Interactive comment on "Permafrost thaw couples slopes with downstream systems and effects propagate through Arctic drainage networks."

by

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The following document provides our replies to the detailed and constructive reviews of our manuscript provided by Dr. Julian Murton (R1) and Dr. Ingmar Nitze (R2). We wish to acknowledge their thoughtful reviews which have resulted in a number of minor editorial revisions to the text and figures that have improved the clarity of this manuscript.

R1. Dr. Julian Murton

The aim of the manuscript is to elucidate the [geomorphic, hydrologic and, to a lesser degree, sedimentary] processes and feedbacks that drive the [decadal] evolution of thaw-related mass movements and hillslope-channel coupling in ice-rich permafrost terrain of northwest Canada (lines, L108-111). The objectives (L121-123) are: " to better understand the (A) processes that drive the intensification of thaw-driven mass wasting and slope to stream coupling, (B) the distribution of catchment effects, and (C) their propagation across watershed scales,". The aim and objectives are important directly to the fields of permafrost geomorphology and hydrology, and indirectly to the fields of biogeochemistry, terrestrial and aquatic ecology, as well as to landscape management and ecosystem services. Personally, I would rephrase the objectives as aims (because the objectives given are really general statements of intent or goals) and identify specific objectives that signpost the ways in which the aims can be achieved and evaluated (because this is clearer in assessing how successfully aims are achieved). But to some degree this is a matter of author and journal preference.

The methods used apply high-resolution three-dimensional survey techniques (light detection and ranging, and drone-based structure-from-motion) and geographical information systems (e.g. to construct digital terrain models and determine stream ordering) to drainage basins whose area varies by orders magnitude in a study region of 1 million km2 in NW Canada. This allows the authors to address terrain characteristics and functional geomorphic-hydrological relationships at localized to regional scales. The methods are appropriate to the aims and objectives, and are presented clearly, systematically and rigorously as far as I can tell, though I am not an expert in GIS analysis, and so I cannot comment usefully on pages 1-8 of the supplementary information.

The results are largely new, clearly structured and presented well. The data represent a major contribution to terrain analysis on ice-rich permafrost, and the authors should be congratulated for bringing together this large and complex dataset. In particular, the focus on location of mass movements within catchments of different area, achieved through simple application of Strahler stream ordering, nicely identifies the first and second-order basins as particular centres of landscape change, and takes up functional and historical geomorphologists' consideration of scale and morphometric issues developed mainly since the 1950s in other regions. The narrative is illustrated by effective figures and tables, though some minor points need clarification (see below). The three videos provide valuable supplementary information. The length of this section is fine.

The interpretation is generally excellent, leading this reader step by step through the reasoning and contextualisation within the wider literature. The latter was particularly strong, as there has been substantial previous research on thermokarst terrain and processes in northwest Canada. The length of the interpretation could perhaps be shortened

by 10-20% to avoid repetition and bring out the key messages more clearly. Likewise, the conclusions, in my view, could you shortened to a number of key points, though again I appreciate that this is a matter of preference.

Overall, I think that this manuscript makes a substantial advance in our knowledge and understanding of the impacts of thaw-related mass movements on hillslope-stream coupling ice-rich permafrost catchments in northwest Canada. The approach used could be more widely applied in other regions of ice-rich permafrost (e.g. northern Alaska, NW Siberia and NE Siberia). I recommend publication subject to mostly minor revisions concerning points of clarification and typos, as listed below. Only two points of moderate significance are raised for consideration:

Reply to comments by Dr. Julian Murton (R1)

We are grateful for Dr. Murton's detailed and thoughtful review and provide replies to his comments in the following document. Following the recommendation of Dr. Murton we now refer to our statements of project intent as "Aims" or "Goals". We have also endeavoured to cut the length of the discussion and conclusions sections to avoid redundancy by about 10%. Minor elaborations required to address a few reviewer comments made greater reduction of manuscript length difficult. We feel that Dr. Murton's comments have improved clarity of the manuscript and we were able to implement his recommended changes through minor editorial modifications to the text and some figures. Dr. Murton's contribution to improving our manuscript is recognized in the Acknowledgements section.

Moderate points

Slope thermokarst (lines, L135-137, 195-197): Active-layer deepening and surface subsidence beneath a hillslope could reasonably be included in 'slope thermokarst', so I think this study is focussing on the most visible type of slope thermokarst, i.e. mass movement types. Perhaps this distinction can be made. 'Thaw-driven mass wasting' (L657) is a more accurate description of the focus of this manuscript than is 'slope thermokarst', in my view.

REPLY. We agree that slope thermokarst could indicate processes that extend beyond mass wasting. In the introduction we clarify that thaw-driven mass wasting process including retrogressive thaw slumping, shallow and deep translational failures comprise the most dynamic forms of slope thermokarst and that these processes are the focus of our study (L104). In some cases we still use the term "slope thermokarst", for instance where we make general statements such as "climate-driven intensification of slope thermokarst". We have made numerous adjustments throughout the manuscript and refer explicitly to thaw slumps where addressing this specific process, and to thaw-driven mass wasting, permafrost landslides or thaw-driven landslides when referring to a wider suite of processes which are included in broad-scale fluvial network analysis (L133).

Stabilization: a couple of sentences might be added to comment on the contrast between the recent decadal intensification of thaw-related mass movement and the stabilization of presumably the same terrain after the early Holocene climate warming. A reader might infer from the present argument that the recent trends are here to stay,

which may be true for decadal and centennial timescales, but I wonder if the early Holocene landscape suffered even more change over even longer periods (millennial), and then stabilized, preserving abundant buried ice. The authors insights into thaw and terrain change may help elucidate negative feedbacks the thermokarst system, as Lawson, Shur and others have done successfully in terms of thermokarst around ice wedges etc.

REPLY. We are not overly comfortable speculating on the negative feedbacks in great detail as it is beyond the scope of this study. Here we focus on contemporary processes and on providing a geological explanation for rates and patterns of slope thermokarst acceleration. The evolution of negative feedbacks is likely to be of relevance over time scales greater than a century. However, we acknowledge Dr. Murton's point and feel that it is a topic for further consideration in research examining conditions in the late Holocene through paleo-environmental methods. We have added a sentence in the discussion addressing Dr. Murton's point on L783-L786 "Several feedbacks could counteract the present intensification of thaw-driven mass wasting and increasing sedimentary and geochemical fluxes including climate cooling, exhaustion of sediment supply and progressive loss of ground ice from the most sensitive slopes, and gradual thaw-driven decreases in slope gradients, however these factors are likely to be most relevant at centennial time-scales or greater."

Minor points

L59: Prince of Wales Strait: mark on Fig. 1

REPLY. Changed as suggested

L62: North America's largest delta may be the Mississippi, a few thousand km2 larger than the Mackenzie. Please check.

REPLY. Minor editorial adjustment made indicating "…North America's largest **Arctic** delta and the Beaufort Sea."

L77: insert 'ice-rich' into this topic sentence, because thermokarst activity will not really affect permafrost with little or no ground ice, e.g. '…evolution of circumpolar ice-rich landscapes…'

REPLY. Changed as suggested.

L85: specify the nature of 'Arctic change' in the topic sentence as this encompasses many things, e.g. 'of environmental change in Arctic terrestrial and aquatic systems'.

REPLY. Changed as suggested.

L93: 'have' [subject is plural]

REPLY. Changed as suggested.

L106: do you mean 'thickness' (an interval) rather than depth (a single point), i.e. permafrost thickness?

REPLY. Changed as suggested.

L108-113: please shorten and simplify this long, complex sentence. It's a bit difficult to follow.

REPLY. Changed through editorial modification.

L121-124: this key sentence identifies the aims of the study. I think it would be clearer to simplify and rephrase along the lines 'The aims of the present study are (1)…' rather than squash them into a long introductory clause. The geographical region is of secondary importance relative to the more generic aims. Also, please specify the type of processes in (A), e.g. geomorphic, thermal …, and the nature of the distribution in (B), e.g. spatial and/or temporal.

REPLY. Changed through minor editorial modification.

L130: append 'climate' to 'cooling Holocene'.

REPLY. Changed as suggested.

L141: Tuktoyaktuk Coastlands [with an 's']

REPLY. Changed as suggested.

L144: clarify what is meant by 'fluvial patterns', e.g. river channel morphology, bedform architecture, sediment transport…?

REPLY. Changed through minor editorial modification.

L145: indicate Mackenzie Delta on Fig. 1

REPLY. Changed as suggested.

L151: indicate Amundsen Gulf on Fig. 1

REPLY. Changed as suggested.

L178: replace 'middle' with 'medium'

REPLY. Changed as suggested.

L181-184: indicate approximate depth of mean annual ground temperatures as much of the deeper layers of permafrost on Banks and Victoria islands etc. will be much warmer than -10^{o}C.

REPLY. Depth reference is now indicated as mean annual temperature at the top of permafrost (TTOP).

L192: insert 'other' before 'glacigenic materials' as tills are glacigenic.

REPLY. Changed as suggested.

L200: datasets: it's essential to identify all of the datasets used in the study rather than the non-specific word 'include'.

REPLY. A new supplementary table has been added (Table S1) to make explicit the datasets used in this study and the research questions that they address.

"To examine processes driving intensification of thaw-driven mass wasting and the patterns of effects across hydrological networks we applied multiple methods involving field study and mapping at slope, catchment, and watershed scales described in the following sections and summarized in Table S1."

L210: clarify what is meant by 'a continuum of slump features'. Continuum in what sense: activity, size, aspect…?

REPLY. Minor editorial adjustment made to clarify that the slumps represent a size continuum.

L228: subsidence: did some of the volumetric change on the slopes resulted from permafrost thaw and thermokarst subsidence beneath slump-floor sediments (cf. Burn 2000, CJES 37:967–981) or can this process be discounted?

REPLY. We make a minor editorial adjustment to clarify that volume changes within the scar zone include both thaw-subsidence and slope erosion.

L238: volumetric erosion: careful, the study is not directly measuring erosion but inferring erosion based on measurement of volume change. So an explicit parameter such as 'volume change' or 'disturbance volume' (L344) is more appropriate. There may be a better term, as I'm not familiar with GIS methodology.

REPLY. We replaced "erosional" with "disturbance".

L240: active or recently-active scar and debris tongues: on what criteria were these identified as such? e.g. lack of living vegetation or some indirect evidence of vegetation? L493 mentions bare or sparsely vegetated landforms. I find it difficult to know from many GIS studies what actually is being observed directly and what is being inferred.

REPLY. We clarify in the text that active or recently-active scar and debris tongues were interpreted by a distinct scarp and bare or sparsely vegetated scar area determined with the support of high resolution orthomosaic imagery.

L245, and supplementary L277: 'including': it is clearer to identify all of the criteria for designating a slump as '2'. Were there any other criteria besides the two mentioned, e.g. turbidity in rivers, as per caption of Figure S3ii?

REPLY. The text is clarified to indicate that evidence of downstream deposition is expressed as a debris tongue deposit in a valley bottom, or a sediment lobe protruding into an adjacent lake or coastline.

L275: insert 'and' after '2010'.

REPLY. Changed as suggested.

L299: "All mapping was reviewed for accuracy and consistency." Please explain how or cite a reference that does.

REPLY. Reference is provided to Kokoszka and Kokelj, 2020, which provides a detailed description of methodology and QA/QC procedures.

L319: data are treated as plural in this sentence; previously (e.g. L166, 209) they are treated as singular. Please ensure consistency.

REPLY. Minor adjustments on L166 and 209 ensure that data are treated as plural.

L331: routing … 'was'

REPLY. Changed as suggested.

L365: intensifying slope thermokarst: this implies that the rate of growth or the increase in number of slumps or both factors is accelerating in all cases. Is this correct for all slumps or just for some, e.g. CB?

REPLY. Minor editorial modification was implemented to clarify the sentence.

L366: 'eroded volume': again, can you be sure that thermal erosion accounted for all of the missing volume, or might thermokarst subsidence have contributed to the missing volume?

REPLY. We clarify that volume loss associated with thaw slump development is a function of both sediment erosion and subsidence due to ground ice thaw.

L383: delete 'retreat' because the photograph shows the headwall but not its retreat.

REPLY. Changed as suggested. Please note that based on comments from both Reviewers we have rearranged Figure 2 and the caption to increase its clarity. We have added elevation normalized slope profiles to the debris tongue profiles to better illustrate the connection between thaw-driven erosion and deposition. We also have created a supplementary figure (S1) to show terrain models of the slumps and locations of these transects.

L384: Ditto 'erosion'; the photograph showed 'eroded glaciofluvial deposits', not their erosion. Also, add 's' to 'deposit'.

REPLY. Changed as suggested.

L387: again, the photograph in panel d does not show 'initial stages of incision', but an incised channel. Panels c and e may show evidence of side valley erosion, but they don't show any erosion itself.

REPLY. Changed as suggested.

L390: please indicate (e.g. with an arrow) the snow patch, as it's not obvious to me at least.

REPLY. Caption was adjusted to increase clarity and reference to the snowpatch was removed.

L383 & 390: please clarify the caption 'Elevation normalized debris tongue profiles…'. The y axis of the plot shows thickness, so I think this should be added to the caption, e.g. 'elevation normalized profiles of debris-tongue thickness'. Also, there are in total three white dashed lines on panels b, f and g, but four lines depicting profiles on the plot in panel h.

REPLY. Figure 2 has been adjusted to increase its clarity and white dashed lines have been removed.

L394: if this refers to slump area as opposed to e.g. headwall height, then it is clearer to rewrite, e.g. '…the area of FM2 was an order of magnitude greater than …'

REPLY. Changed as suggested.

L397-8: 'Increasing thaw-driven sediment flows…': please clarify if this refers to their number, magnitude, rate or …

REPLY. Minor editorial adjustment was implemented to clarify the text.

L401-402: 'pinning of the stream channel to the valley wall (Fig. 2c)': please indicate this (e.g. with an arrow) on Fig. 2c, as it's not very clear to me where the stream channel is.

REPLY. Figure 2 has been adjusted and photograph was removed.

L402: better to replace 'massive deposits' with 'thick deposits', as the former, in the context of sedimentary deposits, suggests that they lack sedimentary structures, which may or not be the case, as they are not described.

REPLY. Changed as suggested.

L406: 'abrupt transition from small valley-side thaw slumps into larger, more dynamic features': I'm not sure that the data on area of slump CB support this, as within 7-9 years of slump initiation CB was 25,900 m2 (by 2011), i.e. growing at a few thousand m2 per year, whereas 4 years later it was 33,370 m2, which suggests a broadly similar rate of expansion. What does look to have been abrupt, is the sudden evacuation of slump-floor deposits since 2017.

REPLY. A slight adjustment in the topic sentence was implemented to better characterize the transition in thaw-driven slope evolution observed in the study area. "The abrupt transition of shallow valley-side thaw slumps into more dynamic failures connected to downstream environments is transforming the geomorphology of ice-rich glaciated landscapes."

L434: delete comma after 'geomorphology'

REPLY. Changed as suggested.

L493, 525-6 and Fig. 6: large translational slides: what criteria are used to identify these landforms and to distinguish them from thaw slumps? Are they different from active-layer detachments? How do you identify bedrock control?

REPLY. Morphology of rotational or translational failures differs from thaw slumps. Field observations throughout Willow River catchment confirmed interpretation of remote sensed imagery. Text has been adjusted accordingly.

L495: Fig. 5a is first mentioned after Fig. 6 (L493). Please correct numbering.

REPLY. Changed as suggested.

L498: depth of maximum thaw: how is this value determined? Do you mean the maximum concavity depth in L506?

REPLY. Changed to "maximum concavity depth".

L511: 'from 2002 to 2018'

REPLY. Changed as suggested.

L515-16, 739-41: "Normalizing by catchment area and differencing with the preceding time interval, the thaw slump component of surface lowering amounts to 0.1 mm yr-1 for 1986-2002 and 0.8 mm yr-1 for 2002-2018." This seems to me to be a rather strange and spurious parameter to calculate because surface lowering in thaw-slump terrain is not uniformly distributed, but focussed in discrete locations. An alternative, perhaps more meaningful parameter to calculate would be volume lost per unit area (cf. sediment yield), because this does not imply that the lost volume is uniformly distributed across space.

REPLY. We have reported as a surface lowering amount (mm yr^{-1}) and also in terms of sediment yield (m^3 km^{-2} yr^{-1}). We initially did not report the later (cf. sediment yield) because it too integrates estimates across the entire catchment source area and assumes that materials are getting to a catchment outlet. Regardless, we now report both values and remind readers that a significant portion of the volumes are attributed to ground ice (50 to 80%), and that a large portion of the sediments mobilized from thawing slopes are placed into transient storage in valley bottoms (see Fig. 2).

L529: were [km are plural]

REPLY. Changed as suggested.

L546: box and whisker plots: please state what each part shows, e.g. horizontal line denotes median, … dots indicate outliers …

REPLY. Minor editorial adjustment implemented to clarify text.

L547: narrative specifies 'concavity thicknesses' whereas Y axis on panel f is … 'depth'. Please ensure consistency.

REPLY. Changed as suggested.

L555: the proportional circles are grey rather than black.

REPLY. Changed as suggested

L559-560: 'Willow Lake (outlined in Orange)': where is this on panel c? Lower case for orange or simply add a label 'Willow Lake'. Please renumber panels to avoid three panels all labelled b, and three labelled c. 'The abandoned channel is shown in dark blue': in panel c the lakes look to be coloured dark blue in Fig. 6. Or are you referring to the unlabelled panel? This is difficult to follow the caption without sequential labels on all panels and text placed accordingly.

REPLY. We have adjusted the caption and made minor edits to the figure. All elements of the main map are indicated in first part of the caption, including reference to the inset boxes. The panels are labelled sequentially and explained in the caption.

L586-591: This summary of literature is more appropriate for a discussion than a results section.

REPLY. References are removed from the text.

L589: indicates (with 's'; compilation is singular)

REPLY. Changed as suggested.

L602 & 604: both 2017 and 2018 are indicated in caption but only 2017 is shown on panels a to c.

REPLY. Editorial clarification implemented. The Sentinel-2 data are for 2016-2017 and text and figures have been checked for consistency.

606: streams and rivers: what is the difference? Insert 'of' before 'the Peel…'

REPLY. Changed to "streams".

L661: suggest [plural subject]

REPLY. Changed as suggested.

L672: 'rapid aggradation of channel beds': perhaps 'rapid aggradation of valley fills or sediment bodies' is more appropriate. Deposition of the valley fill in Fig 2 looks to have been mainly by debris-flow processes rather than channel processes (cf. L716-20). The channel shown in Fig. 2d has incised its bed.

REPLY. Changed as suggested.

L693: is complex [subject is singular]

REPLY. Change as suggested.

L752: is magnified [subject ('the significance') is singular]

REPLY. Changed as suggested.

L775: what is a 'discordant volume'?

REPLY. Minor editorial modification implemented to clarify text.

L823: 'persistent perturbation': please specify the timescale of persistent or omit. Over decadal and possibly centennial scales, the perturbation may well be persistent. But geologically (multi-millennial and longer scales), the perturbation is certainly major but transitory, as the conceptual framework proposed by Ryder, Church, Ballantyne and others infers a pulse of sediment movement that declines over time.

REPLY. Minor editorial modification implemented to provide a timescale (decadal to millennial) over which perturbations are likely to persist.

L839: again, please clarify what timescales are referred to as 'long-term'. L844 identifies centennial timescales.

REPLY. Minor editorial modification implemented to provide a timescale (centennial to millennial) over which perturbations are likely to persist.

SuppL381: correct to 'cloud-free'

REPLY. Change as suggested.

Reply to comments by Dr. Ingmar Nitze (R2)

We appreciate the thoughtful comments provided by Dr. Nitze and have undertaken several minor modifications to address his comments. In particular, constructive critique of several figures has resulted in improvements that have increased their clarity and impact. Dr. Nitze's contribution to improving our manuscript is recognized in the Acknowledgements section. Detailed replies are provided to specific comments below.

General Comments The manuscript "Permafrost thaw couples slopes with downstream systems and effects propagate through Arctic drainage networks." provides a comprehensive overview of the extent and effects of mass wasting processing in NW Canada on its associated drainage networks across different scales. It analyzes different scales from local watersheds to the entire study area of ca. 1 Mkm2 . The authors used numerous methodologies and data sources were applied for each specific scale and target objective. The authors did a great job. This manuscript is of high quality and very comprehensive with a lot of detail and only needs minor corrections.

Here are some general remarks. Detailed comments are stated below. The analysis of many different aspects, with a plethora of datasets in different scales, makes it sometimes hard to follow. I think it is generally very hard to find the balance between details and the overall story. Perhaps minor improvements, such as adding a table of datasets (see detailed comments) will help the readers to understand the scale, objective and significance of the specific analyses. The quality of figures ranges from very good to "room for improvement". Please check detailed comments. Geospatial datasets (Shapefiles or KML) of e.g. the slumps, and perhaps other features as well, would be a helpful addition for readers to easily find the locations and cross-check with other data sources. Overall this manuscript will be a great contribution to the permafrost science community.

REPLY. We acknowledge that the paper covers a wide range of scales as our goals are to link processes on slopes, evolving connectivity with downstream environments and propagation of effects across Arctic drainage networks. To help provide readers with great clarity on what datasets were utilized in the paper and what research questions they address we have constructed Table S1. The table indicates main research objectives and identifies and describes the datasets used to address these questions and their source. We have also made several minor adjustments to figures or captions where possible to improve their quality and clarity. Finally, shapefiles will be published with the associated Open Reports that are referenced in Table S1, which have been reviewed and will be released concurrently with paper publication through the Northwest Territories Geological Survey Open Report system.

Specific Comments Title: The title is rather complicated, particularly reading it for the first time

REPLY. We have made slight modification to the title to improve its clarity.

175: It would be good to somehow provide the exact number, especially since you do that in the abstract.

REPLY. Changed as suggested.

201 ff: You used several different datasets, but it is rather hard to follow this part with text only. I suggest to add a table with basic methodologies and datasets and its related objectives. This will help to keep better track of used methods and spatial scales.

REPLY. Table S1 was developed to indicate the datasets utilized, the research question they pertain to, the base data from which interpretations were made, and reference to data sources.

238: Could you provide a little bit more information who exactly digitized the slumps (how many different people, people with field experience, etc.). I personally find it very challenging to consistently digitize thaw slumps, and even more so with several people.

REPLY. The Authors of the paper did all of the digitisations and have field experience in the study area. It should be noted that to address various research questions in this paper, various base-data layers were used, such that delineation rules and resolution of digitized outputs will vary even if the same individual is mapping features. Methodological aspects of slump digitization is beyond scope of this paper, however co-author Jurjen van der Sluijs is leading a critical assessment of slump delineation and classification within the context of assessing scatter within area-volume relationship functions. The majority of the datasets used in this paper are published as open reports and Authors of those reports were responsible for digitization. Also some examples of the base data and slump digitization are provided in new Figure S1.

258: I think it would make a great supplementary figure to show some examples (e.g. cross sections) of the reconstruction for selected sites. It looks like you provided this in Figure 3e, but did not reference it in the text.

REPLY. Developing these images are of interest but beyond the scope of this paper. The terrain reconstruction methods are explored in a robust manner through a separate methods paper. However, we have added supplementary Figure S1 which shows DTMs of thaw slumps discussed in detail in Sect. 3.1 & 3.2 and the position of topographic profiles shown in Figure 2g

267: Which Sentinel exactly. I suppose you mean Sentinel-2.

REPLY. We have clarified that Sentinel-2 imagery was used in this analysis.

366: "decade": Do you have exact initiation ages or is it rather an estimate? If the former I suggest using a more precise values (year) otherwise it's also fine to leave decade.

REPLY. The feature is present as a very small stream side slump on the 2011 LiDAR (544 m^2) suggesting it had initiated only a few years prior to that. We have left the text as is.

369: see decades 369: I suggest writing "2" as a word, as a few words later.

REPLY. Changed as suggested.

376 Table 1: Please use either negative values without direction (W) or positive values with direction for longitudes. E.g. -135.7555◦ OR 135.7555◦W 381:

REPLY. Changed as suggested.

Figure 2: It would be nice to somehow make a more efficient use of this figure in the next version in case this will be a full page figure, as there is a large blank space on the right. Of course I understand that this version of the manuscript is C2 still a preprint. Figure 2h: This plot is somehow hard to understand at the first glace. XLabel: is not initially clear, which distance you mean. I suggest extending it to "Distance from " (fill with your reference location). The same (to a lesser extent) applies to the Y-Label. I suggest using "Thickness of sediment accumulation" or so.

REPLY. We appreciate the suggestions to improve this figure. We have made the layout more symmetrical and show pictures of slumps across the size continuum. We have also extended the topographic profiles relative to the pre-disturbed surface from the top of the slump headwall to the end of the debris tongue in order to better capture the evolution of slope to stream connectivity associated with enlargement of disturbances. Please note that new Figure S1 shows the digital terrain models, delineations and transect locations of all thaw slumps shown in Figure 2.

425 Figure 3: a-c: I suggest using a more appropriate colorbar and visual scaling with a distinct break at 0 (zero). E.g. greenish/blueish colors for accumulation and orange/reddish colors for erosion. (e.g. https://colorbrewer2.org/#type=diverging&scheme=RdBu&n=9 or something similar) a-d: What is the source and timing of the hillshade? e: (very gentle) gridlines may help to better read the proportions of the plot. However, I am not sure if this add too much information to this plot. The intersection of "(e)" and the lines may need some improvement.

REPLY. We appreciate the suggestions and have adjusted to color scheme to improve clarity of the zero breakpoint. Timing of the hill-shade is indicated in the caption and slight tweak to placement of annotations was implemented to decrease clutter.

434: Please specify what exactly you mean with thaw-slump indices. Volume, area, . . .? (I found them in 443). I suggest using them here.

REPLY. Minor editorial modification was made to clarify the text.

434 ff: You are providing slump related statistics, but it is unclear which total area you analyzed with this dataset or how many features/slumps you detected. At least I cannot find them here in this paragraph.

REPLY. Method Section (2.3) describing the region from which these slumps were selected, how they were subsampled from the entire population, and the base data from which they were digitized is now referenced.

485

465: I suggest using "Scatter plots" instead of only "Scatter" (if you mean scatter plots)

REPLY. We clarify by indicating that we refer to "variation in the residuals, or (scatter)".

543 Figure5: a Inset: The numbers are hard to read especially in the dark grey part. The order in 1986 is reversed (2
490 **bottom) compared to the other years. Technically you could include the same information into the large bars, though the focus shifts to absolute numbers rather than relative to 100%. b-c/d-e: As the information from b & c as well as d & e are highly correlated, using only area or volume might be appropriate. However, this is a "soft" recommendation, but might be ok if you leave it. Perhaps shifting f to position d makes sense to have area and volume in one column.**

495 REPLY. We appreciate the advice and have removed the inset from Figure 5a and present the connectivity by shading on the large bars to portray by count. We have left the remaining figure as it is so a reader can assess both cumulative effects of increasing slump numbers as well as changes in the size distribution of the population.

551 Figure 6: Please check the numbering (a-c) of the insets. The main map does not have a letter. There are
500 **duplicate b and c. Main map: Just out of curiosity, which projection is it? The maps seems to be slightly rotated (clock-wise). The grid shows the rotation but the north arrow does not. Please adapt the north arrow, as I suppose the rotation was made to fit the watershed into the figure. I like the accumulated scar C3 area visualization.**

REPLY. We have adjusted panels so that they are indicated sequentially. Caption has also been adjusted. The orientation of the North arrow has been adjusted.

505

567: Sentinel-2?

REPLY. Minor edit implemented to clarify the text.

596 Figure 7: The data itself are very interesting but the visualization should be improved. I suggest using colors
510 **instead of black and white only. Furthermore please make sure that data is not occluded, particularly in a, b and d. Using colors and semi-transparent markers should help. Is a/b already semi-transparent and the grey part the intersection area? If yes, using colors will help to better see that this might be the intersecting area, as this color is not visible in the legend. Perhaps, you could remove the fill color for the bars at all and use only edge colors. b/c: These plots look good, but it's quite challenging to understand what they mean. Particularly c it is not clear to me what the**
515 **Cumulative disturbance in relation to the catchment area means. I see that there are changes over time (Peel), but the specific data behind it are puzzling to me.**

REPLY. Adjustment of the color scheme and use of semi-transparency was implemented to improve Figure 7a, b. We have slightly adjusted the text to clarify what the data on Figure 7c portray and its significance.

641 Figure 8: Awesome Figure What does NHN mean in the legend?

REPLY. We appreciate the feedback! We have clarified in the caption that NHN refers to National Hydro Network. The dataset and acronym are also provided in the methods section and now in the new Table S1.

859: I think it will help to have a list of publically available datasets in this section have a direct and comprehensive overview of these datasets instead of crawling through the text and references. Access to your datasets, e.g. delineated thaw slumps or aggregated spatial statistics, will be of great benefit to other researchers, particularly for large scale remote sensing and model applications.

REPLY. We appreciate the comment and have addressed this in large part through providing a summary of the datasets in Table S1.

Supplement Figure S1: I suggest using colors for nicer visualization. Please add (a,b,c) to each subplot. A horizontal alignment of plots would be nice, even if the plot size needs to be slightly reduced.

REPLY. Minor adjustments were made to improve the figure (now Figure S2).

Figure S3 iii: Here it would be great if you'd add an arrow/marker to the slide. With a lot of experience it's possible to find it, but without it can be hard. Please mention (and visually indicate) the dam/blockage.

REPLY. Caption adjusted to clarify location of the slide and damming of the river. Photographs have also been added so readers can visualize the magnitude of this landslide. Similar adjustments were implemented to Figure S3ii. Please not this is now Figure S4.

384: bottom of Table S3: Perhaps it is rather nitpicky, but using ISO format of dates would be nicer (e.g. 1986_07_07 –> 1986-07-07)

REPLY. Minor adjustment implemented.

444: Perhaps you should cite https://jstnbraaten.shinyapps.io/snazzy-ee-ts-gif/ as well, which is the second step to create these animations.

REPLY. The URL is now provided.

C4 Technical Comments Supplement 381 Table S3 caption: typo in: ". . . could free Landsat . . ."

REPLY. Adjusted through minor modification to the text.