Dear Editor, Dear Reviewers

We are grateful for the detailed and very constructive reviews we have received for our paper. We expanded our manuscript with more information on how we have conducted the Monte Carlo simulation. We also improve the justification of the assignment of values and uncertainties to the variables. We provide further information on the grain sizes and water runoff patterns in the supplement, and we conduct a sensitivity analysis to explore how variations in uncertainties and particularly channel widths influence the outcome of our analysis. The results are presented in the supplement and discussed in the main text. Most important, the positive relationships between the sorting of the material and the probability of sediment transport remain irrespective of the scenarios that we tested. Please find below a point-by-point response of how we have handled the referees' comments.

Thank you very much for your hard work.

On behalf of the co-authors

Fritz Schlunegger

Review #1 by Georgios Maniatis

We thank the reviewer for the very detailed and careful assessment of our work. Please find below our explanations of how we handle the comments and suggestions.

General comment by the reviewer

The authors quantify and cross-compare the probability of sediment mobilisation in a number of streams in the Alps (Switzerland) and the Andes (Peru). They attribute the observed differences in the probability of mobilisation between the two environments to the different degrees of sediment sorting characterising the two settings (quantified as the D(96)/D(50) ratio). The authors provide adequate context and they use a well-known modelling framework (based on the exceedance of critical shear stress $\tau > \tau^*$) to calculate the probability of sediment mobilisation. They also use standard techniques to approximate grain sizes and merge different sampling techniques in a convincing way. Uncertainties are then propagated using a Monte Carlo framework and the derived results are analysed using standard regression techniques. These two latter components of the paper need to be discussed more. The Monte Carlo calculations need to be introduced separately from the bed load modelling and the grain size sampling framework to a) enhance readability** and b) extend the justification on the assumed uncertainties used in the error propagation.

Our response:
This has been done. We explain the Monte Carlo framework in a separate chapter of the main text along with an explanation of how we have assigned uncertainties to the variables, and how we justify these. Please see lines 110 ff.
We additionally present further information in the Supplement on how we have estimated the uncertainties for the D84. We base this on the analysis of the intra-bar variation of the D84 for selected gravel bars in Switzerland. These data is presented in the Supplement S1.
For the Peruvian streams, the uncertainties on channel slope and particularly on channel widths are much larger, mainly because of the lower resolution of the DEM (2m in Switzerland versus 30 m in Peru), and since the Peruvian streams are to large extents not confined in artificial channels. Therefore, we cannot fully quantify the uncertainty on the channel widths for the Peruvian streams, and we acknowledge this in the main text. However, we run sensitivity tests to explore the

dependency of sediment transport probability on the assigned uncertainties. The dependency between grain size sorting and transport probability will remain. We illustrate this in the Supplement S4 and S5.

In Peru, channel width data were collected from digital images that were taken between March-August, which also corresponds to the season when the digital photos for the grain size analysis were made (Mai 2015). However, we acknowledge that because of the strong seasonality of water discharge in Peru (please see Table 1 in the main text that displays the intra-annual variability, and Supplement S2), widths of active channels vary greatly within one year. We therefore performed a Monte Carlo simulation for the case where active channels are up to twofold wider, and we additionally added a 50% uncertainty to these values. The results show an identical dependency between sediment mobilization probability and grain size sorting. We illustrate the results of these sensitivity tests in the Supplement S4 (Swiss rivers) and S5 (Peruvian streams).

Further general comment by the reviewer

The regression analysis needs further validation and does not directly quantify the relationship explored in this work.

Our response:

This is done, and the results are displayed in the new Figure 3b.

I consider those revisions to be minor since they can be directly addressed using the existing calculations and the should not affect the key outcomes of this work. I find the main message of the paper, the dataset and the methodological approach very interesting, important and within the scope of EarthSurfD. But I also believe that the presentation can be enhanced.

Specific comments

Reviewer:

1. Lines 32-34 Need to clarify this hypothesis. For example, for the first part: "well sorted bars are less frequently reworked", I think it is necessary to add "under relatively low sediment flux conditions". The second part ("braided streams host gravel bars...") is clearer.

Our response:

This has been done. We have changed the introduction and clarified the hypothesis to be tested. Please see lines 30-32.

Reviewer:

2. Lines 41-42: That sentence is vague. How is the mobilisation quantified? If it is an approximation based on a function of critical shear stress then it is a threshold by definition. Is this an a-posteriori evaluation? (implying that the authors observed particular events?)

Our response:

The approximation is based on a function of critical shear stress, so it is a threshold. We have specified and clarified this point. Please see lines 40-42.

Reviewer:

3. Lines 45-46 One can read this as selecting from a braided river the only segment that is not effectively braided. How can the authors justify that the confined segment will have similar (or relevant) mobility with the rest of the (braided) river?

Our response:

We acknowledge that this selection could bias the analysis towards a greater mobility, mainly because the streams have greater shear stresses where water flow is confined in one single channel. We add a related cautionary note in the modified version of the paper. Please see lines 45-48.

Reviewer:
4. Lines 54-55 This is very clear, but it is necessary to clarify the corresponding part of the introduction as well (Comment 2).
Our response:
This has been done. Please see response above.

Reviewer:
5. Lines 63-66 It is not very clear how you employ the full range of ϕ, I assume that you imply a uniform distribution between 0.03 and 0.06 in a randomisation type framework, but it needs clarification.
Our response:
This is indeed the case. We have clarified our methodological approach accordingly and expanded the section where we justify the employment of ϕ. Please see new section *2.3.1 Shields variable* ϕ (Lines 130 ff).

Reviewer:
6. Lines 73-74 I am not sure the reference to the D(50) threshold adds anything to the methodology here. On the contrary, it slightly complicates it.
Our response:
We agree. The D50 is frequently used as threshold by previous authors, and therefore we decided to mention this. However, we specify and clarify why we prefer the D84 as threshold grain size. Please see lines 66 ff).

Reviewer:
7. Line 92. This similarity needs to be explained (or the comment needs to be re- moved).
Our response:
We decided to remove the comment.

Reviewer:
8. Lines 93 to 96 The Monte Carlo framework needs to be introduced earlier. That will put in context some of the methodological comments that are difficult to understand (e.g. Comment 5). It is also possible to separate completely the layout of the bed load equations from the error propagation and devote one short section on the Monte Carlo calculations only.
Our response:
We prepared a new chapter referred to as 'Monte Carlo simulations' where we explain of how we proceeded. We additionally add a new section where we justify the assignment of uncertainties to the variables. Please see lines 110 ff.

Reviewer:
9. Lines 105-106 This is a small detail, but it would be great (for completeness) if the authors could state how they calibrated their photographs (what is the measured dimension that converts from pixels to length?)
Our response:
This has been done. Please see lines 171 ff.

Reviewer:
10. Line 110 "few millimetres" is vague. A number is needed here (preferably in conjunction with the pixel-length conversion).
Our response:

The resolution of the digital images indeed sets the lower boundary for measuring the fine-grained fraction, which adds a bias in the analysis. In our case, grains smaller than 4-5 mm cannot be identified with confidence. Watkins et al. (2020) showed through a comparison of sieving and the application of the Wolman (1954) method that the differences in the results are largest for the smallest grains including the D50, but that the results are quite identical for the D84 and larger grains including the D96. If we would consider the relationships between the probability of sediment transport and the D96/D84 ratio (instead of the D96/D50 ratio), the conclusions will be the same. We address this point more carefully in the revised manuscript. Please see lines 180 ff.

Reviewer:
11. Lines 119 and 121 The assignment of those uncertainties is not justified in a quantitative manner. It would be useful to see (here or in appendices) some quantification on the variance of channel widths and gradients (a simple boxplot would be more than enough) and statistics of the validation of DEMs (which must be already calculated). Similarly, the uncertainty assigned to the grain size data set should also be a function of natural variability and measurement error.
Our response:
We present data in the Supplement that illustrates how the D84 grain sizes vary within the investigated gravel bars (Supplement S1). The mean of these variations is c. 20%, which corresponds to the assigned uncertainty. We cannot precisely constrain the uncertainty on the channel gradients as we don't have the required information. However, it is very likely that the uncertainties on the slopes and the wetted channel widths are smaller in Switzerland (and possibly smaller than 10%) than in Peru because the water runoff in all Swiss streams is confined in single-thread, artificial channels with a constant width over several kilometers, while the Peruvian streams are braided. In addition, the resolution of the available DEM is much higher for the Swiss sites (2 m lidar DEM) than in Peru. For the Peruvian sites, the largest uncertainty for the assignment of values to channel widths stems from the difficulty to precisely determine the width of the wetted cross-section during the conditions of a mean annual water discharge (Q_{mean}), mainly because of the braided character of these streams and since we lack the required information. We therefore run Monte Carlo simulations where we allow the Peruvian channels to be twice as wide for the same Q_{mean}. As will be outlined in the discussion, the positive relationships between sediment transport probability and grain size sorting will remain.

Reviewer:
12. Lines 154-155 Is Maggia the only river with a confluence <1km upstream? I think the argument about the response to an extreme holds better.
Response:
We agree and have adjusted the text accordingly. Please see lines 275 ff.

Reviewer:
B. Lines 158-162 I find this interpretation quite strong. These regressions show (in my opinion), that sorting explains a higher percentage of the variance of the mobilisation probability in the Alps than it does for the Andes.
Response:
We read the diagram in the sense that the probability of transport occurrence is higher for poorly sorted sediments than for better-sorted ones for both the Peruvian and Swiss streams, and we justify this interpretation by because the relationship is significant. We present p-values and the residuals. The data shows that a relationship between transport mobility and sorting does exist for Switzerland and Peru, and it is stronger for Switzerland. However, other parameters/mechanisms such as sediment supply and stochastic processes could influence the sorting, which we discuss in the article.

Reviewer:
Additionally, the weak correlation for the Peruvian rivers indicates that sorting can be a secondary control in the Andes.
Response:
We acknowledge that the correlation coefficient is rather weak for Peruvian rivers, which we explain by the stochastic nature of sediment transport and the large variability of processes at the reach scale.

Reviewer:
Consequently, it is difficult to compare the two regressions (the model for the Alpes and the model for the Andes) in terms of the effect of sorting. That would be the case if they were two very strong regression models and there was a noticeable difference between the regression parameters.
Response:
We agree that it is difficult to compare both cases in terms of the effect of sorting. However, we state that the differences in sediment transport mechanisms between non-confined braided streams in Peru versus single-thread (artificial) channels in Switzerland are likely to explain some of the observations, and they also appear to be reflected by the different relationships between the sorting and the probability of sediment transport occurrence.
We agree that on Figure 3a itself, we do see that the regression of the Swiss rivers (slope=0.16±0.06; intercept -0.34±0.31) appears different to that of the Peruvian streams (slope=0.18±0.11; intercept -0.02±0.46). Admittedly, if we look at the regression parameters (i.e. slope and intercept), the parameters are not significantly different. We acknowledge this observation in the text. Please see lines 289 ff.

Reviewer:
14. Lines 178-180 That is true, however no information on the distribution of the residuals is provided so there is a question regarding the assumed linearity of these relationships.
Response:
We now provide a new Figure 3B, which illustrates the normalized residuals against the sorting. This plot shows that the normalized residuals do not show any specific and significant patterns, and they are therefore independent on the sorting. This suggests that the inferred linear relationships between the probability of transport occurrence and the D96/D50 are statistically robust.

Reviewer:
15. Lines 182-183 I believe that this is the main message of this work, however the regression analysis presented here does not quantify that difference. It is possible make this observation in the scatter graph of Figure 3 but another type of presentation is necessary.
Response:
We additionally present the residuals, which confirm the linearity of the relationships. Please see new Figure 3B.

Reviewer:
16. Lines 193-194 The regression analysis presented here supports that statement although further validation is needed.
Response:
We hope that the presentation of the residuals in the Figure 3B clarifies the situation.

Anonymous Referee #2

We thank reviewer 2 for the very supportive and constructive comments, which we have considered as very useful and helpful. We have considered all suggestions and have adjusted our text accordingly.

Received and published: 18 February 2020
Summary: This paper conducts Monte Carlo simulations to determine the likelihood of bed material mobility of D84 at mean annual flow (maf) in 35 gravel bedded rivers in Switzerland and Peru. The authors find that the probability of gravel mobility varies with the ratio of D96 to D50, such that D84 is less likely to be mobile at maf in channels with more uniform grain size distributions when compared to wide grain size distributions. This is an interesting finding, which should be shared. However, this paper needs substantial work before it is ready for publication.

Reviewer:
Intro/general 1. I found the framing in the Abstract and Introduction confusing. Some of this is due to imprecise wording: - The authors talk about the "mobility of gravel bars", but their work is actually focused on the mobility of individual grains of sediment. While bedform migration does require bedload transport, the work presented here never deals with morphologic change. I suggest the authors re-word.
Our response:
We use the term mobility of grains instead.

Reviewer:
The authors use the phrase "sediment flux" (ln 24) and "sediment discharge" (ln 12) where "sediment supply" would be a more appropriate choice.
Our response:
We changed the term and use 'sediment supply' instead, as proposed by the reviewer.

Reviewer:
In the title (and throughout the text), the authors suggest that grain "sorting" influences the probability of sediment transport. Isn't it just as possible that the causation runs the other direction? (Sorting reflects sediment transport conditions, as controlled by sediment supply?)
Our response:
We find that the mobility probability decreases for better-sorted material. This does imply that the sorting of the material has an effect on the mobility of deposited grains. Therefore, we consider our statement that the sorting influences the mobility as valid. This does not exclude that the ultimate control is sediment supply. We don't have the data to further test this possibility, but we bring this up at the end of the discussion. However, we changed the title to *Field data imply that the sorting (D96/D50 ratios) of grains on fluvial gravel bars influences the probability of sediment entrainment*. We consider that this title better reflects the contents of the paper.

Reviewer:
2. Many of the ideas presented in the hypothesis go unaddressed in the paper. As I read it, the hypothesis (which begins at Ln 27) is that high sediment supply channels tend to be braided, with high bed material mobility, while low sediment supply leads to single threaded channels with armored, well-sorted beds with lower bed material mobility. However, this manuscript presents no data on sediment supply or armoring. Furthermore, the Swiss channels are not (necessarily) naturally single-threaded channels. I suggest that the authors re-frame their hypothesis so that it is testable with the data presented in the manuscript.

Our response:
This has been done. We changed the introduction to better frame the hypothesis to be tested. In particular, the aim of our paper is to explore whether there is a link between the sorting of fluvial gravel bars, in our case quantified by the D96/D50 ratio, and the probability of material transport of individual clasts on these bars. Please see lines 30-32.

Reviewer:
3. The motivation for this study seems a little fuzzy (gravel mobility is important because of bar mobility?). Given that the main findings relate to the mobility of D84, the authors could consider using Mackenzie and Eaton (2017 and 2018) as motivation.
Our response:
Thank you for this reference. We have rewritten the introduction to better motivate our study and to better focus the hypothesis that we wanted to test. Please see also our response above.

Reviewer:
Methods: 4. Channel width was measured from aerial photographs, but I am not sure what width this refers to. Is this the full bank-to-bank channel width? Or the active width at mean flow? Given that mean flow tends to be much lower than the channel-filling flood, this difference has the potential to matter quite a bit for the results. Because flow depth is estimated using Qmaf, the width used in calculations should be Wmaf.
Our response:
All Swiss streams are single-threat channels and confined by artificial banks. Channel widths are therefore constant over several kilometres. For these streams, we measured the cross-sectional widths between the artificial banks, which would thus correspond to bank-to-bank channel widths. For the Swiss streams, flows which correspond to Qmean usually occupy the entire channel. The situation is different for the Peruvian rivers, since they are braided and have a large seasonal runoff variability. We acknowledge that this parameter cannot be as precisely quantified as in Switzerland. We accounted for this and conducted a sensitivity analysis where we allow active channels to be twice as large as reported in Table 1, and we additionally add a 50% uncertainty to these values. The consideration of a larger channel width reduces the probability of transport (because the same amount of water has to be shared by a larger cross-section area). However, the results show that the positive relationship between the grain size sorting and the probability of sediment entrainment will remain. We have clarified this issue and present this additional material in the Supplement S5. Since the overall conclusions do not depend on this point, we decided to present the results of this particular sensitivity analysis in the supplement.

Reviewer:
5. Some of the reported grain sizes are surprisingly small, especially when compared to the images in Litty and Schlunegger (2017). The authors state that “in cases where more than half of the grain is buried, the neighboring grain was measured instead”. This reviewer suspects that this method leads to a bias toward measuring small grains. Large grains are more likely to be buried. (And how do you know if it is “more than half buried”?). Do the authors have any field measurements of grain size to support their “photo sieving”?
Our response:
These images were mainly presented to illustrate the variability of grain sizes and the shape of the clasts. Admittedly, the accuracy to measure the fine-grained material greatly depends on the resolution of the digital photos. In addition, Watkins et al. (2020) could document that the uncertainties on the smaller grains tend to be larger than on the larger ones. We discussed this point more carefully in the revised manuscript. However, a positive relationship is not only visible between the material mobility and the D96/D50 ratios, but also between the transport probability

and the D96/D84 ratios. Therefore, despite a possible bias that is associated with the grain size measuring techniques, the relationships between the parameters characterizing the sorting and the sediment transport mobility will remain. Please see lines 180 ff.

We have additionally analysed the grain size data collected from various photos taken over the same gravel bar, but at different locations. For the D84, the variability and thus the uncertainty along a bar is in the order of 20%. We present these data in the Supplementary file S1.

Reviewer:

6. Peruvian channels have VERY high standard deviation of Qmed. Are these calculated as the standard deviation of the individual years mean annual flow? How many years of Peruvian channel data are there in the dataset? The high stdev of Peruvian channels compared to Swiss channels suggests a very different flow regime. Is it possible that the differences the authors find between Swiss and Peruvian channels is a reflection of flow regime, rather than sediment supply (as they seem to imply)?

Our response:

The discharge data for the Peruvian rivers has been taken from Reber et al. (2017) and Litty et al. (2017). The uncertainties reported by these authors correspond to the intra-annual variability (i.e. seasonal) and not to the inter-annual variability like in Switzerland. We acknowledge that we did not specify this point, which has now being done in the revised manuscript. We keep the intra-annual variability for the Peruvian streams to account for the large seasonal character of water runoff. We additionally calculated the inter-annual variability of mean annual runoff (Qmean) for 7 Peruvian streams where the water gauging stations are close to the grain-size sampling sites (distance c. 5 km, please see also Reber et al., 2017, for further characterization). We find that the inter-annual variability is much less (c. ±50% around the Qmean). We conducted the same analysis and propagated a lower discharge uncertainty through our Monte Carlo modelling framework. The results are the same. We present the results of this sensitivity analysis in the Supplement S2 and S5.

Unfortunately, we have no sediment supply data to fully address this point. However, find that the consideration of either an up to >100% (intra-annual or seasonal variability) or 50% (inter-annual variability) uncertainty on Qmean has a negligible implication on the probability of sediment transport. Therefore, we do not consider that discharge variability explains the differences between Peru and Switzerland. This then suggests that supply control is more important. However, it is beyond the scope of this paper to address the relationships between supply and transport probability because we have no supply data, as mentioned above. Our focus remains on the sorting and how it influences the entrainment of the deposited material.

Reviewer:

Results/Discussion: 7. I am surprised by the finding that D84 is mobile at mean annual flow in near 100% of the simulations in many of the Peruvian channels. That is an extremely mobile bed! Consider that other researchers have predicted D50 mobility of only ~12% of the year (Torizzo and Pitlick, 2004), and that in some regions, bed mobility is exceeded only a few days a year (Pfeiffer and Finnegan, 2018). The authors should consider making comparisons to these previous findings in their discussion.

Our response:

The relatively high mobility in the Peruvian streams is very likely to be real, but is admittedly biased by the selection of the Qmean, which gives more weight to the larger runoff magnitudes. We are convinced that the Qmean is a good choice because this is the runoff value, which is conventionally being considered in a large number of geomorphological and sedimentological studies, and related data can be found in many tables even for very remote areas.

Nevertheless, we ran a test, where we explored how the mobility changes if we take a series of models for various runoff quantiles and then calculate the resulting probability of sediment mobilization accordingly. We then multiplied the probability of occurrence for each quantiles with the corresponding transport probability and summed the values. This integration provides an estimate of the ‘real’ probability of transport. The analysis shows that this new estimate is positively and linearly correlated with the probability of transport estimated with the Qmean. In addition, these correlations are very similar between the Swiss (slope: 0.74±0.02; intercept: 0.05±0.01) and Peruvian streams (slope: 0.73±0.19; intercept: 0.03±0.14). This then means that the positive relationship between grain size sorting and sediment transport probability remains for both settings and for both scenarios (consideration of quantiles and Qmean). We present the results of this test in the Supplement S3. Nevertheless, since the Qmean is commonly selected in a large number of studies mainly because these data can be readily extracted even for very remote areas (e.g., calculation via TRMM data), we decided to keep the results of the model run based on Qmean in the main text and to illustrate the alternative solutions in the Supplement S3.

We note, that Pfeiffer and Finnegan (2018) reported lower transport probabilities that range between 8% and nearly 100% for the West Coast, 1% and 12% for the Rocky Mountains, and <10% for the Appalachian Mountains. In a broader sense, these authors considered the ratio between sediment flux and sediment transport capacity as criteria for the incipient motion of bedload material, which differs from the mobility criteria that we set in our paper. However, the largest dissimilarity stems from the differences in channels slopes. In particular, while the D_{50} of Pfeiffer and Finnegan (2018) has nearly the same size the D_{84} reported here, their channel gradients tend to be 3 times lower. Because shear stress linearly depends on gradient (equation 7), then the probability where $\tau > \tau_c$ will be directly and proportionally affected by this. Nevertheless, even if we would select a different channel gradient, the sediment transport probability will go down (most likely linearly), but the dependency of the transport probability on the grain size sorting will remain. We mention this in the revised text. Please see lines 350 ff.

Reviewer:

I have focused my comments on content, rather than prose. There were several gram- matical errors (e.g. Lines 33, 91) and awkward sentences throughout the manuscript. I suggest that the authors give the next version a more thorough read before re- submitting.

Our response:

We apologize for this and corrected the text accordingly.

Anonymous Referee #3

We thank referee 3 for the very helpful comments, which we have considered. Please find below an explanation of how we have addressed the open questions.

Reviewer:

This manuscript addresses the question of whether bed sorting reflects transport rates of the bed material using a compilation of grain size measurements from (mostly?) gauged stream reaches and Monte Carlo simulations of flow competence. The dataset is useful and warrants eventual publication. However, the analysis does a poor job of testing the hypothesis, given what we know about thresholds for motion in gravel- bedded rivers.

Our response:

We have focused the introduction and better specified the hypothesis to be tested. The thresholds for motion of coarse-grained sediment particles are set by assignments of values to the Shields variable ϕ. As the reviewer indicates, there is a large body of literature on this topic. However, most analysis concur on the notion that a range of ϕ-values between 0.03 and 0.06 adequately constrains the threshold conditions for sediment entrainment along streams where energy gradients are between 0.001 and 0.03 (please see compilation by Lamb et al., 2008), which is the case in our setting. We explained this point more carefully in a new section where the Monte Carlo simulation is described. We additionally add a new section where we justify the assignments of uncertainties to the variables. Please see lines 129 ff.

Reviewer;
Moreover, the framing of the argument and the interpretation needs some improvement to help the reader understand the purpose and findings of the study.
Our response:
This has been done. The introduction has been sharpened and more clearly focused.

Reviewer:
Below, I list a number of concerns related to the analysis presented in this manuscript, followed by suggestions to improve the presentation. Finally, I list some comments by line number, some of which echo or substantiate my main concerns/suggestions.

Reviewer:
Concerns with analysis: Transport probabilities are estimated via a Monte Carlo ap- proach, where "mean annual" shear stress is compared against the threshold stress for motion (i.e., is tau>tau_c?) for 10,0000 simulations for each site. Some of the variability between simulations results from measured standard deviations in mean annual discharge. However, any real transport variability that results from variability in water discharge is contaminated by synthetic variability in the other parameters (width, slope, critical shear stress, and grain size). The standard deviation of these parameters (except for tau_c) is set to 20% for all sites, without any justification.
Our response:
This point has also been made by reviewer 1. We have added a new chapter where we discuss the uncertainties, and how we have estimated them. We present additional material in the new Supplement. Please see new sections in lines 110 ff.

Reviewer:
The authors should justify their use of a mean-annual discharge. Why not use bank- full or channel-forming discharges, which typically occur every 1.5 or 2 years? Or, if the goal is actually to quantify the fraction of time that the threshold shear stress is exceeded, wouldn't it make the most sense to just estimate a threshold discharge for each site and count the number of flow measurements that exceed that discharge?
Our response:
Reviewer 2 rose a similar concern, but from a slightly different prospective. We have addressed this point in the following way (please see also see response to reviewer 2): we ran a test, where we explored how the transport probability changes if we take a series of models for various runoff quantiles and calculate the resulting probability of sediment mobilization accordingly. We then multiplied the probability of occurrence of each quantiles (listed by the Swiss authorities and calculated for the Peruvian streams based on daily records) with the corresponding transport probability and sum the values. This integration provides an estimate of the 'real' probability of transport and accounts for the non-negligible temporal variability of water discharge (up to 3 order of magnitude for some Peruvian rivers). The analysis shows that this new estimate is positively and linearly correlated with the probability of transport estimated with the mean annual water discharge Qmean. In addition, these correlations are very similar between the Swiss (slope: 0.74±0.02; intercept: 0.05±0.01) and the Peruvian streams (slope: 0.73±0.19; intercept: 0.03±0.14). This means that the positive relationships between grain size sorting and sediment transport probability remains for both settings. We present the results of this test in the Supplement S3. Nevertheless, because

Qmean is commonly selected in a large number of studies mainly because these data can be readily extracted even for very remote areas (e.g., calculation via TRMM data), we decided to keep the results of the model run based on Qmean in the main text and to illustrate the alternative solutions in the Supplement S3.

Reviewer:
To estimate bed shear stress from discharge measurements, the study relies on a Manning's-n flow resistance calculation, in which Manning's n does not depend on any roughness length scale (e.g., D50 or D84). While this approach has been shown to compare favourably to measured flow velocities in some cases (Jarrett, 1984; Ferguson, 2007), it strikes me as an odd choice for this study, which is focused on the relationship between bed sediment size and transport conditions. Would including sediment size in flow resistance calculations affect the results?
Our response:
We did explored whether equation (2) could be solved using the Darcy-Weisbach friction factor f instead of Manning's n. According to Ferguson (2007), the friction factor f varies considerably between shallow- and deep-water flows and depends on grain size D relative to water depth d, and thus on the relative roughness. Ferguson (2007) developed a single equation to compute f, referred to as the Variable Power Equation (VPE), that considers roughness-layer and skin friction effects. Calculations where the VPE was employed indeed revealed that roughness-layer effects have an impact on flow regimes where $D_{84}/d>0.2$ (Schlunegger and Garefalakis, 2018), which is likely to be the case in our settings. However, similar to Litty et al. (2016), we are faced with the problem that we have not sufficient constraints to analytically solve equation (2) with the VPE. We therefore selected Mannings's n instead, which allows to solve equation (2) analytically. We have addressed this point in the revised manuscript. Please see lines 97 ff.

Reviewer:
Finally, I'm concerned that the analysis underestimates variability in the critical Shields stress and ignores the covariability between critical and bankfull Shields stresses. The critical Shields stress for bed motion varies by more than an order of magnitude between sites (e.g., Phillips and Jerolmack, 2019). Moreover, that study (Phillips and Jerolmack, 2019) makes a compelling case that the best predictor of critical Shields stress is the bankfull Shields stress. This suggests that the inferred differences in excess shear stress between sites may not even exist. This is impossible to test without measurements of bedload transport (which I assume is outside the scope of this study), but this potential issue with the approach should be acknowledged.
Our response:
Yes indeed. In our case we cannot really constrain the bankfull runoff conditions, but we consider the range of Shields stresses (please see compilation by Lamb et al., 2008) that are appropriate for most channel gradients between 0.001 and 0.02 as is the case in our setting. We discuss this point and justify our selection in the revised manuscript, and we also refer to the Philips and Jerolmack (2019) and Turowski et al. (2011) in this context and discuss the outcomes. Please see lines 149 ff.

Reviewer:
Suggestions to improve clarity: Causality needs to be consistent throughout the paper. The title of the paper states that sorting influences transport (this causality is repeated in the conclusions, lines 174 to 177). However, the mechanistic argument stated in the intro (lines 28 to 32) is that lower bed mobility leads to enhanced armoring (winnowing of fines), which is expressed as differences in bed sorting. In reality there is likely a feedback between the two and causality in both directions, but the paper, in its title, intro, and conclusion, should at least be internally consistent.
Our response:

We rephrased the introduction to better explain the focus of our paper. Feedback mechanisms between sediment supply, sorting and transport probability are discussed towards the end of the paper. Please see lines 368-370.

Reviewer:
The mobility of bars (which are bedforms) is used as the main motivation of the paper in the introduction and is mentioned several times in the short abstract, but this paper does nothing to discuss the mobility of bedforms. Please revise these sections to match the actual subject matter of the paper, which seems to be the extent to which the transport of bed material sorts that bed material.
Our response:
We have clarified this point. We actually refer to the mobility of individual clasts on gravel bedforms. This has been clarified throughout the manuscript.

Reviewer:
Line comments
21 – 23. I don't think this reference suggests that the mobility of bars affects channel form.
Our response:
The introduction has been changed. Please see responses above.

Reviewer:
39. It's unclear to me what mean-annual discharge is and why it's used. Is it the average discharge for the entire record? Or the mean of the maximum annual discharge? I assume that it's the mean of the entire record, in which case there is nothing "annual" about this measure.
Our response:
In Switzerland, the mean annual water discharge corresponds to the arithmetic mean of the means of the annual flows, measured over several decades (c. 20 years). We present the data in the Supplement S2. In Peru, the case is more difficult because the gauging stations for many streams are situated upstream of the grain size measurement sites. Reber et al. (2017) have discussed of how the gauging records have been scaled to the sites where the grain size data by Litty et al. (2017) were collected. In this work, we present hydrological data for those 7 sites where the gauging stations are close to the grain size surveys (Supplement S2). We additionally performed sensitivity tests to explore the consequence on sediment transport probability for the case where runoff quantiles are used (Supplement S3). The patterns and conclusions remain the same.

Reviewer:
45 – 46. So you avoided braided channels, but the intro suggests comparing braided and single-threaded channels is the main motivation of the study.
Our response:
In the Peruvian streams, the single-threat reaches are only a few hundred meters long (compared to the several kilometres in Switzerland where channels are all confined by artificial banks), which is actually very short if the overall braided character over tens of kilometres is considered. We have clarified this point in the revised manuscript. Please see lines 42 ff.

Reviewer:
66 – 68. It doesn't "account" for slope dependency by bracketing a certain range of values, and Lamb et al. (2008) show that the slope dependency extends to the lowest- sloping gravel bed rivers.
Our response:

Yes indeed, it doesn't. However, this range includes most (admittedly not all) of the reported values for stream segments where energy gradients are between 0.001 and 0.02, as is the case in our setting (Lamb et al., 2008). We discuss this point in the revised manuscript. Please see lines 231 ff.

Reviewer:
88. There is no roughness length scale in this roughness calculation.
Our response:
Indeed, this variable is not considered because we don't have data as constraints. We mention this in the revised manuscript. Please see lines 95-96.

Reviewer:
106-108. How can you be sure that you're measuring the b-axis in a 2-D image? If assuming that the short axis is vertical, this should be stated.
Our response:
We indeed infer that the shortest axis is vertical. We mention this in our revised manuscript. Please see lines 177-178.

Reviewer:
109-110. By only counting the large particles once, you systematically underestimate the areal coverage by coarse particles. The correct solution to this is to choose a grid with a spacing that's larger than the largest grain.
Our response:
That's what we have done. In some very few cases where some grains were larger than the spacing of the grid, then we proceeded as described above. We have specified this point in the revised manuscript. Please see lines 171 ff.

Reviewer:
119 – 124. Is there any justification for the 20% uncertainty?
Our response:
We present a new chapter where we discuss and justify the selected uncertainties (see also response to the major comments by reviewer 1).

Reviewer:
126 – 127. Critical Shields stress at a site varies much more than this (see Turowski et al., 2011 for example).
Our response:
Yes indeed. The selected ϕ-range between 0.03 and 0.06 includes most published data about the slope dependency of the critical ϕ where channel gradients were between 0.001 and 0.03 (which includes the energy gradients of our streams, Table 1), as a compilation by Lamb et al. (2008) has shown. We acknowledge that field-based data by Turowski et al. (2011) has shown that critical conditions for sediment entrainment cover a much larger spread than employed here. However, the four reaches that were analysed by these authors were at least five times steeper (energy gradients between 0.06 and 0.1) than the Swiss and Peruvian streams considered in this paper, with the consequence that sediment entrainment in these streams most likely requires the condition of ϕ-values that are greater than 0.06 (Lamb et al., 2008). This is discussed in the revised manuscript. Please see also response above and lines 129 ff.

Reviewer:

130-132. Maybe I missed it, but are these streams also gauged? Are the data similar in quality and duration to the Swiss data? It seems worthwhile to state this since the results are so different between the two study areas (e.g., Fig. 3).

Our response:

Yes, these streams have been gauged on a daily basis. 7 gauging stations are close to the sites where grain size data has been collected. The other gauging stations are further upstream. Reber et al. (2017) used the records of the 7 aforementioned stations and TRMM data to scale the gauging data from the other streams to the sites where the grain size data has been collected. This has been explained and discussed in detail in Reber et al. (2017) and Litty et al. (2017). Therefore, we decided not to repeat their statements, but we present water discharge data from the 7 gauging stations in the Supplement S2.

Reviewer:

143. Is Qmed the mean or median? This is confusing.

Our response:

It is Qmean. We have corrected this error.

Reviewer:

156. It seems very difficult to say that the relationships in Figure 3 are linear.

Our response:

Following the request by reviewer 1, we present the normalized residuals against the sorting. This plot shows that the normalized residuals do not show any specific and significant patterns, and they are therefore independent on the sorting. This suggests that the inferred linear relationships between the probability of transport occurrence and the D96/D50 are statistically robust. Please see new Figure 3b.

Reviewer:

157. I'm missing the justification for why the switch to D96 when D84 was stated to be the grain size of interest (line 69).

Our response:

We could have selected the D84 as well, and the results would have been the same (see also Figure 2 that illustrates that the grain size distributions are self-similar). We decided to take the D96 instead of the D84 because the ratios to the D50 are larger, and differences in sorting patterns will become clearer.

Reviewer:

159. Bedload is not measured; D96/D50 is for the bed sediment.

Our response:

Yes indeed, we measured the bed material. This has been corrected.

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Short communication: Field data imply that the sorting (D96/D50 ratios) of grains on fluvial gravel bars influences the probability of sediment entrainment

Running title: transport probability of coarse-grained material

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Abstract

Conceptual models suggest that the mobility of grains on coarse-grained gravel bars is mainly controlled by sediment supply. Here we present field observations from streams in the Swiss Alps and the Peruvian Andes to document that for a given water runoff, the probability of material transport also depends on the sorting of the bed material. We calculate shear stresses that are expected for a mean annual water discharge, and compare these estimates with grain-specific thresholds. We find a positive correlation between the predicted probability of material transport and the sorting of the bed material, expressed by the D_{96}/D_{50} ratio. These results suggest that besides sediment supply, the bedload sorting exerts a measurable control on the mobility of clasts in coarse-grained streams.

1 Introduction

It is generally accepted that sediment supply is one of the most important parameters, which not only controls the mobility of the sediment in coarse-grained streams but also the channel form (Dade and Friend, 1998; Church, 2006). In particular, flume experiments (Dietrich et al., 1989) and numerical models (Wickert et al., 2013) have shown that a large sediment supply is commonly found in braided rivers where the material mobility is high, while a low sediment mobility is rather encountered in single-threat channels where the sediment supply is expected to be low. However, much less research has been conducted to investigate whether the granulometric composition, and particularly the sorting of the bed material, also exerts a measurable control on the mobility of coarse-grained material in streams. Here, we focus on this aspect and explore whether there is a link between the sorting of gravel bars, here expressed by the D_{96}/D_{50} ratios of the material, and the transport probability of individual clasts on these bars. We focus on gravelly streams in the Swiss Alps where artificial banks keep the flow in fixed, single-threat channels over several kilometres, and in the Peruvian Andes where streams are braided. We selected gravel bars close to water gauging stations, determined the grain size distribution of these bars and calculated the probability of sediment transport for a selected water runoff, which in our case corresponds to the mean annual water discharge Q_{mean} for comparison purposes. We explored whether these flows are strong enough to shift the D_{84} grain size, which is considered to build the sedimentary framework of gravel bars as recent flume experiments have shown (MacKenzi and Eaton, 2017;

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MacKenzie et al., 2018). We thus considered the mobilization of the D_{84} grain size as a priori condition, and thus as a threshold, for a change in the sedimentary arrangement of the target gravels bars. The braided character of streams in Peru complicates the calculation of the sediment transport probability mainly because water flows in multiple active channels, and channel widths vary over short distances. For these streams, we selected reaches (c. 100 m long) where several active braided channels merge to a single one, before branching again. We are aware that this could eventually bias the results towards a greater material mobility, mainly because flows in single-threat segments are likely to have greater shear stresses than in braided reaches where the same water runoff is shared by multiple channels. The research sites thus offer conditions that are similar, or close, to a laboratory flume experiment (e.g., Dietrich et al., 1989) where channel gradients are nearly constant, and where sediment transport, conditioned by grain size specific thresholds, mainly depends on water runoff and channel widths, and therefore on the resulting flow strengths.

2 Methods and datasets

2.1 *Entrainment of bedload material*

Sediment mobilization is considered to occur when flow strength τ exceeds a grain size specific threshold τ_c (e.g., Paola et al., 1992):

$$\tau > \tau_c \quad (1).$$

We estimated the probabilities of $\tau > \tau_c$ for a given water discharge using a Monte Carlo modeling framework (see section 2.2). We conducted 10'000 simulations, and the results are reported as probability (or percentage) where $\tau > \tau_c$ during these iterations.

Threshold shear stress τ_c for the dislocation of grains with size D_x can be obtained using Shields (1936) criteria ϕ for the entrainment of sediment particles:

$$\tau_c = \phi(\rho_s - \rho) g D_x \quad (2),$$

where g denotes the gravitational acceleration, and ρ_s (2700 kg/m³) and ρ the sediment and water densities, respectively. Among the various grain sizes, the 84th percentile D_{84} has been considered to best characterize the sedimentary framework of a gravel bar (Howard, 1980; Hey and Thorne, 1986; Grant et al., 1990). Accordingly, flows that dislocate the D_{84} grain size are strong enough to alter the gravel bar architecture (Grant et al., 1990). We acknowledge that many authors preferentially selected the D_{50} grain size as a threshold to quantify the minimum flow strengths τ_c to entrain the bed material (e.g., Paola and Mohrig, 1996; Pfeiffer and Finnegan, 2018). The selection of the D_{50} thus results in relatively low thresholds and in a greater entrainment probability. However, recent analogue experiments have shown that the coarse-grained trail of a material composition such as e.g., the D_{84} better characterizes the threshold conditions for the incipient motion of material on gravel bars than the D_{50} (MacKenzi and Eaton, 2017). We therefore followed the recommendations by MacKenzie et al. (2018) and selected the D_{84} grain size to quantify the

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threshold conditions in equation (2).

Bed shear stress τ is computed through (e.g., Tucker and Slingerland, 1997):

$$\tau = \rho g R S \quad (3).$$

Here, S denotes the energy gradient, and R is the hydraulic radius, which is approximated through water depth d where channel widths $W > 20 \times d$ (Tucker and Slingerland, 1997), which is the case here. The combination of expressions for: (i) the continuity of mass including flow velocity V, channel width W and water discharge Q:

$$Q = VWd \quad (4);$$

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(ii) the relationship between flow velocity and channel bed roughness n (Manning, 1891):

$$V = \frac{1}{n} d^{2/3} S^{1/2} \quad (5);$$

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and (iii) an equation for the Manning's roughness number n (Jarrett, 1984):

$$n = 0.32 S^{0.38} d^{-1/6} \quad (6);$$

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yields a relationship where bed shear stress τ depends on gradient, water flux and channel width (Litty et al., 2017):

$$\tau = 0.54 \rho g \left(\frac{Q}{W} \right)^{0.55} S^{0.935} \quad (7).$$

This equation is similar to the expression by Hancock and Anderson (2002), Norton et al. (2016) and Wickert and Schildgen (2019) with minor differences regarding the exponent on the channel gradient S and on the ratio Q/W. These mainly base on the different ways of how bed roughness is considered. Note that this equation does not consider a roughness length scale (both vertical and horizontal) because we have no constraints on this variable.

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We explored whether equation (2) could be solved using the Darcy-Weisbach friction factor f instead of Manning's n. According to Ferguson (2007), the friction factor f varies considerably between shallow- and deep-water flows and depends on grain size D_x relative to water depth d, and thus on the relative roughness. Ferguson (2007) developed a solution referred to as the Variable Power Equation (VPE), which accounts for the dependency of f on the relative importance of roughness-layer versus skin friction effects and thus on the D_x/d ratios. Calculations where the VPE was employed indeed revealed that roughness-layer effects have an impact on flow regimes where D_{84}/d>0.2 (Schlunegger and Garefalakis, 2018), which is likely to be the case in our streams. However, similar to Litty et al. (2016), we are faced with the problem that we have not sufficient constraints to analytically solve equation (2) with the VPE. We therefore selected Mannings's n instead, which allowed us to solve equation (2) analytically. But we acknowledge that this might introduce a bias.

2.2 Monte Carlo simulations

Predictions of sediment transport probability are calculated using Monte Carlo simulations performed within a MATLAB computing environment. All variables that are considered for the calculations of both sheer and critical sheer stresses (equations 7 and 2, respectively) are randomly selected within their possible ranges of variation (see next sections and Table 1). Except for the Shields ϕ variable that we consider to follow a uniform distribution between 0.03 and 0.06 (see section 2.3.1 for justification), we infer that all other variables follow a normal distribution, defined by its mean and one standard deviation. To ensure that no negative values introduce a bias to these iterations, only strictly positive values for channel widths and gradients are considered. In the case of water discharge, both null and positive values are kept for further calculations. Values excluded from the calculations, i.e. returning negative water discharge or null or negative channel width / slope gradient, yield "NaN" in the resulting vector. For each of the 10'000 iterations τ and τ_c are compared, which yields either "1" ($\tau > \tau_c$) or "0" ($\tau \leq \tau_c$). The sediment transport probability is then calculated as the sum of ones divided by the number of draws, from which the number of "NaN" values was subtracted before. Note that <2500 "NaN" were obtained for Rio Chico (PRC-ME17), which we mainly explain by the c. 150% relative standard deviation of the mean annual water discharge estimated for that river.

2.3 Parameters, datasets, uncertainties and sensitivity analysis

2.3.1 Shields variable ϕ

Assignments of values to ϕ vary and diverge between flume experiments (e.g., Carling et al., 1992; Ferguson, 2012; Powell et al., 2016) and field observations (Mueller et al., 2005; Lamb et al., 2008). Here, we considered that at the incipient motion of the D_{84}, the Shields variable ϕ is equally distributed between 0.03 and 0.06 (Dade and Friend, 1998) during the 10'000 iterations. However, based on a compilation of ϕ-values that were derived from field investigations and flume experiments, Lamb et al. (2008) revealed that ϕ is likely to depend on the energy gradient itself, where

$$\theta = 0.15S^{0.25} \quad (8).$$

We refrain from using a slope dependency of ϕ at this stage for three major reasons: First, the consideration of equally distributed ϕ-values, in the range between 0.03 and 0.06, includes the Shields values of most field investigations and flume experiments where channel gradients were between 0.001 and 0.02 (spread of energy gradients of our streams, Table 1), as Lamb et al. (2008) and Bunte et al. (2013) have shown in their compilations. Second, ϕ-values show a large scatter in their slope-dependencies (Lamb et al., 2008). Accordingly, the consideration of equally distributed ϕ-values within a given range better complies with the large variability in ϕ–values that are commonly encountered in experiments and field surveys (Lamb et al., 2008). Third, the selected range considers most of the complexities that are related to the hiding of small clasts and the protrusion of large constituents (Buffington et al, 1992; Buffington and Montgomery, 1997;

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Kirchner et al., 1990; Johnston et al., 1998), which, in turn, results in a large scatter of ϕ-values. In this context, Turowski et al. (2011) reported a larger variation in the threshold conditions for the mobilization of clasts than employed here. However, their streams have energy gradients between 0.06 and 0.1, with the consequence that some of the material is entrained during torrential floods where entrainment mechanisms are different. Finally, the selected ϕ-range also includes the hydrological conditions of channel forming floods where thresholds for the evacuation of sediment may be up to 1.2 times larger than for the incipient motion of individual clasts (Parker, 1978; Philips and Jerolmack, 2016; 2019; Pfeiffer et al., 2017). For instance, a 1.2- times larger threshold will increase the commonly employed ϕ value of 0.047 (Meyer-Peter and Müller, 1948), or alternatively 0.0495 (Wong and Parker, 2006), to the range between 0.036 and 0.0594, which is considered in the brackets of 0.03 and 0.06 that we employed in this paper. In summary, we consider that the selection of equally distributed ϕ-values between 0.03 and 0.06 does the best job to account for the large variability in ϕ–values that are commonly encountered in experiments and field surveys where energy gradients were between 0.001 and 0.02 (Lamb et al., 2008).

2.3.2 Grain size data

We collected grain size data from streams where water discharge has been monitored during the past decades. These are the Kander, Lütschine, Rhein, Sarine, Simme, Sitter and Thur Rivers in the Swiss Alps (Fig. 1a). The target gravel bars are situated close to a water gauging station. At these sites, 5 to 6 digital photographs were taken with a Canon EOS PR. The photos covered the entire lengths of these bars. A meter stick was placed on the ground and photographed together with the grains. Grain sizes were then measured with the Wolman (1954) method using the free software package ImageJ 1.52n (https://imagej.nih.gov). Following Wolman (1954), we used intersecting points of a grid to randomly select the grains to measure. A digital grid of 20x20 cm was calibrated with the meter stick on each photo. The size of the grid was selected so that the spacing between intersecting points was larger than the *b*-axis of most of the largest clasts (Table 1, Supplement S1). The grid was then placed on the photograph with its origin at the lower left corner of the photo. The intermediate or *b*-axis of approximately 250 – 300 grains (c. 50 grains per photo; Supplement S1) underneath a grid point was measured for each gravel bar. In this context, we inferred that the shortest (*c*-axis) was vertically oriented, and that the photos displayed the *a*- and *b*-axis only. In cases where more than half of the grain was buried, the neighboring grain was measured instead. In the few cases where the same grain lay beneath several grid points, then the grain was only measured once. Only grains larger than a few millimeters (>4-5 mm, depending on the quality of the photos) could be measured. While the limitation to precisely measure the finest-grained particles potentially biases the determination of the D_{50}, it will not influence the measurements of the D_{84} and D_{96} grain sizes, as the comparison between sieving and measuring of grains with the Wolman (1954) method has disclosed (Watkins et al., 2020). In addition, as will be shown below, the consideration of the

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D_{96}/D_{84} instead of the D_{96}/D_{50} ratios yields a similar positive relationship to the mobility of grains. We complemented the grain size data sets with published information on the D_{50}, D_{84} and D_{96} grain size (Litty and Schlunegger, 2017; Litty et al., 2017) for further streams in Switzerland and Peru (Figs. 1a and 1b; Table 1). For a few streams in Switzerland, Hauser (2018) presented D_{84} grain size data from the same gravel bars as Litty and Schlunegger (2017), but the photo was taken one year later and possibly from a different site. For these 5 locations, we took the arithmetic mean of both surveys (Table 1, data marked with three asterisks). All authors used the same approach upon collecting grain size data, which justifies the combination of the new with the published datasets.

We finally assigned an uncertainty of 20% to the D_{84} threshold grain size, which considers the variability of the D_{84} within a gravel bar as the analysis of the intra-bar variation of the D_{84} for selected gravel bars in Switzerland shows (Supplement S1). The assignment of a 20% uncertainty to the D_{84} threshold grain size also considers a possible bias that could be related to the grain size measuring technique (e.g., sieving in the field versus grain size measurements using the Wolman method; Watkins et al., 2020). However, it is likely to underestimate the temporal variability in the grain size data, as a repeated measurement on some gravel bars in Switzerland has suggested (Hauser, 2018), but this aspect warrants further research.

2.3.3 Water discharge data

The Federal Office for the Environment (FOEN) of Switzerland has measured the runoff values of Swiss streams over several decades. We employed the mean annual discharge values over 20 years for these streams (Supplement S2) and calculated one standard deviation thereof (see Table 1). For the Peruvian streams, we used the mean annual water discharge values Q_{mean} reported by Litty et al. (2017) and Reber et al. (2017). These authors obtained the mean annual water discharge (Table 1) through a combination of hydrological data reported by the Sistema Nacional de Información de Recursos Hídricos and the TRMM-V6.3B43.2 precipitation database (Huffman et al., 2007). They also considered the intra-annual runoff variability as one standard deviation from Q_{mean} to account for the strong seasonality in runoff for the Peruvian streams, which we employed in this paper. For the Peruvian streams, the assigned uncertainties to Q_{mean} are therefore significantly larger than for the Swiss rivers (Table 1). A re-assessment of the inter-annual variability of water discharge for those streams in Peru where the gauging sites are close to the grain size sampling location (distance of a few kilometers) yields a one standard deviation of c. 50%, which is still much larger than for the Swiss rivers (Appendix S2). We therefore run sensitivity tests where we considered scenarios with different relative values for 1σ standard deviations of Q_{mean}.

We additionally ran sensitivity tests to explore how the mobility probability changes if runoff quantiles instead of Q_{mean} are considered (Supplement S3). In particular, we ran a series of Monte Carlo simulations for various runoff quantiles and then calculated the resulting probability of

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sediment mobilization for each of these quantiles. We then multiplied the occurrence probability of each runoff quantiles (listed by the Swiss authorities and calculated for the Peruvian streams based on 4 to 98-years equivalent daily records) with the corresponding transport probability and summed the values. This integration provides an alternative and more realistic estimate of transport probability (Supplement S3).

2.3.4 Channel width data

For the Swiss streams, channel widths and gradients (Table 1, Supplement S4) were measured on orthophotos and LiDAR DEMs with a 2-m resolution provided by Swisstopo. From this database, gradients were measured over a reach of c. 250 to 500 m. All selected Swiss rivers are single-thread streams following the classification scheme of Eaton et al. (2010), and flows are constrained by artificial banks where channel widths are constant over several kilometers. For these streams, we therefore measured the cross-sectional widths between the channel banks, similar to Litty and Schlunegger (2017).

We complemented this information with channel width (wetted perimeter) and energy gradient data for 21 Peruvian streams that were collected by Litty et al. (2017) in the field and on orthophotos taken between March-June. This period also corresponds to the season when the digital photos for the grain size analysis were made (Mai 2015). We acknowledge that widths of active channels in Peru vary greatly on an annual basis because of the strong seasonality of runoff (see above and large intra-annual variability of runoff in Table 1). We therefore considered scenarios where channel widths are twice as large as those reported on Table 1 (see Supplement S5).

The uncertainties on slope and channel width largely depend on the resolution of the digital elevation models underlying the orthophotos (2-m LiDAR DEM for Switzerland, and 30-m ASTER DEM for Peru). It is not possible to precisely determine the uncertainties on the slope values. Nevertheless, we anticipate that these will be smaller for the Swiss rivers than for the Peruvian streams mainly because of the higher resolution of the DEM. We ran sensitivity models where we explored how the probability of material transport changes in the Swiss rivers for various uncertainties on channel widths, energy gradients and mean annual discharge values (Supplement S4)

3 Results

3.1 Grain size, critical shear stress, and probability of transport

The grain sizes range from 8 mm to 70 mm for the D_{50}, 29 mm to 128 mm for the D_{84}, and 52 mm and 263 mm to the D_{96}. The smallest and largest D_{50} values were determined for the Maggia and Rhein Rivers in the Swiss Alps, respectively (Table 1). The grain sizes in the Swiss Rivers also reveal the largest spread where the ratio between the D_{96} and D_{50} grain size ranges between 2.2 (Sarine) and 17.7 (Maggia Losone I), while the corresponding ratios in the Peruvian streams are

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between 2.1 (PRC-ME9) and 5.8 (PRC-ME17). In the Swiss Alps, the critical shear stresses τ_c (median values) for entraining the D_{84} grain size ranges from c. 20 Pa (Emme River) to c. 90 Pa (Rhein and Simme Rivers). In the Peruvian Andes, the largest critical shear values are <80 Pa (PRC-ME39). The shear stress values related to the mean annual water discharge Q_{mean} range from c. 15 Pa to 100 Pa in the Alps and from 20 Pa to >400 Pa in the Andes. Considering the strength of a mean annual flow and the D_{84} grain size as threshold, the probability of sediment transport occurrence in the Peruvian Andes and in the Swiss Alps comprises the full range between 0% and 100%.

Rivers that are not affected by recurrent high magnitude events (e.g., debris flows) and where the grain size distribution is not perturbed by lateral material supply are expected to display a self-similar grain size distribution (Whittaker et al., 2011; D'Arcy et al., 2017; Harries et al., 2018), characterized by a linear relationship between the D_{84}/D_{50} and D_{96}/D_{50} ratios. In case of the Maggia River, the largest grains are oversized if the D_{50} and the grain size distribution of the other streams are considered as reference (Fig. 2). This could reflect a response to the supply of coarse-grained material by a tributary stream where the confluence is <1 km upstream of the Maggia sites. Alternatively, and possibly more likely, it reflects the response to the high magnitude floods in this stream (Brönnimann et al., 2018). In particular, while the ratio between the last and first quantiles is <150 in the Swiss streams on the northern side the Alps, the ratio is 860 in the Maggia River. Interestingly, such ratios are not rare in Peru. However, we anticipate that the Peruvian streams are capable to accommodate such large runoff variabilities through much wider channel belts that are not confined by artificial banks along most of the streams. If we exclude the Maggia dataset, then the probability of sediment transport occurrence scales positively and linearly with the D_{96}/D_{50} ratios (Fig. 3A). The observed relationship appears stronger for the Swiss rivers (R^2 = 0.74, p-value = 2E-4) than for the Peruvian stream (R^2 = 0.33, p-value = 4E-3). These correlations suggest that gravel bars with a poorer sorting of the bed material, here expressed by a high D_{96}/D_{50} ratio, have a greater probability for the occurrence of sediment transport than those with better-sorted material. If the normalized residuals are plotted against the sorting, then they do not show any specific and significant patterns, and therefore appear independent of the sorting (Fig. 3B). This suggests that the inferred linear relationships between the probability of transport occurrence and the D_{96}/D_{50} are statistically robust. Although Fig. 3A suggests that the regression for the Swiss rivers (slope= 0.16±0.06; intercept= -0.34±0.31) differs from that of the Peruvian streams (slope= 0.18±0.11; intercept= -0.02±0.46), the regression parameters do not significantly differ when considering them within their 95% confidence intervals.

The use of discharge quantiles yields sediment transport probabilities within a large range between <10% and >50%, and they are higher than reported values from other streams (Torizzo and Pitlick, 2004; Pfeiffer and Finnegan, 2008). Additionally, the resulting probabilities are positively and linearly correlated with the probability of transport estimated with Q_{mean} (Figure S3 in Supplement), and the correlations are very similar between the Swiss (slope: 0.74±0.02; intercept: 0.05±0.01) and

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Peruvian streams (slope: 0.73±0.19; intercept: 0.03±0.14). The mean annual discharge estimates Q_{mean} are likely biased by infrequent, but large magnitude floods, which could explain the 25% larger transport probabilities if Q_{mean} is used as reference runoff.

The assignments of different uncertainties on reach slopes, channel widths and discharge has no major influence on the inferred relationships between transport probability and sorting (Supplement S4, S5). For the Peruvian streams, however, assignments of twofold larger values to channel widths will decrease the probability of transport for a given sorting by c. 10-15%. The inferred linear relationship between both variables, however, will remain (Supplement S5).

4 Discussion and Conclusions

The sediment transport calculation is based on the inference that water discharge is strong enough to entrain the frame building grain size D_{84}. Therefore, the relationships between the mobilization probability and the D_{96}/D_{50} ratio could depend on the selected grain size percentile (e.g., the D_{84} versus the D_{50}), which sets the transport threshold. However, recent experiments have shown that the D_{84} better characterizes the thresholds for sediment entrainment than the D_{50} (MacKenzie et al. (2018). Besides, grain size D linearly propagates into the equation (2) and thus into the probability of $\tau > \tau_c$. Therefore, although the resulting probabilities vary depending on the threshold grain size, the relationships between the D_{96}/D_{50} ratio and the mobilization probability will not change. In addition, because of the linear relationship between the D_{84}/D_{50} and D_{96}/D_{50} ratios (Fig. 2), the same dependency of transport probability on sorting will also emerge if the D_{96}/D_{84} ratios are used. For the case where different discharge estimates are considered, here expressed as the ratio Δ of a specific runoff to the mean annual discharge Q_{meam}, then the corresponding probability of sediment transport will change by $\sim\sqrt{\Delta}$ (equation 7), but the dependency on the D_{96}/D_{50} ratio will remain. This is also valid if transport probabilities are calculated based on discharge quantiles (Supplement S3), and if larger channel widths particularly for Peruvian streams are considered (Supplement S5). This suggests that the sorting of the bed material has a measurable impact on the mobility of gravel bars and thus on the frequency of sediment mobilization irrespective of the selection of a threshold grain size and the choice of a reference water discharge. We note that while the data is relatively scarce and scattered (i.e., the same transport probability for a c. twofold difference in the D_{96}/D_{50} ratio), the relationships observed between the probability of transport occurrence and the degree of material sorting are significant with p-values <<0.01. We explain the scatter in the data by the natural stochastic nature of processes that are commonly encountered in the field.

For a given D_{96}/D_{50} ratio, the probability of material transport tends to be greater in the Peruvian than in the Swiss rivers (Fig. 3A). We explain the albeit small divergence in the transport probability between both settings (i.e. regression parameters overlap within their 95% confidence interval) by (i) the differences between the geomorphic conditions and sediment supply processes in both mountain ranges, (ii) the anthropogenic corrections of the Swiss streams, and (iii) the generally stochastic nature in sediment supply. In the Swiss Alps, the channel network, the processes on the

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hillslopes, and the pattern of erosion and sediment supply has mainly been conditioned, and thus controlled, by the glacial impact on the landscape and the large variability of exposed bedrock lithologies (e.g., Salcher et al., 2014; Stutenbecker et al., 2016). In addition, the intra-annual runoff variability is much lower than in the Peruvian streams (Supplement S2). In contrast, the erosion and sediment supply in the western Peruvian Andes is mainly driven by the combined effect of orographic rain (Montgomery et al., 2001; Viveen et al., 2019) and earthquakes (McPhilips et al., 2014), and the intra-annual runoff variability is quite large (Table 1). Because the patterns, conditions and mechanisms of sediment supply largely influence the grain size distribution of the supplied material (Attal et al., 2015), and as consequence, the downstream propagation of these grain size signals (Sklar et al., 2006), we do not expect identical relationships between grain size parameters and probability of sediment transport in both mountain ranges. In the same sense, the large variability and stochastic nature of sediment supply and transport processes could also explain the large spread in transport probability that we report for the Swiss and Peruvian streams. A large spread in transport probability was also inferred for mountainous rivers in the USA (Torizzo and Pitlick, 2004; Pfeiffer and Finnegan, 2018). We note, however, that Pfeiffer and Finnegan (2018) report lower transport probabilities that range between 8% and nearly 100% for the West Coast, 1% and 12% for the Rocky Mountains, and <10% for the Appalachian Mountains. In a broader sense, these authors considered the ratio between sediment supply and sediment transport capacity as criteria for the incipient motion of bedload material, which differs from the mobility criteria that we set in this paper. However, the largest difference stems from the values of the database. While the D_{50} of Pfeiffer and Finnegan (2018) has nearly the same size as the D_{84} reported here, their channel gradients tend to be 3 times lower. Because shear stress linearly depends on gradient (equation 7), then the probability where $\tau > \tau_c$ will be directly and proportionally affected by this. Nevertheless, even if we would select a different channel gradient, the probability of material mobilization will go down (most likely linearly), but the dependency of the transport probability on the grain size sorting will remain. Accordingly, despite the large scatter in the dataset, the relationships between transport mobility and sorting is statistically significant with p-values <<0.01, which suggests the sorting of coarse-grained bed sediments has a measurable impact on the mobility of the bedload material. We therefore conclude that besides the generally accepted controls including transport regime and sediment supply (Dade and Friend, 1998; Church, 2006), the sorting of the bed material represents an additional, yet important variable that influences the mobility of material on gravel bars. In addition, further research could possibly disclose a mechanism where sediment supply, material sorting and transport probability may be closely linked through a positive feedback.

Figure 1

A) Map showing the sites where grain size data has been measured in the Swiss Alps. The research sites are close to water gauging stations; B) map showing locations for which grain size and water discharge data is available in Peru (Litty et al., 2017).

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Figure 2

Relationship between ratio of the D_{96}/D_{50} and D_{84}/D_{50}, implying that the D_{96} grain sizes of the Maggia gravel bars are too large if the D_{50} is taken as reference and if the other gravel bars are considered.

Figure 3

A) Relationships between the probability of sediment transport occurrence and the D_{96}/D_{50} ratio, which we use as proxy for the sorting of the gravel bar, in the Swiss and Peruvian rivers. B) Normalized residuals that are plotted against the sorting. The normalized residuals do not show any specific and significant patterns.

Table 1

Channel morphometry (width and gradient), grain size and water discharge measured at the research sites. The table also shows the results of the various calculations (critical shear stress τ_c, shear stress τ of a flow with a mean annual runoff Q_{med}, and probability of sediment transport occurrence related to this flow).

Acknowledges

The Federal Office for the Environment (FOEN) is kindly acknowledged for providing runoff data for the Swiss streams.

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TABLE 1. GRAIN SIZE, CHANNEL METRICS, SHEAR STRESSES AND RELATIVE TRANSPORT TIME

Id	River	Site coordinates Latitude (DD WGS84)	Site coordinates Longitude (DD WGS84)	Channel width along reach (m)	Reach gradient (m/m)	Qmean: Mean annual water discharge (m3/s)	Standard deviation of Qmean (m3/s)**	D50 (m)	D84 (m)	D96 (m)	D96/D50	D84/D50	Critical Sheer (median) (Pa)	Critical Sheer (16th%) (Pa)	Critical Sheer (84th%) (Pa)	Sheer stress in response to Qmean (median) (Pa)	Sheer stress in response to Qmean (16th%) (Pa)	Sheer stress in response to Qmean (84th%) (Pa)	Relative transport time for Qmean and the D84 as threshold
1	*Emme**	46.96	7.75	30	0.007	11.9	2.5	0.009	0.029	0.052	5.8	3.2	21	15	29	30	23	39	81%
2	*Landquart**	46.98	9.61	32	0.018	24.1	5.1	0.025	0.083***	0.135	5.4	3.3	60	42	82	102	79	130	90%
3	*Waldemme Littau**	47.07	8.28	27	0.011	15.5	2.8	0.009	0.050***	0.084	9.3	5.5	36	26	50	55	42	69	85%
4	*Reuss**	46.88	8.62	48	0.007	42.9	4.7	0.009	0.032***	0.064	7.2	4.1	27	19	37	48	38	60	93%
5	*Maggia Losone II**	46.17	8.77	84	0.005	22.7	10.8	0.011	0.046***	0.127	11.3	4.1	33	23	46	19	12	26	11%
6	*Maggia Losone I**	46.17	8.77	22	0.005	22.7	10.8	0.008	0.033***	0.140	17.7	4.1	24	17	33	39	26	53	83%
7	*Rhein*	47.01	9.30	92	0.002	167.5	24.5	0.070	0.128	0.169	2.4	1.8	92	65	127	26	20	32	0%
8	*Sarine*	46.36	7.05	24	0.004	21.0	3.9	0.049	0.080	0.108	2.2	1.6	58	41	80	27	21	35	4%
9	*Lütschine*	46.38	7.53	32	0.007	19.0	1.7	0.061	0.111	0.153	2.5	1.8	80	56	110	39	31	49	4%
10	*Thur*	47.30	9.12	52	0.002	37.9	6.8	0.024	0.045	0.069	2.9	1.8	32	23	45	13	10	17	2%
11	*Simme*	46.39	7.27	15	0.014	12.0	1.8	0.062	0.119	0.263	4.2	1.9	86	61	118	87	68	109	51%
12	*Sitter*	47.24	9.19	26	0.005	10.2	1.6	0.028	0.064	0.094	3.3	2.2	46	33	64	24	19	30	6%
13	*Kander*	46.39	7.40	26	0.009	20.0	2.3	0.054	0.116	0.193	3.6	2.1	84	59	115	58	46	72	19%
14	*Sense**	46.89	7.35	24	0.005	8.7	1.7	0.024	0.060	0.096	4.0	2.5	43	31	60	22	17	28	6%
15	PRC-ME1#	-18.12	-70.33	6	0.015	3.4	0.8	0.023	0.062	0.100	4.3	2.7	45	32	62	76	58	97	89%
16	PRC-ME3#	-17.82	-70.51	6	0.013	4.0	5.0	0.025	0.055	0.110	4.4	2.2	40	28	55	83	46	126	86%
17	PRC-ME5#	-17.29	-70.99	7	0.018	3.4	1.0	0.026	0.051	0.078	3.0	2.0	37	26	51	82	61	107	96%
18	PRC-ME6#	-17.03	-71.69	26	0.051****	38.1	37.8	0.015	0.036	0.075	5.0	2.4	26	18	36	432	244	643	100%****
19	PRC-ME802#	-16.34	-72.13	15	0.019	30.1	21.7	0.020	0.060	0.100	5.0	3.0	43	31	60	193	116	278	98%
20	PRC-ME7#	-16.51	-72.64	100	0.005	68.4	52.7	0.052	0.087	0.120	2.3	1.7	63	44	86	31	18	45	8%
21	PRC-ME9#	-16.42	-73.12	70	0.004	91.1	82.2	0.048	0.068	0.100	2.1	1.4	49	35	68	37	21	54	29%
22	PRC-ME1402#	-15.85	-74.26	3	0.014	20.4	29.9	0.013	0.030	0.060	4.6	2.3	22	15	30	336	182	510	100%
23	PRC-ME15#	-15.63	-74.64	23	0.003	12.1	16.7	0.029	0.064	0.096	3.3	2.2	46	33	64	19	10	29	5%
24	PRC-ME16#	-13.73	-75.89	20	0.013	13.6	17.8	0.030	0.066	0.130	4.3	2.2	48	34	66	85	47	129	80%
25	PRC-ME17#	-13.47	-76.14	5	0.010	10.1	14.8	0.013	0.038	0.076	5.8	2.9	28	19	38	126	68	191	97%
26	PRC-ME19#	-13.12	-76.39	60	0.010	26.4	25.9	0.020	0.046	0.088	4.4	2.3	33	23	46	49	28	72	72%
27	PRC-ME20#	-12.67	-76.65	22	0.008	8.2	9.8	0.016	0.048	0.088	5.5	3.0	35	25	48	38	21	57	55%
28	PRC-ME22#	-12.25	-76.89	5	0.022	3.7	4.3	0.030	0.050	0.088	2.9	1.7	36	26	50	141	78	212	96%
29	PRC-ME39#	-11.79	-76.99	40	0.018	4.9	5.1	0.053	0.105	0.150	2.8	2.0	76	54	104	42	24	63	13%
30	PRC-ME23#	-11.61	-77.24	20	0.010	8.9	7.8	0.055	0.083	0.120	2.2	1.5	60	42	82	48	27	70	32%
31	PRC-ME25#	-11.07	-77.59	5	0.012	3.8	4.6	0.028	0.077	0.130	4.6	2.8	56	39	77	82	45	124	72%
32	PAT-ME#	-10.72	-77.77	30	0.014	30.9	24.3	0.018	0.036	0.060	3.3	2.0	26	18	36	102	60	148	97%
33	PRC-ME38#	-10.07	-78.16	15	0.004	9.8	12.7	0.017	0.034	0.052	3.1	2.0	25	17	34	28	15	42	56%
34	PRC-ME27#	-8.97	-78.62	40	0.005	96.1	67.7	0.020	0.054	0.090	4.5	2.7	39	27	54	61	37	87	77%
35	PRC-ME30#	-7.32	-79.48	40	0.007	25.4	27.7	0.029	0.063	0.100	3.4	2.2	45	32	63	44	24	65	46%

Italic=Swiss Rivers, plain=Peruvian Rivers

Water discharge data from the Swiss Rivers is taken from the Swiss Federal Office for the Environment (FOEN: www. hydrodaten.admin.ch). Reported values represent discharges monitored over the period 1990-2011; Except for the Rhein (1977-1990).

Water discharge and drainage basin size data from the Peruvian Rivers is taken from Reber et al. (2017) and Litty et al. (2017)

#The grain size data from the Peruvian streams is taken from Litty et al. (2017)

*The grain size data, channel width and gradient data from the Emme, Landquart, Reuss, Maggia and Sense Rivers is taken from Litty and Schlunegger (2017)

**While standard deviation on annual water flow represents inter-annual variance for Switzerland, it represents intra-annual ones in Peru.

***Mean values of measurement results by Hauser (2017) and Litty and Schlunegger (2017)

****The results are possibly biased by an error on the slope, which appears too steep; the consideration of a flatter slope (0.013) still yields 99%

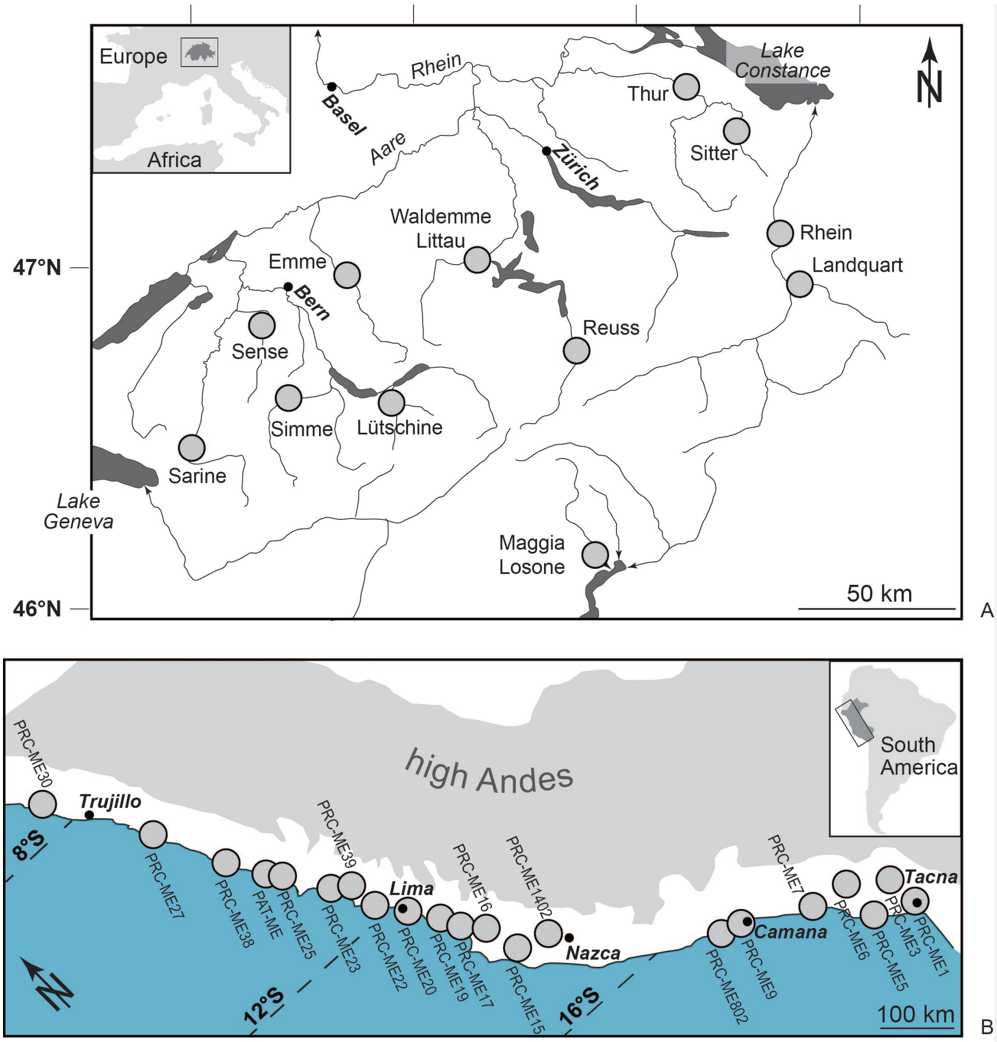
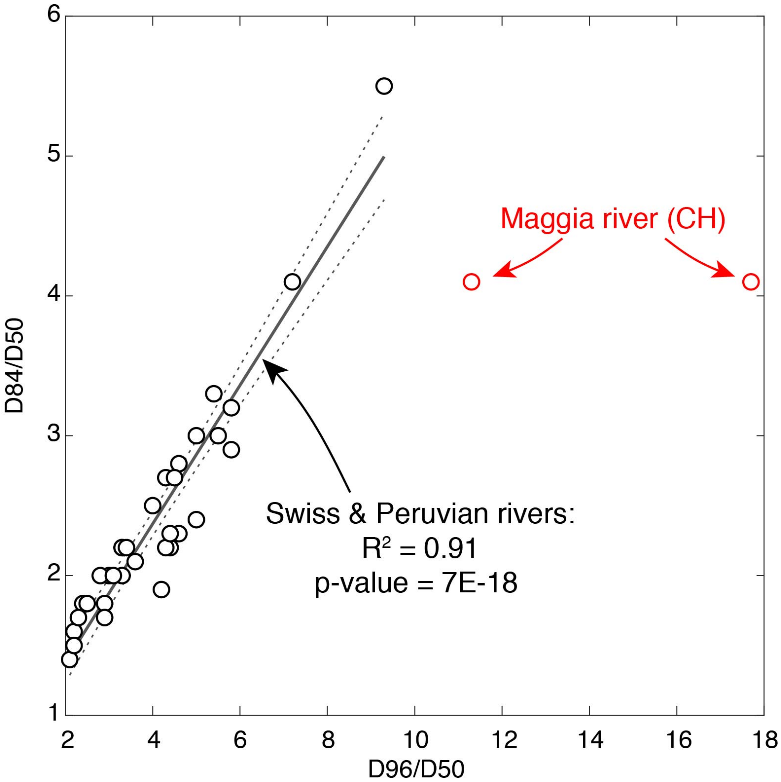

Europe
Africa
Rhein
Basel
Aare
Zürich
Lake
Constance
Thur
Sitter
Waldemme
Littau
Emme
Bern
Rhein
Landquart
47°N
Sense
Reuss
Simme
Lütschine
Sarine
Lake
Geneva
Maggia
Losone
50 km
46°N
A
high Andes
South
America
PRC-ME30
Trujillo
8°S
PRC-ME27
PRC-ME38
PAT-ME
PRC-ME25
PRC-ME39
PRC-ME23
PRC-ME22
Lima
PRC-ME20
PRC-ME19
PRC-ME16
PRC-ME17
PRC-ME1402
PRC-ME15
Nazca
12°S
16°S
PRC-ME802
PRC-ME9
Camana
PRC-ME7
PRC-ME6
PRC-ME5
PRC-ME3
Tacna
PRC-ME1
100 km
B

Figure 1



Maggia river (CH)
Swiss & Peruvian rivers:
R² = 0.91
p-value = 7E-18
D84/D50
D96/D50

Figure 2

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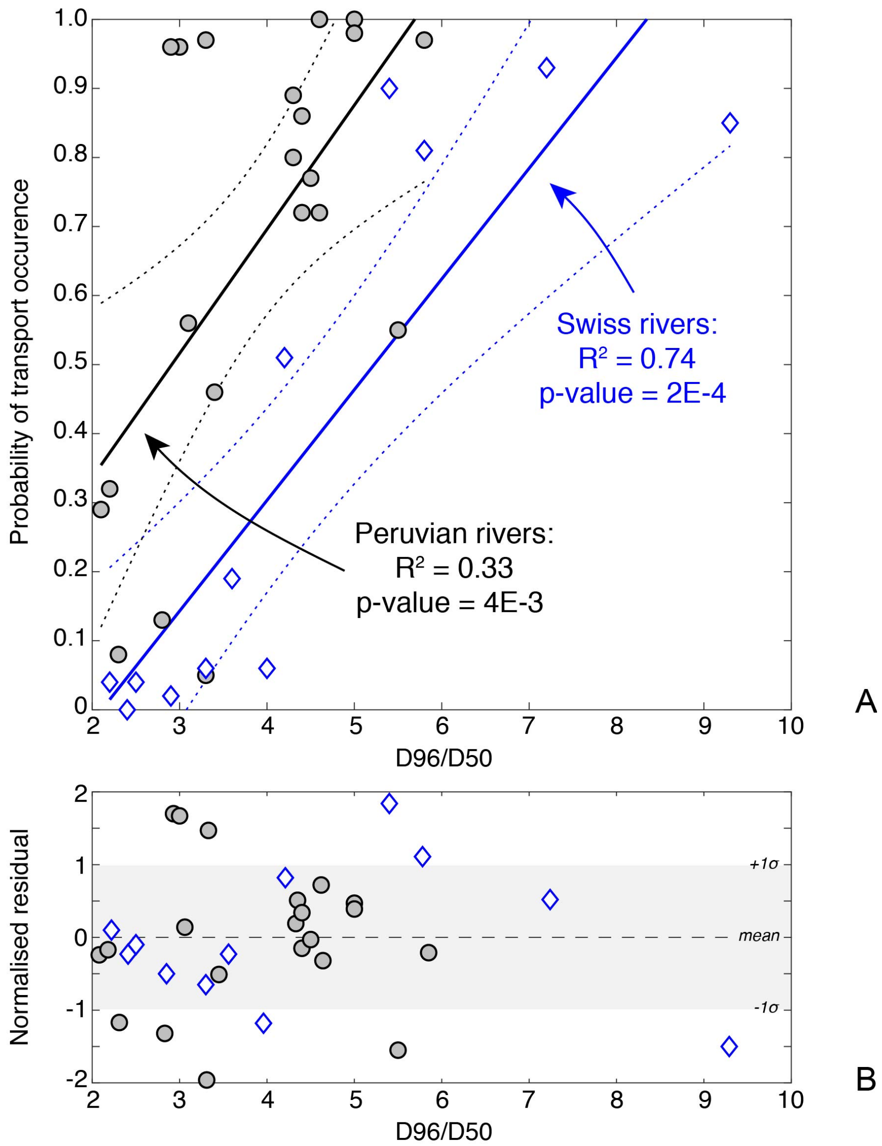
Probability of transport occurence
D96/D50
Swiss rivers:
R² = 0.74
p-value = 2E-4
Peruvian rivers:
R² = 0.33
p-value = 4E-3
A
Normalised residual
+1σ
mean
-1σ
B

Figure 3