Manuscript ID: egusphere-2025-5178

Original Title: *At-a-site and between-site variability of bedload transport, inferred from continuous surrogate monitoring, and comparison to predictive equations*

Author: Dieter Rickenmann

Dear Jonathan Laronne, Reviewer #1,

I thank Jonathan Laronne for his positive review and for his comments that have helped to improve the quality of the manuscript. In the detailed response remarks below, I explain how I have addressed these comments in the revised version of the manuscript.

Reviewer #1, Jonathan Laronne, attached a marked manuscript with a total of 26 comments (my count). In the detailed response remarks below, I explain how I have addressed these comments in the revised version of the manuscript.

All important changes have been highlighted in the revised manuscript, in red colour in the track-change version. In my detailed point-by-point responses to each comment, the part of the manuscript marked by reviewer #1 is reproduced within quotation marks in normal font, and the comment of reviewer #1 is given in italic font on a new line. My response is given in blue font.

Responses to the Comments from Reviewer #1

This is an overall high quality manuscript in terms of the topic, the techniques of obtaining and analyzing data. With some edits this will be a useful addition to indirect bedload monitoring. Several of the latter parts of this submission are best moved from the manuscript to the supplement.

I thank the reviewer for this positive assessment of the manuscript.

Comment 1 (Title)

The ms is very long. In places I have suggested moving material to Supplement, but more such moves are required.

As suggested by the reviewer, I have moved Table 6, Figure 7, and the paragraph L389-397 to a new Appendix B. Also, I have inserted two new columns in Table 6 (new: Table B1) to more easily summarize the quantitative results in the main text.

I an earlier draft version of the manuscript, I have had put a (large) part of the bedload transport equations into the Appendix. However, since many elements of the transport equations are key for the analysis and the discussion of the results, I have had decided to put the transport equations back into the main text.

As a result of the request of both reviewers for more discussion elements, I have added new text that prevented me from shortening the main text.

Comment 2 (L15-17)

“Overall, continuous monitoring highlights the strong role of temporal spatial variability on bedload transport levels, possibly due to changing sediment availability and bed surface composition, and with implications for predictive modelling and river management.”

most important conclusion of this study

A further discussion of the role of sediment availability has been suggested by reviewer #2. I have included more discussion elements on the role of both variable sediment availability and changing reference Shields stress (new section 4.5), reflecting possible changes in transported material and bed surface composition. (see also my response to comments 1, 2, 3 of reviewer #1.)

Comment 3 (L55-57)

"Hydrograph dynamics further amplify variability: transport often peaks disproportionately on the rising limb relative to falling stages due to supply exhaustion and channel adjustments (Pretzlav et al., 2020; Mao et al., 2019; Rickenmann, 2024)." [underlined word marked by reviewer #1]

not often in rivers that lack a stable cover

I have modified the above sentence in the Introduction section to read: "Hydrograph dynamics further amplify variability: in perennial streams transport often peaks disproportionately on the rising limb relative to falling stages due to supply exhaustion and channel adjustments (Pretzlav et al., 2020; Mao et al., 2019; Rickenmann, 2024), whereas in ephemeral streams typically lacking an armour layer such as in the Nahal Eshtemoa no clear hysteresis pattern could be found for the majority of the flood events (Cohen et al., 2010)."

Comment 4 (L83-85)

"In the same study, Rickenmann (2018) found that correlation between bedload transport rates and discharge is considerably increased, if these values are aggregated over about one to two hours."

explain why this is so

Possible reasons for this are mentioned in Rickenmann (2018): Fluctuations with a periodicity of 14–35 min were found both in natural streams (Habersack et al., 2012; Hilldale, 2015; Reid & Frostick, 1986) and in flumes (Kuhnle & Southard, 1988, Strom et al., 2004) under a variety of hydraulic conditions and sediment supply. Possible reasons for such fluctuations may be moving bed load sheets or the formation and destruction of gravel clusters (Hilldale, 2015; Kuhnle & Southard, 1988).

I have summarized these possible reasons in the following additional sentence in the revised manuscript: "This finding may be associated with fluctuations of bedload transport with a periodicity of 14–35 min observed both in natural streams and in flumes for a variety of hydraulic conditions and sediment supply, possibly due to moving bed load sheets or the formation and destruction of gravel clusters (Rickenmann, 2018)."

Comment 5 (Table 2, fourth column)

"R2"

power 2; give all r2 values to 2 decimal locations

These suggestions have been implemented in Table 2.

Comment 6 (Table 2, last line)

"(*)"

explain

The meaning of (*) is explained in the caption of Table 2.

Comment 7 (L151)

"Q (in m3 s-1)"

write as accepted (and everywhere else)

These corrections have been implemented.

Comment 8 (L163)

"grain sizes larger than 4 mm"

Here and everywhere in this ms refer to the sensitivity of the monitoring system, which is well above 4 mm.

Thank you for having identified some inconsistency and missing information regarding grain sizes. Indeed, as indicated on L135, the SPG system can only detect grains with a diameter D larger than 9.5 mm. An additional paragraph was added and some more information included in Table 2 to clarify this point. The additional paragraph reads:

"For the Erlenbach, for 12 flood events basket samples were available with information regarding transported grain sizes in the range of 4 mm < D < 10 mm (see also Table 2). Based on these data, a mean coefficient m_{fg} = 1.54 was estimated, to multiply the mass M in Eq. 1 to account for this fine fraction undetected by the SPG system, and applied to the Erlenbach measurements (Rickenmann, 2024). For the individual basket samples, the coefficient m_{fg} varied between about 1.4 and 1.9, with a tendency to decrease for increasing total transport rates Q_b in the range of about 0.02 kg s^{-1} to 0.8 kg s^{-1}. For the Albula, Navisence, and Avançon, no such information was available, so for these streams no correction was applied. For the Riedbach, the calibration relation of the SPG system considered also fine material deposited in the settling basin of the water intake, and therefore likely included also some sand sized particles (Schneider et al., 2016). For the later comparison with bedload transport equations it would be more correct to also account for the fraction of particles in the range of fine gravel, i.e. for 4mm<D <10 mm. However, given the large variabilities of bedload transport rates often extending over one or more orders of magnitudes and the goals of this study, this uncertainty about partly lacking information on finer transported bedload particles may be considered acceptable."

Comment 9 (L168)

"Equation 3"

at the end of an equation and where relevant as it is here, add a comma

These corrections have been implemented.

Comment 10 (L245-246)

"The comparison of all six bedload transport equations applied to the Albula site is shown in Fig. 2"

Please add a paragraph to summarize what these figures show, including the fact that for a given water discharge of shear stress the difference between given equations is in some cases small, and in several [are] of several orders of magnitude (as expected). An additional paragraph here on [or] more relevant to the discussion will be useful to attempt explaining some of these large differences. Without these comments the exercise of showing where the data lie is useless.

The main purpose of Fig. 2 is to illustrate the general shape of the different transport functions. As you mentioned, the difference between the predicted transport rates depends on the case (field site). The three major comments of reviewer #2 request more discussion on several elements that have a partly strong link to the bedload transport equations. In line with these comments I have tried to strengthen and complement my statements the discussion section regarding these aspects.

Comment 11 (L302)

"fitted to only"

fitted only to

This correction has been implemented.

Comment 12 (L326, Figure 3)

The relatively narrow range of bedload discharge values for the Riedbach is 'another world' of conditions when compared to the very widely ranging values for the Navisence and Avancon, though large variance at higher flows is evident in all the streams with the exception of the Riedbach. Please discuss this

It should be noted that IMP values were stored only for 10-minute intervals for the Riedbach stream (L127), as compared to the 1-minute intervals for all the other streams. This results in comparatively less data points and in some averaging of the transport rates due to the temporal aggregation. I have added a clarifying sentence below Fig. 3: "A caveat for the Riedbach data in Fig. 3 is that IMP values were stored only for 10-minute intervals, with a corresponding temporal aggregation of the transport rates, a likely reason for less variability than in the other four streams."

Comment 13 (L358, Figure 4)

The Erlenbach and Albula data for phase 2 involve much less scatter than in the other 3 rivers. Please refer to this

I have added the following sentence below Fig. 4 to highlight this point: "The more well-defined patterns of the temporally smoothened data in Fig. 4 for the Albula and the Erlenbach likely reflects the generally smaller variability of Qb values in Fig. 3, as compared to the other two streams."

Comment 14 (L358, Figure 4 caption)

"The trend lines were determined by a loess smoothening function in the R code."

loess?

The sentence has been modified to: "The trend lines were determined by a loess smoothening function, a local polynomial regression fitting, in the R code."

Comment 15 (L368)

"In general, the distribution of m and τ*ref for the Swiss streams is more similar to that for the SEA_SS data"

more similar but still very variable

The sentence has been modified to: "In general, the distribution of m and τ*ref for the Swiss streams is more similar to that for the SEA_SS data (and also variable)."

Comment 16 (L369)

"~~Interestingly, looking at~~ the τ*rD50 values, ~~they~~ show a dependence for"

[deleted words suggest simplification of sentence]

This correction has been implemented.

Comment 17 (L386, Table 6)

Table 6 is best moved to an appendix with a short description of its contents

Thank you for this suggestion. I have moved Table 6, Figure 7, and the paragraph L389-397 to a new Appendix B. I have inserted two new columns in Table 6 (new: Table B1) to more easily summarize the quantitative results in the main text as follows: "The results of the analysis reported in Appendix B allowed to derive the approximate duration from the beginning of the transport season to the time point after which the rx_chron values were within about a factor of 3 above or below the rx_incQ values, x = t or r. Although there is quite some variability from year to year, the average relative duration, in terms of a fraction of the total transport duration of a year, was as follows (first number refers to the x = t and the second number to the x = r analysis): 51 % and 44 % for the Albula, 48 % and 39 % for the Navisence, 15 % and 21 % for the Avançon, and 6 % and 11 % for the Erlenbach (Table B1)."

<u>Comment 18 (L397-401)</u>

"Navisence (Fig. S14 to S19), the Avançon (Fig. S22 to S27), and the Erlenbach (Fig. S29 to S30). A similar picture becomes apparent when comparing the ratios rt_year and rr_year (Fig. 8a) and the ratios rt_incQ and rr_incQ (Fig. 8b) for the four streams, for both the W*tot analysis and for the W*red analyses: While there is a tendency to under-estimate the observed bedload masses for two streams (Albula, Erlenbach), a tendency for an over-estimation is apparent for the other two streams (Navisence, Avançon)."

Suggest moving to appendix

I prefer to keep Fig. 8 in the main text, because I think that it nicely illustrates the variability of the ratios of annual calculated to measured bedload masses, and it supplements the finding reported in the (new) paragraph before.

<u>Comment 19 (L409, Figure 7 caption)</u>

liner

[-> typo]

This correction has been implemented.

<u>Comment 20 (L449-450)</u>

"(TV for temporal variation), and the data set of Recking et al. (2016) is labeled "REA_BT" (BT for β and τ*ref) henceforth; 450 these labels are used in Fig. 10, 11, and 12 below."

This paper includes a very large number of labeled names - much to many for readers to remember. The author is recommended to use simple terms/descriptions.

I prefer to keep these abbreviations because they also appear in many figure legends or figure axis labels. Using simple terms/descriptions there is not very practical. However, I have expanded the list of variables (new in Appendix E) to include also the abbreviations for the data sets, for easier readability.

<u>Comment 21 (L461-462)</u>

"Fig. 6 compare fairly well with the results of Recking et al. (2016) as illustrated in Fig. 10."

as most log-log relations tend to show to the reader, but a large mass of the data fall far from the relationship. r2 is warranted

I believe that giving r2 for each data set here would rather confuse than help, with regard to the main message. [In Recking et al. (2016), the solid black line presented in Fig. 10 was derived from the data of the plane bed streams only, making up about 1/3 of the entire REA_BT data set shown in Fig. 10; for this partial data set Recking et al. (2016) found r2 = 0.90.] The main point is that most data points of the other three data sets in Fig. 10 (and particularly those for S larger than about 0.01) lie within the data points of the entire REA_BT data set. Also, the focus of the comparison is on the channel slope range 0.01 < S < 0.1, for which the τ*ref values predicted by (32) and (33) are similar to those predicted by Eq. (4), as can also be seen by comparing Fig. 6 and 10. So these results suggest that a comparison between the two approaches may be justified. [see paragraph above Fig. 10]

However, due to differences in the transport equations and the underlying assumptions, a more quantitative comparison of the t*ref vs. S relation is not very meaningful.

Comment 22 (L476, Figure 11 caption)

"19 out of 21 data points fall into the slope class shown here."

define how large is the slope class

The slope class is defined by the square brackets in the abscissa label tick information. For the comparison of Fig. 11b and Fig. 11c the slope classes are the same and extend over a little more than one order of magnitude.

Comment 23 (L510-512)

"A possible reason for this may be that more fine particles are available in flatter streams, leading to larger transport and generally lower β or m values according to the Recking Eq. (14)."

so why do equations that consider slope not 'deal' with this obvious effect?

According to the studies of Schneider et al. (2015), Recking et al. (2016) and this study, a slope effect could be primarily identified with regard to the reference shear stress in the bedload transport equations. For our W^*_{tot} analysis and for the Recking equation, this requires to increase τ^*_{ref} with increasing slope. (An increase in τ^*_{ref} with increasing channel slope had also been reported in earlier studies, e.g. Mueller et al. 2005, https://doi.org/ 10.1029/2004WR003692.) For our W^*_{red} analysis, τ^*_{ref} is approximately constant or independent slope, but a "slope effect" is indirectly accounted for by using a reduced shear stress, which becomes increasingly important for smaller relative flow depths of large channel slopes.

Sediment supply (and likely implying changing grain sizes) may also be observed to vary not only between stream sites, as is evidenced in Fig. 5 by the varying m values, but also to vary considerably at a given site between years, if sufficient observations are available, as is illustrated by our data sets for the multiple year observations in the Albula (Fig. S1, S2, S3), the Navisence (S12, S13), and Avançon (S20, S21). Thus, a combined between and at-a-site variation makes it more difficult to detect any slope effect if present. On the other hand, the case 2 analysis of Recking et al. (2016) showed some trend for generally lower β values for decreasing S values, for a quite large data set extending over more than three orders of magnitude (Fig. 11).

A further discussion of the role of sediment availability has been suggested by reviewer #2. I have included more discussion elements in the new section 4.5 "Roles of variable sediment supply and of changing Shields stress" (see also my responses to comments 1, 2, 3, 6, and 7 of reviewer #2.)

Comment 24 (L517-518)

"However, to better quantify such effects both continuous bedload transport measurements are needed along with more detailed information on streambed characteristics and sediment availability."

indeed so!

I agree with the importance of this statement (and I have tried to strengthen this point in the revised discussion elements).

Comment 25 (L542, Figure 13)

both Figure 13b and especially 13a have a database that to a large extent varies considerably from the average trend for all the streams. For instance, as the Albula data are far above (an order of magnitude) the Avancon data, what use is there of an average trend?

Indicating an average trend line is meant primarily to help visualize a linear trend between the yearly bedload masses (measured or calculated) and a simple measure of flow strength. In addition, the simple measure of flow strength much resembles a simple form of a bedload transport equation (Rickenmann, 2001, https://doi.org/10.1029/2001WR000319) and appears to be a reasonable indicator of yearly bedload masses, and selecting an appropriate coefficient for the trend line can roughly represent either the Albula data or the data of the other three streams (Avançon, Erlenbach, Navisence) together.

<u>Comment 26 (L558-559)</u>

"this only applies when channel slopes larger than about 2 % are considered. For the streams with channel slopes smaller than about 2 %,"

delete space before % throughout the ms

According to the ESurf submission guidelines a space is required (https://www.earth-surface-dynamics.net/submission.html#references), so I have checked the correct format throughout the ms.

Manuscript ID: egusphere-2025-5178

Original Title: *At-a-site and between-site variability of bedload transport, inferred from continuous surrogate monitoring, and comparison to predictive equations*

Author: Dieter Rickenmann

Dear Reviewer #2,

I thank this reviewer for his positive review and for his comments that have helped to improve the quality of the manuscript. In the detailed response remarks below, I explain how I have addressed these comments in the revised version of the manuscript.

All important changes have been highlighted in the revised manuscript, in red colour in the track-change version. In my detailed point-by-point responses to each comment, the comments of reviewer #2 are given in black font, and my responses are given in blue font.

Responses to the Comments from Reviewer #2

The present manuscript offers a thorough and data-rich analysis of bedload transport variability in four Swiss mountain streams, drawing upon long-term continuous Swiss Plate Geophone (SPG) monitoring. The study's findings, which are based on an explicit examination of variability at both sub-seasonal (event to multi-week windows) and annual timescales, provide a compelling evidence base demonstrating that the steepness of transport relations (m) and the reference shear stress (τ^*ref) are subject to significant temporal and geographical variation. This finding is of significant importance for the field of sediment transport theory as well as for the development of applied models and the management of rivers.

The dataset is exceptional, the methodological approach is largely sound, and the comparison across transport equation families (SEA-1/SEA-2, Recking-type formulations, and MPM variants) is informative. In sum, the submitted manuscript constitutes a substantial contribution and is well suited for EGUsphere.

This manuscript provides a robust and timely contribution to understanding the temporal and spatial variability of bedload transport and highlights fundamental limitations of stationary transport formulations. The manuscript would benefit from minor to moderate revisions, mainly aimed at improving clarity, contextualization, and figure presentation.

I thank the reviewer for this positive assessment of the manuscript.

Major comments:

1) Sediment availability and non-stationarity

The manuscript plausibly identifies sediment supply as a dominant control on the observed variability of transport parameters and model performance. However, sediment supply is mostly inferred indirectly from bedload transport processes and disequilibrium concepts. The discussion would benefit from a clearer conceptual and, where possible, quantitative framing of sediment supply (e.g. antecedent flow conditions, cumulative transport since major events, or catchment area-related measurement data). This would strengthen the interpretation of m and τ^*_{ref} values and improve reproducibility.

I agree that this aspect merits some more discussion. However, the fact that bedload transport variability may be due to a combination of changing sediment supply and grain size composition of the bed surface or of the transported material complicates a clear separation of these effects.

Also, Recking (2012) proposed to classify mountain streams into three categories of sediment supply, namely "high supply, "moderate supply", and "low supply". This classification was based on bedload transport measurements, where the possible boundaries between the three categories were indicated the Θ_{84} vs τ^*_{Re84}/τ^*_c plane (or alternatively in the plane bedload transport efficiency e vs. dimensionless stream power ω^*). I have checked this approach for the four Swiss streams Albula, Navisence, Avancon, and Erlenbach, and I found that the numerous minute values of the bedload measurements fall into all the three categories of sediment supply according to Recking (2012). Therefore, such a quantitative classification is not very helpful for a further discussion of sediment supply conditions in the different streams. In the study of Recking (2012) only a limited number of measurements were available per stream, which allowed some between-site differentiation. However, our study essentially shows that the at-a-site temporal changes in conditions results in a similar variability as when comparing the transport behaviour at many different sites.

I have added a new section 4.5 "Roles of variable sediment supply and of changing reference Shields stress" to extend the discussion on these aspects.

2) Transferability of results

The selected sites are characterized by their pristine alpine mountain streams, which are well-instrumented to facilitate scientific analysis. A more precise articulation regarding the anticipated transferability of the findings to disparate channel categories, such as less precipitous gravel-bed rivers, regulated channels, or wider channels, would enhance the general relevance of the conclusions and facilitate readers' evaluation of where analogous variability can be anticipated.

In the new section 4.5 "Roles of variable sediment supply and of changing reference Shields stress" I have included the following paragraph at the end: "It may also be mentioned that the four study streams Navisence, Avançon, Erlenbach, and Riedbach represent pristine mountain streams, whereas the Albula is a larger mountain river with important hydropower installations upstream of the SPG measuring site. Nevertheless, the range of bedload-transport variability found for these study streams from the combined between-site and at-a-site comparison is generally comparable to the between-site variability associated with the REA_BT data set including a large number of stream sites."

3) Adjustment options?

The manuscript unequivocally substantiates the constraints imposed by time-invariance parameterizations. The discussion would be strengthened by the provision of more explicit guidance on how these findings could be translated into practical modeling strategies, such as event-based or state-dependent calibration, adaptive parameterizations, or conditional formulations linked to sediment availability.

Also based on the added discussion elements in the new section 4.5, I have to conclude that it is difficult to come up with clear guidance for practical modeling strategies. Nevertheless, I have added a new section 4.6 "Implications for bedload prediction and modelling", and in this section I have included three discussion elements with some relevance for this topic: (i) possibly higher availability of fine particles in flatter streams; (ii) yearly aggregated bedload masses depend approximately linearly on a simple measure of flow intensity; (iii) in the Swiss study streams, SEA equations tend to provide mostly medium to minimum estimates, whereas the Re_ss equation tends to mostly provide maximum estimates.

Minor comments

4) Workflow: Section 2 comprises a multitude of equations and processing steps. A concise workflow schematic that summarizes the analysis would improve accessibility, especially for readers who are less familiar with the individual formulations.

I agree that a summary of the six equations used in the study can be helpful for readers less familiar with the individual formulations. I have therefore prepared a new table, Table B1 in Appendix B, which summarizes the bedload transport equations and the interrelation of steepness exponents. Beyond that, I am not convinced that a flow chart would help much for the understanding of the specific analysis methods described in sections 2.3 and 2.4.

5) Definition of Phase-2 transport conditions: Phase-2 conditions are identified through a visual inspection of smoothed trends and discharge ranges. A concise, precise operational definition (even if site-specific) would enhance clarity and reproducibility. At this juncture, a thorough elucidation of the rationale behind the selection of a static interval of two weeks would be advantageous for the reader's comprehension.

I have added the following text in section 2.3: "There is not much quantitative guidance in the literature regarding the definition of phase-2 transport conditions. Bathurst (2007, Eq. 8, 9, therein) proposed two empirical equations for the begin of phase-2 transport in mountain streams, Q_{c2a} as function of S and D_{50}, and Q_{c2b} as function of S and D_{84}, and I have included these two estimates in Table 3. A comparison with the values in Table 3 indicates that some of these estimates approximately agree for two streams (Avancon, Q_{c2a}; Erlenbach, Q_{c2b}) with my values determined from the direct transport measurements."

6) Sediment supply and implicit assumptions (Figure 3): The application of transport equations presupposes transport-limited conditions, that is to say, there is no explicit supply limitation. In light of the observed scatter and site-specific trends depicted in Figure 3, it would be beneficial to elucidate the potential influence of variations in sediment availability between sites and years on the comparison between measured and predicted transport rates. This clarification would assist in determining the extent to which deviations might be indicative of supply-limited behavior rather than being solely governed by hydraulic controls.

I do not fully agree with the statement that "the application of transport equations presupposes transport-limited conditions". To emphasize and clarify this point (also for the further discussion of "sediment supply"), I have added the following paragraph to the section "4.1 General comments on the bedload transport equations":

"In the study of Schneider et al. (2015) both the equations SEA-1 and SEA-2 (Fig. 2, equations for Q_{btot} and Q_{bred}) and the original Wilcock and Crowe (2003) equation were compared to field data from a total of 35 mountain streams and gravel-bed rivers (SEA_SS and SEA_HS data sets). The original Wilcock and Crowe (2003) equation is based on flume experiments representing transport-limited conditions. Yet this equation is not too dissimilar to the SEA-1 and SEA-2 equation, and all the three equations approximately represent a mean trend of the field data of the 35 streams, which show a variability in transport levels of three to four orders of magnitude for a given Shields stress (Schneider et al., 2015, Fig. 7 therein). Thus, it cannot be claimed that the flume-based bedload transport equation SEA-1 and SEA-2 truly represent transport-limited conditions."

For a further discussion of the role of sediment supply I refer to the new section 4.5 “Roles of variable sediment supply and of changing reference Shields stress”.

7) Relation to recent literature: The discussion could be further strengthened by briefly positioning the results within recent publications addressing sediment supply effects based on long-term surrogate monitoring (including plate geophone data), as well as recent transport-equation or comparison studies. This would provide a more accurate placement of the findings within the rapidly expanding body of surrogate-monitoring literature.

I have added a new section 4.5 “Roles of variable sediment supply and of changing Shields stress”, where I have also summarized sediment supply effects found for two Austrian streams with SPG measurements.

8) Figures 2, 3, and 7: layout and interpretability:

a) In Figures 2 and 7, legends partly overlap the plotted curves and, in places, extend beyond the plotting area, reducing readability. Adjusting legend placement (e.g. outside the axes) would improve clarity.

I have modified these figures to improve clarity.

b)Figure 3 shows a Qb–Q relationship that is typical of Alpine environments and comparable to published datasets from Italy and Austria. A brief comparison to such studies could help contextualize the observed scatter.

I have added a new section 4.5 “Roles of variable sediment supply and of changing Shields stress”, where I have also summarized sediment supply effects found for two Austrian streams with SPG measurements.

c) Furthermore, it is not possible to discern individual years in Figure 3. The utilization of distinct colors or symbols to denote different years would significantly enhance interpretability and facilitate a more transparent discussion of interannual variability.

Only one year of measurements are shown in Fig. 3 for four sites. The Erlenbach data includes multiple years; however, the total of the observations (1-minute values) is of a similar order of magnitude as for the Albula, Navisence and Avancon. For a year-to-year comparison, the reader is referred to the Supplementary Material (see L333-343 in the original manuscript). For the sub-seasonal scale, a differentiation of the transport levels is illustrated in Fig. 4. Concerning the observations about the interannual variability, Table C1 was added in Appendix C, and new text was added in the section 3.3.

9) Global figure comment

Several figures would benefit from minor layout adjustments (e.g. legend placement, margins, and font sizes), as some legends overlap with plotted data; a consistent re-layout would improve readability without affecting the scientific content.

I have modified also several figures in the Supplementary Information document to improve clarity.