Reply on anonymous Reviewer #1

I am afraid that this paper is either fundamentally flawed, or there are critical steps in the explanation of what is done that are not explained. This needs to be addressed before a full review is possible.

The work in the paper is based upon the Rickenmann (1990) proposal of a formula for estimating the critical (specific) discharge required for sediment transport (qc). This was modified in Rickenmann (2006) and vulgarized more widely in Chiari and Rickenmann (2007, Table 1, Equation 7, modified as the authors note) to treat the effects of a reduced energy slope given macroroughness elements in streams. The critical (specific) discharge is commonly combined with an actual discharge (q) in a threshold-based sediment transport equation (Chiari and Rickenmann (2007), Table 1, Equation 6) to estimate time-varying sediment transport capacity (i.e. the transport rate is a f (q-qc)). The authors have taken some future predictions of discharge (q) and want to see how the sediment transport competence changes as the glacier shrinks and goes through "peak water". This is all a very legitimate thing to do, well justified by the literature which the authors know and use well. The idea that a river erodes and sorts its bed as a glacier retreats and so progressively stabilizes is a good working hypothesis for known river response following glacier retreat; although the authors don't quite pick up on wider knowledge regarding the temporality of this process as argued in the work of Marren and others (i.e. a river erodes close to the glacier but then deposits eroded sediment further downstream causing an erosion-aggradation response).

> ***Reply:*** *Thank you for the appreciative words on the idea of the paper, the working hypothesis, the literature review/knowledge, and the discussion of the results. Thank you for critically reviewing the submitted manuscript (MS).*
>
> *We agree that the initial version of the manuscript needs a revision regarding the points the reviewer made. A detailed discussion of the comments can be found in the following section. We believe that we have considered all comments appropriately.*

1. General comments

A) But, this is where I get lost and this is not helped by Section 3.5 which is poorly explained.

First, when they present their results, they compare the "characteristic grain sizes" with those measured (e.g. Figure 5). Of course, if you know qc and its changes through time, you can invert the Rickenmann type equations to get a characteristic grain size. But you have to know qc and you don't know it or how it will evolve. My only explanation of what they have done here is that they have completely misunderstood the associated equations. In the paper, at L199, the authors define qc as the specific discharge whereas qc is actually the **critical** specific discharge, that which the q must exceed for transport to occur. I fear that they have taken their future discharge scenarios (some measures of q) as qc and then estimated the associated grain-size. That is, in their Eq. (1) they have used q and not qc. This is completely flawed. Now I may have mistaken something here, but to make it clear, if q is being used instead of qc, this is a very basic mistake that makes the analysis meaningless. If I am mistaken it is because how they go from q to qc to a characteristic grain-size is not explained in the paper sufficiently.

Reply: *(1) As the reviewer correctly pointed out, the condition $q>q_c$ is required for the initiation of motion of bedload. We used Eq. (1) according to Rickenmann (1990) in the inverse form to calculate the characteristic grain size d_{50}, which is in any case permissible, which was also considered by the reviewer.*

(2) Our goal in the paper was to calculate the largest characteristic grain size d_{50} with the highest predicted discharge by the glacio-hydrological model GERM. In other words, we have calculated the d_{50} at the maximum predicted specific discharge q_{max}.

(3) To make it easier understandable, we added new indices to the relevant terms of Eq. (1), which is shown in the original version below.

$$q_c = 0.065 * \left(\frac{\rho_s}{\rho_w} - 1\right)^{1.67} * g^{0.5} * I_R^{-1.12} * \boldsymbol{d_{50}^{1.5}} \quad (1)$$

In our paper, we use the assumption: $q_c=q_{max}$, whereby q_{max} is calculated by Eq. (2).

$$q_{max.i} = v_{max.i} * t_{v.max.i} \quad (2)$$

Here, the maximum specific discharge per cross-section ($q_{max.i}$) is calculated by the maximum flow velocity ($v_{max.i}$) and the corresponding depth ($t_{v.max.i}$) in each cross-section. This calculation step was already mentioned in the initial MS (LN 200).

When we are using now the inverse Eq. (1), we calculated in a way the critical characteristic grain size $d_{50.crit.i}$ for the given maximum specific discharge $q_{max.i}$. Thus, the Eq. (3) looks like:

$$d_{50.crit.i} = \left[\frac{1}{0.065} * \frac{q_{max.i}}{\left(\frac{\rho_s}{\rho_w}-1\right)^{1.67} * g^{0.5} * I_R^{-1.12}}\right]^{\frac{2}{3}} \quad (3)$$

This means, the calculated characteristic grain size $d_{50.crit.i}$ is theoretically the critical grain size for the initiation of motion for the given predicted maximum specific discharge $q_{max.i}$ according to the glacio-hydrological model GERM.

To illustrate the entire calculation approach here in the reply, Eq. (4) by Chiari and Rickenmann (2007) is also presented. This modification is needed to consider the increased flow resistance due to macro roughness elements in the canyon (LN 197 and 203-206 in the initial MS).

$$I_{red} = I_R * \left[\frac{0.133 * Q^{0.19}}{g^{0.096} * I_R^{0.19} * d_{90}^{0.47}}\right]^{a} \quad (4)$$

The reduced energy gradient (I_{red}) is used in Eq. (3) instead of I_R for the CS in the canyon.

(4) To illustrate that the approach described above has been used correctly, Eq. (1) was applied in its original form for this revision. After the characteristic grain size $d_{50.m.i}$ (indices 'm' for 'measured') is available from the line sampling (headwater and delta) and digital line sampling

(canyon), the critical discharge q_c can be calculated for the given measured $d_{50.m.i}$. These results show, that $q_{c.i}>q_{max.i}$ for all grain size distributions and for all discharges used (see Tab. 1). This analysis was also done with predicted maximum mean daily discharge (highest resolution possible by GERM) until 2050 (modeling period). Since q_c is – among others (see Eq. 1) a function of I_R (energy gradient), q_c for $d_{50.m}$ is changing between the used discharges.

Tab. 1: *Comparison of the results between the critical specific discharge ($q_{c.i}$) for the measured $d_{50.m}$ by Eq. (1) – modified by Eq. (4) – and the calculated maximum specific discharge ($q_{max.i}$) according to Eq. (2) for the observation years 2018, 2035 (highest predicted mean monthly discharge) and 2045 (predicted maximum mean daily discharge).*

River station *[m]*	$q_{c.2018}$ *[m³/sm]*	$q_{max.2018}$ *[m³/sm]*	$q_{c.2035}$ *[m³/sm]*	$q_{max.2035}$ *[m³/sm]*	$q_{c.2045}$ *[m³/sm]*	$q_{max.2045}$ *[m³/sm]*
502	7.532	1.804	6.145	2.457	5.556	3.596
409	9.302	2.873	8.795	3.744	33.878	4.054
327	25.265	2.094	12.196	2.762	11.865	3.792
252	51.943	1.155	9.968	1.872	5.267	2.418
168	6.921	2.574	6.238	3.176	5.455	4.109
52	23.674	1.842	7.956	2.337	3.121	1.292

This table clearly shows – despite the given study limitations (LN 326-344 in the initial MS) – the maximum specific discharge by the maximum mean daily discharge according to GERM ($q_{max.2045}$) is still smaller than q_c for the corresponding $d_{50.m}$.($q_{c.2045}$).

B) Second, Eq. (1) shows that the reduced energy slope (Ir) and the grain-size (D50) drive qc. Erosion/deposition will lead to the sediment sorting that drives changes in Ir and D50 and hence qc. This is not addressed in the modelling as far as I can see. To address this you would need a time-dependent sediment sorting treatment that also took into account changes in subglacial sediment export. Sediment sorting is at its most intense when capacity is greater than supply (subglacial sediment export, sediment supply from banks) and so how the critical discharge and the competence will evolve has to take into account supply as well. The authors recognize this in the introduction and the discussion but none of their analysis actually simulates this process, as far as I can see.

Reply: *(1) We agree with the reviewer, that a changing geometry (by erosion/deposition) changes q_c. We will add to the study limitations (LN 326-344) in the revised MS, that the prediction model is a steady-state 1D hydraulic model.*

(2) Sediment supply is a relevant parameter for the process (e.g., Bathurst, 2007; Rickenmann et al., 2006), but is not considered in the calculation approach for the initiation of motion of bedload. It determines the specific discharge for a given characteristic grain size – or it is used inversely (as it was done in the presented study) to calculate a critical characteristic grain size for a defined specific discharge.

C) Third, I should add that there is likely one other fundamental flaw. The analysis is done for the maximum mean monthly runoff and the hydrological model is daily; but the actual maximum daily discharge will be substantially greater than this due to diurnal discharge variation. Any analysis of this kind would need to work with downscaled daily discharge data as and used the mean maximum monthly runoff calculated from an hourly timescale. This diurnal discharge variation is also likely to change significantly as the glacier declines in size.

Reply: *(1) The input data of the glacio-hydrological model GERM (LN 189 in initial MS) are in daily resolution resulting in output data is mean daily discharge (Huss et al., 2008).*

(2) The input data in the hydraulic model (HEC-RAS) is the maximum mean monthly runoff, calculated by the output of GERM in daily resolution.

(3) For this review, the calculations were done for the maximum predicted mean daily discharge until 2050 (end of the modeling period) – see Tab.1 for the results.

(4) Correct, the diurnal discharge variation is predicted to change as the glacier size declines. Less amount of the meltwater discharge in the total discharge is predicted after the exceedance of the moment of peak water. According to the data by GERM, this turning point is predicted in the 2030s according to the applied A1B climate scenario (LN 227 in the initial MS).

D) The discussion is well-situated in the literature but deviates substantially from the results that are provided. Indeed, very few results are provided in the paper.

Reply: *Thank you for this comment. We have a different opinion, as the applied methods provide substantial results for discussion (which is well situated in the literature, annotated also by the reviewer) and the conclusions are valid.*

The authors should attend to the following more minor issues if they can resolve the above flaws, redo the analysis, and then resubmit the paper.

2. Specific comments

L29 “by” should be “with”

Reply: *Thank you, we changed the wording as suggested.*

L35 “exceeds the geological norm”; not clear

Reply: *Thank you for this comment. The sediment yield declines towards the geological norm during the paraglacial period (Ballantyne, 2002). We change the wording during the revision.*

L47 “last” in what sense?

Reply: *Glacifluvial sediment transport is the last process of a sediment cascade of a spatially defined area (e.g., catchment)*

L50 what is “triggered”?

Reply: *This is not an appropriate term in this context. Thus, we rephrase this sentence during the revision.*

L56 “to” should be “from”

Reply: *Thank you, we changed the wording as suggested.*

L58 “parallel to …” should be “as glaciers retreat”

Reply: *Thank you, we changed the wording as suggested.*

L64 “blankets” is a poor term

Reply: *This is a well-known term describing landform (dis)connectivity: “Bed armor acts as a blanket that inhibits the reworking of subsurface sediments.” (Fryirs et al., 2007; Church et al., 1988).*

L73 “by …” poorly phrased

Reply: *In literature, different terms/phrases are used to describe this turning point, like ‘expected moment of peak water’ by Schaefli (2015) or just ‘peak water’ by Huss and Hock, 2018.*

L74 but it depends on the glacier

Reply: *Correct, the expected moment of peak water depends on the glacier size, but this turning point “has already been reached or passed or is expected to occur in the coming two or three decades” (Huss and Hock, 2018 and literature therein).*

L84-85 but have you measured bedload sediment?

Reply: *(1) Yes, we measured bedload sediment. Depending on the discharge, flow velocity, and the expression of the armor layer, the threshold grain size between suspended sediment and bedload is 1 mm in alpine rivers (Maniak, 2005).*

(2) With the applied sediment sampling approaches, only bedload sediment can be measured. The applied state-of-the-art field method for gravel-to-cobble-bed mountain rivers is line sampling (Fehr, 1987; described in LN169-181 in the initial MS). This approach only considers coarse fractions with a cut-off at b≥ 1 cm. In the digital line sampling, the image resolution is decisive for truncation – which ranges between b> 10 px (Detert et al., 2018) and b> 20 px (Purinton and Bookhagen, 2019).

(2) That mainly suspended sediment is deposited in the downstream located reservoir Margaritze is known from literature (Knoblauch et al., 2005; Krainer and Poscher, 1992; LN 85 in initial MS).

L107-109 does not make sense as written

__Reply:__ This is a statement by Avian et al., 2020: "From 2004 onwards, a braided river system evolved into a second lake (Pasterzensee), which was established in 2010."

L131 "kettle-holes"

__Reply:__ Correct, kettle-holes can be found at the proglacial area of the Pasterze Glacier. We corrected it as suggested.

L138 "on" should be "for"

__Reply:__ Thank you, we corrected it as suggested.

L172-173 be clearer here that you measured the grain-size off digital images where the canyon was inaccessible. You also need to explain how you guaranteed the equivalence of grain-sizes from the line-sampling in the field which measured b-axes and the line-sampling of the imagery which measures surficial exposure of grain-sizes. See also **L208-209** – the b axis measured on an image is not the same as the true b axis – there is a bias – and one that increases as a function of the level of sediment reworking.

__Reply:__ (1) Thank you for this comment. The difference in the grain size composition between the headwater and canyon is clearly visible in Fig. 6 in the initial MS. Finding the true b-axis can be also challenging in the field, especially in proglacial areas with randomly distributed very big, often non-fluvial grain sizes (see Hauer and Pulg, 2018). Thus, finding the true b-axis is not only an uncertainty in the digital line sampling or automatic image analyzing software.

To guarantee the equivalence between line sampling in the field and digital line sampling on the high-resolution images, reference samples from the canyon are missing due to inaccessibility (LN 328 in initial MS and other replies). But if the measured $d_{50.m}$ by the digital line sampling is reduced by 20 % (in parts by up to 30 %), $q_{max.2045}$ is still too low for the initiation of motion.

(2) Sediment reworking is limited according to the calculation results.

L182 and onwards – the topography you use here will not be the river bed – how did you deal with this in your cross-sections? The same issue also applies to the digital grain-size survey; how do you get the grain-sizes for underwater zones?

__Reply:__ (1) The UAV photogrammetry was carried out during low flow conditions in the morning at the end of the ablation season (LN 146 in the initial MS). Due to the inaccessibility (canyon) for cross-sectional terrestrial survey, the water surface during the UAV photogrammetry corresponds to the channel bed in the hydraulic model. However, the steep channel gradient and the low discharge during UAV photogrammetry allow this kind of application with minimal uncertainties in the hydraulic predictability of bedload movement (stated in the study limitations – LN 331 of the initial MS).

(2) According to the approach by Fehr (1987), the virtual line for the digital line sampling was drawn in the flow direction near the permanently wetted area. Thus, the digital line sampling was done in the temporarily non-wetted area. So, it can be assumed that the same grain size composition is present in the permanently wetted main channel, although it will probably be already coarser due to constant exposition to glacifluvial erosion (stated in the study limitations – LN 333 in the initial MS).