunetti et al., 2009). As an advantage, taking the same thresholds for the whole mountain range allows for a simple model, where topography is the main control of landsliding. Indeed, the similarities between our results (Fig. 3) and inventory events imply that topography is indeed the main control on the spatial distribution and scaling of landslides and landslide-dammed lakes on this large scale of analysis.

RC: ***In addition, the overall work, stressing on the importance of the chain of hazards from landslide occurrence, runout, damming and lake formation seems a bit incomplete. The authors do quantify the probability of failure of each potentially unstable rock mass but, not provide a probabilistic assessment of the conditions that might trigger such instabilities (e.g., a return period of a triggering rainfall, a return period of a triggering earthquake). I suggest the authors to refer Fan et al. (2019) and add a line of discussion regarding the limitations of the landslide simulations and the validity of the assumption adopted in this study.***

AR: We added a new section in the Discussion on the absence of a timescale in our model, which prevents us from discussing the return period of triggering events. As a result, we talk about landslide "densities" for the number of landslides per area. Temporal constraints will be investigated in following work.

l. 461:
4.6.3 Lack of temporal constraints

While the employed landslide release area model (Hergarten, 2012) can provide release areas and related volumes, which cluster in the same regions as the events recorded in landslide inventories, and which are consistent with power-law scaling of landslides observed in nature, the model cannot predict timing or probability of failure of individual events. While such information would be of great value for natural hazard mitigation, neither field data as input parameters nor any of the existing state-of-the-art models can currently provide such an information at the scale of an entire mountain range. Hence, modeling results cannot be interpreted in terms of landslide-damming probability, nor in terms of return periods, which is also far beyond the scope of this study. As a consequence, we use the term landslide "densities" for the number of landslides per area to avoid misinterpretations in terms of time dependence (e.g. probability of occurrence or recurrence interval).

1.2. Major comment #2: Landslide runout simulation and #3: Estimation of landslide dam geometry

RC: ***The authors adopted Voellmy rheology to model the landslide runout with variables $\xi = 150 m.s^{-2}$ and $\mu = 0.12$. It is common to use such constant values for different lithologies within a large area of a numerical model. However, the same need to be justified. In general, these values are obtained through back calculation of landslide runouts using known case examples. Regarding the calibration of the models, and in particular of Gerris, the authors need to discuss the choice of their parameters. Also, the authors should discuss why they think the parameters should be the same for all the subsequent events all over the study area (e.g., why should the acceleration remain the same? and the friction?).***

RC: ***It is appreciable that the author attempted to simulate the landslide dam geometry at a larger scale. Their explanation of the calculation of landslide dam volume and geometry seems simple cutting down different realities but still acceptable considering the scale of the numerical simulation. However, the limitation of the approach used in this study need to be clearly mentioned. Please refer to Hungr (2011) for more insights on a comparative study on the use of landslide runout models to predict landslide dam geometries.***

AR: Two very good points, indeed. We chose to discuss and take into account the comments #2 and #3 together since they are strongly linked.

Rheology determination is important and especially tricky for landslide runout modeling. Rheology matters because its choice controls the landslide dam geometry (Hungr, 2011), as shown by the consistent impact our Voellmy parameters have on dam height (Supplementary Fig. A1). However, rheology determination is not an easy task, and usually needs the back analysis of a case study. Since rheology is linked to lithology, different landslides will present different runout rheologies. Rheology can also vary spatially in a single landslide event, when two different rock types are involved, or temporally, when a change in physical conditions happens during the landslide runout (Hungr and Evans, 2004).

However, we have no way of knowing how the rheology might vary over the study area, let alone temporally or spatially in a single case study. Using the same rheology over the whole Austrian Alps enables an easier analysis of the results based on the topography. If we were to add too much complexity, we would not be able to infer which effect controls which result.

Furthermore, landslide dam geometry influences the lake geometry in a complex manner. We show that although the Voellmy parameters have a consistent impact on dam height, this does not translate to consistent changes in lake depth or lake volume (Supplementary Fig. A1). Thus we assume that different rheologies would not necessarily lead to a statistically significant change in lake volumes.

For those two reasons, we decided to use the same rheological coefficients for all events in our study. We assume that all landslides are similar and exhibit the same rheology. Furthermore, using homogeneous parameters ensures we can easily compare the resulting dam geometries. Thus, we relied on the back analysis of landslide runout from Sanne (2015) on the Val Pola event to set our Voellmy rheology parameters.

We dedicated a section of the Discussion on rheology and its impact on landslide runout and landslide dam geometries.

> l. 470:
> 4.6.4 Rheological model
>
> The determination of the rheology of the moving landslide mass is crucial as the chosen flow resistance law (i.e. Voellmy rheology) and the applied parameters control the run-out distance and the landslide

dam geometry (Hungr, 2011). Landslide rheology may be controlled by lithology, but may also vary spatially within a single landslide event, when different rock types are involved, or temporally, when a change in physical conditions (e.g. water content, path material) happens during the landslide runout (Hungr and Evans, 2004; Aaron and McDougall, 2019). For individual landslides, rheology parameters are in general determined by a back analysis of the event itself or events in the same region (Mergili et al., 2020). However, considering this level of detail for an entire mountain range would require back-analyzing a large number of landsliding events, which is far beyond the capabilities of this investigation.

Runout simulations are type-specific (Hungr et al., 2001; Dorren, 2003), but most of the rockfalls with $V > 10^5$ m^3 have a long runout (i.e termed "rock avalanche") and can be simulated accurately if the correct rheology model is used (Körner, 1976). Here, we apply the Voellmy flow resistance law with the parameter set determined by a back analysis of the well documented Val Pola landslide (Sanne, 2015) to all simulated landslides of this study. As a benefit of a uniform parameter set, we can directly compare dam geometries and related lakes across the Austrian Alps and attribute spatial variations to topography. To explore the influence of the two Voellmy parameters ξ and μ on dam height, we performed a parameter study starting with the ξ / μ parameter set originally determined by Sanne (2015) (Supplementary Fig. A1). The parameter study at ten different locations shows that dam height increases with μ. While increasing ξ causes an increase in landslide velocity and runout distance, we only observe a slight negative impact on dam height. As long as the parameter sets are suitable to describe the behavior of large landslides in alpine regions (and not mudflows or lahars with a completely different rheology unsuitable to form major dams) our parameter study implies that different rheologies will change the dam geometry to some extent but will not necessarily lead to a statistically consistent change in lake depth and volume (Supplementary Fig. A1).

1.3. Major specific comment #4

RC: ***Landslide dam characterization: In addition to the height ratio-based characterisation of the simulated landslide dams, is it possible to identify the type of dams according to Costa and Schuster (1988); Fan et al. (2020); Hermanns et al.(2011)? The authors do mention the type of landslide dams in lines 150 using simplified planform geometry. There are also other predominant types of landslide damming based on morphology though not specific to rockfall/rockslide formed landslide dams.***

AR: In the current state of our work, a planform characterization of the simulated landslide dams would be difficult: it implies an automatic recognition of shapes in planform view. Our dams sometimes exhibit complex shapes, with landslide deposits spread across valley flanks and valley floors. The planform geometries would require we make the distinction between deposits that sedimented on the valley flanks and those that actively contribute to valley damming. Furthermore, some landslides separated in two valleys during their runouts, and thus form two distinct deposit areas. This distinction would require another non-trivial algorithm. The reviewer comment is however a very good idea for further work.

RC: ***I would like to see some discussion regarding the preciseness of the geomorphometric parameters identified and used in this study (Table 1).***

AR: We added a sentence which explains the difference between preciseness and uncertainty for our geomorphometric parameters, and introduces the aforementioned methodological limits which are responsible for this uncertainty.

l. 437:
In contrast to field measurements, geomorphometric parameters obtained in a modeling study are highly precise, but assumptions and approximations made along the numerical process chain introduce uncertainty to the results.

1.4. Major specific comment #5

RC: ***Dam formation and stability indices: The authors mentioned that their model cannot predict the stability of landslide dams. It is okay that the authors predict only the occurrence of landslide dam and lake formation and not the dam-breach or breach-induced flooding. However, the most significant part of this study on a hazard point of view is also to envision the relative stability of longevity of a landslide dam in the future if such events occur. On a true sense, the dam-breach and the outburst flood caused is the most threatening hazard than the landslide and damming itself. In a similar study by Fan et al. (2019), the actual dam-breach and flooding was simulated for different scenarios and the same has been compared with different empirical stability indices. I suggest the authors to refer and add some lines of expressions.***

AR: We added a few lines on the necessity to model the dam-breach to assess the hazards coming from landslide-dam failures.

l. 510:
From a hazard point of view, our study statistically models the initial steps of a natural hazard cascade. A logical extension of this work to be covered in future research would thus be a dam-breaching model (Fan et al., 2019) to simulate the longevity and stability, as well as the failure mode of the created dams.

RC: ***I also suggest the authors to add more lines of discussion regarding the performance of stability indices. The authors do mention BI,II, DBI, Is, Ia and HDSI are inconclusive in the Eastern Alps. This also depends on the availability of data as mentioned in a previous study by Fan et al. (2020).***

AR: We reformulated this part. The reviewer's concerns about the availability of data (Fan et al., 2020) apply to the study of Dufresne et al. (2018), which found the BI, II, DBI, Is, Ia and HDSI inconclusive in the Eastern Alps based on a handful of case studies. However, our study presents a total of 1057 events, and those events do not present consistent stability assessments across indices. Although we cannot infer from this study which indice and which thresholds are best suited for the Eastern Alps, we can conclude that they do not agree with each other.

l. 410:
~~Our model cannot directly predict the stability of the modeled landslide dams, but we calculated several common stability and obstruction indices for our results. The obtained obstruction and stability patterns differ tremendously. A correspondence with the metrics of our modeled landslides, represented by $\frac{H_{lake}}{H_{dep}}$ in Fig. 6, is only obvious for the II and the DBI. For these indices, stability decreases with increasing size and depth of lakes and increasing lake depth relative to deposit height. All other investigated indices seem to depend on regionally constrained stability classes and are thus not easily transferable to other regions. This finding is backed by the results of Dufresne et al. (2018), who found the BI, II, DBI, Is, Ia and $HDSI$ inconclusive in the Eastern Alps.~~

The obstruction and stability indices calculated from our 1057 simulated landslide dams do not provide consistent assessments. This finding corroborates the results of Dufresne et al. (2018), who also found the indices BI, II, DBI, Is, Ia and $HDSI$ inconclusive in the Eastern Alps.

However, since our model cannot directly predict the stability of the modeled landslide dams, we can only conclude that they are inconsistent but cannot rate the performance of the indices in the Austrian Alps. The II and DBI are the two only indices showing a relationship with the metrics of our modeled landslides, represented by $\frac{H_{lake}}{H_{dep}}$ in Fig. 6. For these indices, stability decreases with increasing $\frac{H_{lake}}{H_{dep}}$, as well as increasing catchment area, lake volume and depth. All other investigated indices seem to depend on regionally constrained stability classes and are thus not easily transferable to the Austrian Alps.

1.5. Minor comment #1

RC: ***The authors performed a well throughout study and I appreciate their efforts. I feel the English language presentation need improvement though myself neither a language expert or a native English speaker.***

AR: We noted the reviewer comment, asked for English feedback from colleagues and corrected some language issues.

1.6. Minor comment #2

RC: ***Since the introduction part I felt many sentences are not connected to form a nice story. The authors shall imagine the geological processes in sequence and start from the conditions of landsliding and go on write about the events until for the formation of landslide dam and lakes. This will help the readers to understand the authors are focusing on an important large-scale geological hazard chain.***

AR: We re-wrote part of the introduction to form a nicer story.

References cited by the reviewer:

Costa, J.E. and Schuster, R.L., 1988. The formation and failure of natural dams. Geological society of America bulletin, 100(7): 1054-1068.

Fan, X., Dufresne, A., SivaSubramanian, S., Strom, A., Hermanns, R., Tacconi Stefanelli, C., Hewitt, K., Yunus,A.P., Dunning, S., Capra, L., Geertsema, M., Miller, B., Casagli, N., Jansen, J.D. and Xu, Q., 2020. The formation and impact of landslide dams – State of the art. Earth-Science Reviews, 203: 103116.

Fan, X., Yang, F., Siva Subramanian, S., Xu, Q.,Feng, Z., Mavrouli, O., Peng, M., Ouyang, C., Jansen, J.D. and Huang, R., 2019. Prediction of a multi-hazard chain by an integrated numerical simulation approach: the Baige landslide, Jinsha River, China. Landslides.

Hermanns, R.L., Folguera, A.,Penna, I., Fauqué, L. and Niedermann, S., 2011. Landslide dams in the Central Andesof Argentina (northern Patagonia and the Argentine northwest), Natural and artificial rockslide dams. Springer, pp. 147-176.

Hungr, O., 2011. Prospects for prediction of landslide dam geometry using empirical and dynamic models, Natural and Artificial Rockslide Dams. Springer, pp. 463-477.

2. Anonymous Referee #2, Received and published: 8 March 2021

RC: ***I have revised the article "Controls on the formation of potential landslide dams and dammed lakes in the Austrian Alps" submitted by Anne-Laure Argentin and co-authors. The article discusses modeled landslides, landslide dams and dammed lakes, introducing an approach that combines a probabilistic approach to determine landslide release areas and a fluid dynamic model to compute runouts. The article is interesting but requires revisions before publications. A short introduction of the study area and available data should be added in chapter 2. It's not very clear what type of failures you model (debris flow, slide). Several comments are reported throughout the text. The manuscript should be revised by an English speaking person before publication.***

AR: We thank the reviewer for the thorough review of our manuscript and the pertinent comments formulated. We are pleased that the reviewer found our article interesting. Some of the raised issues originate from a lack of clarity on our part and we are convinced we overcame those problems by restructuring and improving our wording. We discuss here the revisions suggested by the reviewer line by line.

2.1. Comments

RC: ***l. 2: the entire territory of the Austrian Alps?***

AR: Yes.

RC: ***l. 3: it's not very clear which type of landslides? & l. 4: debris flow? & l. 72: Describe better which type of landslides you are considering in your modelling. Rockfall and rockslide? Debris flow? & l. 78-79: (About slope thresholds) this is quite different from rockfall or rockslide & l. 96: (About runout simulation) Now you are not considering the failures as rock fall (line 74). Correct? & l. 114-115: (About runout simulation) You have selected "The approach proposed by Hergarten (2012) still seems to be the only model in this context which is able to predict the observed power-law distribution of rockfall and rockslide volumes" and now rockfall are not evaluated. Explain better.***

AR: Good questions. We do not specify the type of landslide, as this model (triggering + runout simulation) can be applied to any landslide type with high volume. The triggering model from Hergarten has been defined to reproduce the statistic distribution of rockfalls (Hergarten, 2012). Since slides also follow the same distributions (Brunetti et al., 2009) we can use the same algorithm. Runout simulations are indeed type-specific (Hungr et al., 2001), but most of rockfalls with $V > 10^5\ \mathrm{m}^3$ would have a long runout and be termed "rock avalanche" (Dorren, 2003). Rock avalanche runouts can be simulated accurately if the correct rheology is used (e.g. Val Pola Sanne, 2015). We chose to use the same rheology for all events to keep a simple dataset.

We discussed this landslide type question in the sections 4.6.2 and 4.6.3 of the Discussion.

> l. 456:
> Furthermore, the power-law scaling applies to rockfalls but also to slides (Brunetti et al., 2009).

> l. 479:
> Runout simulations are type-specific (Hungr et al., 2001; Dorren, 2003), but most of the rockfalls with $V > 10^5\ \mathrm{m}^3$ have a long runout (i.e termed "rock avalanche") and can be simulated accurately if the correct rheology model is used (Körner, 1976).

RC: ***l. 7: "small landslides damming large lakes" is the opposite of "lake volume increases linearly with landslide volume" that you say in the same sentence & l. 9-11: what do you mean with more efficient?***

AR: We meant to define what we call "efficient damming", but we reformulated the text since it was not clear.

> l. 6:
> In line with real-world inventories, ~~and~~we further found that lake volume increases linearly with landslide volume in case of efficient damming ~~, i.e. small landslides damming large lakes~~- when an exceptionally large lake is dammed by a relatively small landslide deposit.

RC: ***l. 55: Add a short description of the study area and the available data, including the inventories you mention in the text. & l. 62: which is the resoluton?***

AR: We added a descriptive paragraph of the study area to the manuscript, as well as the mentioned inventory. The ASTER DEM has a 1 arc second resolution. We added this information to the article.

> l. 59:
> The Austrian Alps are a perfect natural laboratory to investigate the impact of differing landscape geometries on properties of potential landslide-dammed lakes. Beside the availability of a high resolution DEM (Open Data Österreich, starting 2015), a detailed geological map (Bousquet et al., 2012; Schmid et al., 2004) and an extensive landslide inventory (Kuhn, visited 2020.07.27), the study area features various topographic patterns related to contrasting lithological units and different climatic forcing (e.g. Robl et al., 2015). The topographic evolution of the Eastern Alps, of which the Austrian Alps are an essential part, started with the Late Oligocene - Early Miocene indentation of the Adriatic microplate into Europe (e.g. Handy et al., 2015). While timing and rates of topography formation of various parts of the Eastern Alps are still debated (see Bartosch et al., 2017, and references therein), north-south shortening and crustal thickening in concert with fluvial dissection by major alpine drainage systems (e.g. Inn, Salzach, Enns, Mur, Drau drainage systems) caused the formation of mountainous topography, with deeply incised valleys separated by interfluves with mountain peaks rising above 3 km. Located at mid-latitudes, the Austrian Alps were partly glaciated during the Pleistocene and still feature glaciers at the summit domains. While the topography in the western half of the study area was intensely reshaped by repeated glaciations, the eastern half shows a purely fluvial landscape (Fig. 3; Robl et al., 2008, 2015). Since major tectonic units with their characteristic lithological inventory strike west-east (Fig. 4; Bousquet et al., 2012; Schmid e we can directly compare the impact of glacial and fluvial dominated landscapes on occurrence and size of landslide dammed lakes within individual tectonic units. This allows a distinction between lithological and climatic control.

> l. 82:
> The geophysical relief is based on the 1 arc second ASTER GDEM V3 (NASA/METI/AIST/Japan Spacesystems, and U.S./Japan ASTER Science Team, 2019). We use an Austrian landslide inventory containing the location of 194 events (Kuhn, visited 2020.07.27).

RC: ***l. 65-66: this semtence here has no real meaning***

AR: We reformulated the sentence.

> l. 87:
> However, ~~as the geological and structural variability remains high within the tectonic units~~the tectonic units are not homogeneous and comprise a high lithological and structural variability. Since lithology and discontinuities are a big control for erosion resistance, we do not venture to classify ~~them~~the tectonic units according to resistance to erosion.

RC: ***l. 68: moving window***

AR: We changed the wording.

RC: ***l. 73-74: About "The approach proposed by Hergarten (2012) still seems to be the only model in this context which is able to predict the observed power-law distribution of rockfall and rockslide volumes." -> Can you justify better this choice? Can you justify better the context of your application that justify this choice? & l. 88-89: (On the dependency of slope thresholds on lithology) In your analysis you have assumed that this statement it's acceptable. Is this reasonable in the test area?***

AR: Yes, we dedicated a section in the Discussion to talk about the use and limitations of this method. The context of this study is the requirement to use a computationally efficient algorithm. We reformulated this part.

> l. 96:
> The approach proposed by Hergarten (2012) still seems to be the only model ~~in this context~~ which is able to predict the observed power-law distribution of rockfall and rockslide volumes in a simple and computationally efficient manner.

Very good question. The model we use for this simulation is empirical and reproduces the size frequency distribution of landslides at the mountain range scale (Fig. 2). We answered this question in more detail in the reply to the Major comment #1 of Referee #1.

RC: ***l. 75: explain better***

AR: We added some explanation.

> l. 98:
> First, the algorithm stochastically chooses a seed pixel (i.e. a randomly picked pixel), then classifies the pixel slope to determine the stability of the local rock mass.

RC: ***l. 79: landslide area or volume?***

AR: Well, it's both at the same time. The source area is expanding when the slope of the neighboring pixels is not stable, thus also increasing the landslide volume.

RC: ***l. 83: how do you evaluate the thickness?***

AR: With the algorithm mentioned above, we remove material until a stable slope condition is reached. The height of removed material per pixel is the evaluated thickness of the landslide at the pixel location.

RC: ***l. 86: Removed typo.***

AR: Thank you.

RC: ***l. 92: (About memory issues) which is the extent of your study area?***

AR: The study area is the whole of Austria, and the DEM weights more than 7.4 Go. Some computations do not support such a massive input area.

RC: ***l. 93: this means that the tiles are overlapping? what is the dimension of the buffer?***

AR: Exactly, the tiles are overlapping because we need space to simulate the landslide runouts. However, those overlapping areas are only taken once into account for triggering landslides. The buffer dimension is 10.25 km.

RC: ***l. 107-108: It's not clear how did you model the lake volume starting from the runout of the landslides. Cases shown in fig. A1, are real cases?***

AR: I see, I guess we mention this too early on, since we have not yet explained how we obtained the lake volumes.

No, the cases shown in A1 are simulated cases. We modified the figure caption.

> Supplementary Figure A1:
> for 10 ~~example~~simulated landslides.

RC: ***l. 123-124: not clear***

AR: Just a technical detail. We need to cut the DEMs again in smaller parts for the landslide simulations. We deleted this sentence which seems to distract the readers from the process.

RC: ***l. 161: can you explain better?***

AR: We reformulated the sentence.

> l. 185:
> stability criteria aim to assess dam stability (e.g. the probability of the dam not failing) from simple geomorphometric parameters.

RC: ***l. 162: In most of the indices you have Volumes. Explain how did you compute them***

AR: The landslide volumes are computed using the algorithm from Hergarten as described previously: the total of all removed material on top of each pixel in the source area constitutes the landslide volume. The lake volume is computed by filling the DEM (with simulated landslide) with a common GIS algorithm and making the difference with the topography before filling. This is explained in the previous sections.

RC: ***l. 165 & 168: explain***

AR: A_b is the catchment area upstream of the landslide dam (l. 138 & l. 141). We modified the text to remind the reader of the meaning of A_b so they do not have to scroll back up.

RC: ***l. 191: 1) how did you selected the seed pixel? 2) this the procedure proposed by Hargarten. Correct?***

AR: 1) The seed pixel is randomly chosen. 2) Yes, exactly.

RC: ***l. 192: did you select all the Austrial Alps?***

AR: Yes, we launched the simulation on all the Austrian Alps.

RC: ***l. 193: 1) Is this an available dataset? if this is the case it should be described before (in the material) 2) can you add this data and its use in the workflow ?***

AR: No this is not an available dataset, this is the result of the simulation on the Austrian Alps. To avoid any confusion, we added a priming sentence to the result sections, and we modified the title of the first section.

> l. 216:
> We calculated landslide release areas with 100 landslide seeds per km^2 and obtained 1057 ~~landslides with volumes~~release volumes larger than 10^5 m^3 in the Austrian Alps. We then used these release volumes and simulated the runout of landslides. We further investigated if landslide-dammed lakes are formed. In the following result sections, we describe the 1057 simulated landslides and landslide-dammed lakes: their spatial distribution, their geometric characteristics and their associated stability and obstruction indices.
>
> 3.1 Distribution of simulated landslides and landslide dams across the Austrian Alps

RC: ***l. 197-198: not clear***

AR: We reformulated the sentence.

> l. 224:
> Modeled landslides (Fig. 3, white circles) and inventory landslides (Fig. 3, green circles) show ~~a~~ similar spatial pattern ~~(Fig. 3, white circles). This indicates~~s, thus implying that the spatial heterogeneity in landslide occurrence arises from ~~differences in~~ landscape characteristics.

RC: ***l. 198-199: high slope angle?***

AR: Yes, definitely. If the local slope is high, the landslide density will be higher. We reformulated.

> l. 226:
> ~~For our modeled landslides,~~High local slope has a strong positive influence on simulated landslide density, while high landslide volume is rather ~~controlled~~driven by high relief.

RC: ***l. 200: what do you mean?***

AR: We changed the formulation.

> l. 228:
> ~~Spatial coincidence of a~~Areas with high and low geophysical relief values spatially coincide with contrasting tectonic units (compare Figs. 3 and 4) . This suggests that lithology ~~as~~exerts an important control on geophysical relief and hence landslide occurrence in the study region (Fig. 4).

RC: ***l. 202-203 & 204-205: it is very difficult to find the formations in the map becouse colours are too similar***

AR: We tried to improve the readability of the map by numbering the tectonic units on the map and in the legend. However, we found the current figure to be more clear. We added a reference to an article presenting a high-definition version of the map for better readability (Schmid et al., 2004).

RC: ***l. 206: add reference***

AR: Ok, we added a reference.

RC: ***l. 211: Did you mapped fluvial and glacial valleys in the entire Austria? In table 3 what is the area? How did you compute the area of density? km2 of what? glacial and fluvial valleys? I would expect larger volumes in glacial valley but smaller density.***

AR: No, we used the extent of the Last Glacial Maximum to deduce the extent of glacially imprinted landscapes. The area in Table 3 is the glacially imprinted area (glacial) and non-glacially imprinted one (fluvial). We computed the densities by dividing the number of landslides happening in the glacially imprinted landscapes (resp. fluvially imprinted) by the glacial area (resp. fluvial area). The unit is thus in "landslide.km^{-2}".

Yes, very good point. We indeed have larger landslide volumes in glacially imprinted areas. However, glacial valleys are prone to high landslide frequencies following glacial recession (Hartmeyer et al., 2020). Nonetheless, the "density" we are talking about in this section is not a "frequency", since we do not include any temporal constraints in our model. We added an explanatory paragraph in the discussion about this.

> SAME AS REVIEWER #1 COMMENT 1:
> l. 461:
> 4.6.3 Lack of temporal constraints
>
> While the employed landslide release area model (Hergarten, 2012) can provide release areas and related volumes, which cluster in the same regions as the events recorded in landslide inventories, and which are consistent with power-law scaling of landslides observed in nature, the model cannot predict timing or probability of failure of individual events. While such information would be of great value for natural hazard mitigation, neither field data as input parameters nor any of the existing state-of-the-art models can currently provide such an information at the scale of an entire mountain range. Hence, modeling results cannot be interpreted in terms of landslide-damming probability, nor in terms of return periods, which is also far beyond the scope of this study. As a consequence, we use the term landslide "densities" for the number of landslides per area to avoid misinterpretations in terms of time dependence (e.g. probability of occurrence or recurrence interval).

RC: ***l. 263-264: Can you add in the figure the real data as done before?***

AR: We tried adding the real data to the Figure 6 as done for the Figure 5, but found the resulting figure displayed too much information.

RC: ***l. 263-264: Have you tried to plot in different graphs fluvial and glacial landslide dams? & l. 291: Have you tried to plot separately glacial and fluvial data?***

AR: Yes, we plotted in Supplementary D1 the fluvial and glacial landslide dams separately.

RC: ***l. 264: can you explain why there are many undefined?***

AR: Yes, a range was said to be "Undefined" when the events found in it exhibited variable behaviors (Partial obstruction, Complete Obstruction, Stable, Unstable). The "Undefined" ranges are particularly wide since no consistent trend was found in it (Korup, 2004; Tacconi Stefanelli et al., 2016). We changed the formulation.

> l. 292:
> Undefined: ~~A mix of other categories~~the landslide dams are either partial, (complete-)unstable or (complete-)stable.

RC: ***l. 296: English is not always very clear: it should be revised by an English speaking person***

AR: We asked one of our colleagues to revise the manuscript and made small corrections.

RC: ***l. 311: ?***

AR: "in" We corrected our typographical error.

RC: ***l. 313 & 314: not clear***

AR: We restructured this paragraph.

l. 341:
~~We suggest, that this can be attributed to the influence of valley geometry, such that efficient damming in well-developed valleys (i.e. valleys with distinct valley flanks) is predominantly reported in inventories, while small lakes dammed by large landslides outside of clear valley structures are missed. We further impute this variability in our results to the disposition of the deposited mass in the valley. Landslides that do not reach the main stream or deposit on the valley flank may only produce small lakes and hence present a low~~ $\cancel{\frac{H_{lake}}{H_{dep}}}$~~. On the other hand, landslides depositing homogeneously across the river bed should dam larger lakes and have a higher~~ $\cancel{\frac{H_{lake}}{H_{dep}}}$ ~~ratio, in particular in narrow valleys.~~
We relate this variability to the position of the landslide deposit in the valley. Landslides not reaching the main stream or depositing on the valley flank may only produce small lakes, and hence present a low $\frac{H_{lake}}{H_{dep}}$, while landslides depositing homogeneously across the river bed dam larger lakes and have a higher $\frac{H_{lake}}{H_{dep}}$ ratio. In contrast to our model, inventories predominantly report efficient damming in main valleys (i.e. valleys with distinct valley bottom and two flanks), while small lakes dammed by large landslides outside of clear valley structures (e.g. on valley flanks) are missed.

RC: ***l. 320: I do not see the valley geometry in the discussion below (chapter 4.1)***

AR: We are indeed not using any valley geometry metrics in this section, but we think that the valley topography partly explains the relations highlighted here. We replaced the first sentence.

l. 349:
~~Differences in valley geometry also seem to impact the scaling found in our data.~~
Modeled deposit (resp. lake) height decreases with increasing volume for large landslides, as found by Larsen et al. (2010), while small modeled landslides display an opposite scaling.

RC: ***l. 346: It's a little boit confusing what is is real and what has been modelled.***

AR: All this section discusses simulation results. We added some precision to the subsection titles.

l. 364 & 377:
4.2 Impact of glacial imprint on simulated landsliding and dam formation

4.3 Most efficient simulated lake damming in Austria

RC: ***l. 348: Do you mean Alpine regions?***

AR: Yes, we mean the Alpine regions, more precisely the Alpine tectonic units. We will change "regions" to "tectonic units".

RC: ***l. 371: where is the Ab in the graph?***

AR: A_b and $V_{landslide}$ are not directly plotted in the graph. We compute $V_{p\ lake}$ from A_b and $V_{landslide}$ and then plot $V_{p\ lake}$ against V_{lake}. We modified the graph caption and the equation and corresponding paragraph to avoid any confusion.

RC: ***l. 387: which one?***

AR: Climate and tectonics are two of those big differences between mountain ranges. Climate and tectonics include among other parameters precipitation rates and earthquakes. Those parameters are two of the main triggers for landsliding. Precipitation rates, in particular, influence the rheology of the landslides (Chen and Lee, 2003; Wang and Sassa, 2003) and thus the geometry of the formed landslide dams (Hungr, 2011). Thus rain-triggered landslides exhibit a different shape than earthquake-triggered ones (Chen et al., 2014). We reformulated the sentence.

> l. 420:
> ~~Topographic and other differences between mountain ranges likely explain p~~Part of the ~~differences~~discrepancies between modeled and real-world metrics ~~and correlations, but they~~(e.g. landslide and lake volume) are likely explained by topographic differences between our study area (Austrian Alps) and other mountain ranges we used for comparison. Variations in the topographic expression are related to lithological heterogeneity (contrasts in rock mass strength), climatic conditioning (e.g. fluvial versus glacial, rates of precipitation) and tectonic forcing (variations in timing and rates of uplift). However, the differences between modeled and real-world metrics may also be a consequence of uncertainties in field measurements and oversimplifications in the models.

RC: ***l.392-393: do you agree?***

AR: Yes, we agree with Korup and think uncertainties in the estimation of dam heights are partly responsible for differences between field and model results. We modified the sentence.

> l. 429:
> This effect is also mentioned by Korup, who suggests that uncertainties in the estimation of landslide dam heights are responsible for the difference between field and model results.

RC: ***l. 417: there not much evaluations on the drainage system***

AR: We modified "drainage system" to "drainage area".

> l. 494:
> Based on our results, we explored relationships between properties of landslides, landslide dams and lakes, and the drainage ~~system~~area and valley shape.

RC: ***l. 426 & 427: write the complete name***

AR: Ok, we added "Impoundment Index" and "Dimensionless Blockage Index" to the abbreviations.

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