Letter to associate editor

Dear associate editor,

We have revised our manuscript along the lines that the two reviewers suggested. In the letter below, you can find our point-by-point response to all comments. For the sake of clarity, the comments raised by each reviewer are copied in italic black font, and our response is given in blue below each comment. All changes were marked in yellow in the revised manuscript (below our response to reviewers), and we added the line numbers in our reply to the reviewers.

We want to take the opportunity to thank the reviewers for the thoughtful and constructive reviews that greatly contributed to improve the quality of our work.

We are looking forward to reading from you.

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Reply to Reviewers.

Reviewer #1:

The science in this paper seems sound. I simply have one concern regarding potential recycling of glacial sediment for the cosmogenic radionuclide erosion rates. And I am confused by the interpretation of the catchment as a supply-limited vs. transport-limited system. The language and the figures of the article are good. Though the dynamics of the earthflow are too summarily described and I have not really understood what is actually measured. The manuscript, however, could be much improved by reworking its structure. At the moment, the novel contribution of the authors is somewhat buried under a discussion of known elements. I strongly encourage the authors to rethink the introduction and the motivation of their study to increase its impact. I provide some suggestions below. All in all I recommend to accept this manuscript once the issue of potential sediment recycling is addressed and after 1) the sediment dynamics of the earth flow are more clearly defined and 2) the novel elements of the article are better highlighted.

We thank Luca Malatesta for his constructive comments. The recommendations helped us to better structure the manuscript and improve the quality of the science presented. Below, we provided a detailed reply to the issues raised.

Sediment recycling: Figures 3 and 4 show a downstream increase in erosion rates and sediment fluxes once the Entle river flows in the inner gorge. The authors attribute this to the fast rate of postglacial incision in the gorge. To me, it however seems that the recycling of buried glacial sediment could be at least in part responsible for the trend of apparent increase in erosion rates caused by the increasing admixture of sediment with lower CRN concentration. If that is not a driver behind the increase in incision rate it should be explained. And if, on the contrary, this plays a role, this should be quantified.

The Entle catchment was covered by glaciers during the LGM (24 ka BP, Bini et al., 2009). In the central part of the catchment, a 7 km-long inner gorge cuts through 100 m thick unconsolidated glacial deposits. The onset of incision of the inner gorge is still subject to debate. Van den Berg et al. (2012) argued that the incision age can be postglacial, given the high erodibility of the glacial material and high incision rate that might have operated during most of the knickzone propagation time.

Norton et al. (2008) showed that the ^{10}Be concentration of the glacial deposits in the Trub area (15 km to the W of our study site) equals 0.76 ± 0.13 × 10^4 atoms g qtz^{-1} at 8.5 m depth. Also, they reported concentrations of 3.58 ± 0.33× 10^4 atoms g qtz^{-1} at 1.5 m depth, about 15% to 50% higher than the catchment-wide CRN concentrations of nearby rivers. These data indicate that the decrease in ^{10}Be along the Entle River (Figure 4; Figure 5) is not necessarily linked to the incorporation of buried glacial material in the inner gorge.

In agreement with earlier work by Korup and Schlunegger (2007) and Van den Berg et al. (2012), we attribute the downstream decrease in ^{10}Be concentrations to the contrasting geomorphic regimes between the inner gorge and the hillslopes above the knickzone. We have addressed this point in Sections 4.3 and 5.1.

Meaningfulness of the earthflow sediment dynamics: I do not think that I correctly understood what was being surveyed and what that entails for the sediment cascade. I have commented several parts of the manuscript (attached) where I might have been confused by a lack of clarity. Surface lowering on the earthflow is described as being the result of erosion (p. 6 l. 10-13). Isn't it also due to subsidence of the surface? I would expect erosion to mainly affect the bulging parts of the flow and mitigate the rate of *surface uplift. Are subsidence and erosion differentiated? The lowering and rising parts of the flow both do so at the exact same mean rate. This is a rather arresting coincidence. It could be useful to add one sentence to explain/confirm this to avoid it being perceived as a red flag! The net mass flux of the earthflow is close to zero. This implies a constant volume though time. Then wouldn't the throughput flow, instead of the net balance, be the quantity that matters for sediment yield from the earthflow? Or alternatively, considering firstly the flux from bedrock to sediment (production) and secondly the loss of sediment from the earthflow to the channel (transfer). It would be potentially useful to reproduce a figure of deformation (bulging/lowering) on the earthflow in the manuscript to contextualize the values.*

Thank you for this comment. We revised the paragraphs related to the annual sediment dynamics of the Schimbrig earthflow, and clarified what is measured and how we interpreted the datasets. We added Figure 3 to illustrate the work done on the topographic reconstructions so that this part can stand alone without making much reference to our previous work in Clapuyt et al. (2017). The sentence in p.6 l.10-13 stating that surface lowering is equivalent to erosion is an overstatement. Indeed, surface lowering does not necessarily mean erosion, especially in this context, as surface lowering occurs in the upper part of the earthflow while surface bulging occurs in the lower parts, i.e. highlighting the rotational structure of the mass movement. From the annual assessment of the earthflow sediment dynamics, we show that surface lowering is nearly equal to surface bulging. The mass balance of the earthflow is therefore roughly in equilibrium, meaning that the sediment mobilised by the earthflow is accumulating on the hillslope, indicating that the throughput flow is negligible during the short period 2013-2015. This is, however, not the case at the decadal scale (1962-1998), as Schwab et al. (2008) showed that about 78% of the total mass displaced by the earthflow was evacuated by the channel network.

Sediment system: transport-limited or supply-limited? The catchment is framed as being supply-limited (p. 4 l. 24 and p. 17 l. 6-7). But it seems that the authors provide arguments for it being transport-limited at least in the first orders tributaries (p. 15 l. 25) the two conflicting accounts need to be reconciled. It is possible that a supply-limited catchment switches to being transport-limited when a landslide pulse overwhelms the transport paths.

We agree with this comment. Both field observations and quantitative data presented in this research point to the hypothesis of a transport-limited drainage system. In the discussion, we argue for the capacity of the landscape to buffer stochastic sediment pulses from landslides. We emphasised this point in the Discussion section in this sense to gain in consistency.

Structure: As it stands, I find that the article fails to properly motivate the study and to highlight the novelty the authors provide. In the discussion section, the authors use a significant amount of space to present already well-established conceptual models (sediment cascades, buffering of sediment pulses, stochasticity of landslides). The effect is to dilute the author's work. I believe it would be much more effective to introduce all these known/established elements at the beginning of the manuscript. This would allow the authors to explicitly define the gap in knowledge that their work directly addresses: a dataset across timescales, and not a conceptualisation of sediment transfer. I believe this would make it easier for the reader and increase the impact of the presented work. This section would also be the good place where to describe how the different processes affecting earthflow dynamics contribute to the sediment routing system.

We have revised the structure of the manuscript according to your suggestions. The last paragraph of the introduction was rewritten as to state the knowledge gap that we are addressing in the paper. Also, we followed up on your suggestion, and have reorganised the paper by inserting a section with the conceptual framework (Section 2) between the introduction and the methods. The discussion part was rewritten accordingly, to avoid repetition with the theoretical concepts presented in the conceptual framework.

I would like to encourage the authors to make better use of their data. Instead of synthetic data on the last figure, why don't they actually plot a distribution of erosion rates vs. timescale of integration (not time!) to present what is their truly significant contribution (data across timescales)? See Fig. 1 of Sadler 1981 for reference.

We updated Figure 7 (formerly Figure 4) in the discussion, depicting sediment fluxes over time scale of integration based on our data, i.e. at the millennial scale over the entire Entle catchment and at the decadal scale (black square markers) for the Schimbrig catchment.

Line-by-line comments

- *p. 3 l. 11: maybe define what the meaning/nature of that buffer is (sediment flux).*
  We specified it in the text p. 3 l. 14.
- *p. 3 l. 23: no comma.*
  Comma removed.
- *p. 4 l. 1: Few people will know right of the bat where the Entle River flows. Mention that it is in the Swiss Alps. the earth flow should probably be introduced as "the Entle River catchment contains a large earthflow named Schimbrig." (I don't think that this earthflow has reached a level of fame warranting a "the").*
  We rephrased it accordingly p. 7 l. 4.
- *p. 4 l. 5: it = sediment flux?*
  Yes. We rephrased p. 5 l. 13-15.
- *p. 4 l. 11: The largely review aspects of the discussion could be moved in a new section between intro and material. This section could end with a clear identification of a gap in knowledge motivating the current study. Thus the authors' work could more directly address a need. Effectively this would streamline the article*
  We have carefully revised the structure of the article. We have added a separate section with the conceptual framework (Section 2), between the introduction and the method section. This allowed us to move part of the discussion to this new section. Also, we have clearly phrased the research questions in a new paragraph that was added at the end of the introduction, p. 3 l. 30-32 and p. 4 l. 1-5.
- *p. 4 l. 16: have Schlunegger et al. 2016a defined "Swiss Plateau"? Maybe this ref should cover the next sentence?*
  Correct, we have changed the location of the reference on p. 6 l. 9.
- *p. 4 l. 21: in the figure 1 the gorge is mostly cut into the Molasse.*
  We updated Figure 2 with the updated version of the geological map, which shows a larger spatial extent of glacial till deposits, corresponding to the sentence in the text p. 6 l. 9-11.
- *p. 4 l. 23: erosion or incision? the latter would be the rate of lowering of the river itself. the former is ambiguous because we don't know over which area it is averaged.*
  It is incision indeed.
  We replaced "erosion" by "incision" p. 6 l. 15.
- *p. 4 l. 24: i don't follow the causality here. you haven't said anything about the transport regime or the upper reach geometry. for all i know the upper half of the catchment could be choked in sediment that are not being evacuated through the lower gorge. As a matter of fact, the poor efficiency in evacuating hillslope material suggests that there is a transport-limited dimension to the problem (p. 15, l. 21)*

We agree with the reviewer, and have adapted the text accordingly. The weak hillslope-channel coupling points to the existence of transport-limited systems.

- *p. 4 l. 26: "cut by" or "dissected by". to clarify that the moraine is not sitting next to and out of the gorge.*
  We rephrased the idea p. 6 l. 12.
- *p. 4 l. 28: these areas are not "covered" by Flysch they are "made" of Flysch. Is there a reference for the abundance of earthflows in Flysch lithology?*
  Sentence modified and reference added p. 6 l. 17-18.
- *p. 5 l. 1: I doubt that the satellite imagery would be useful when printed at this size. It might be better to have only political borders and main water bodies. potentially 1order tectonic boundaries (Alps - Foreland basin)*
  Thanks for the comment. We modified the inset by including the first order geological setting and updated the extent of glacial deposits in panel (b) of Figure 2 (formerly Figure 1).
- *p. 5 l. 4: been particularly*
  Modified in the text p. 7 l. 4.
- *p. 5 l. 7: is it esoterically connected to it then? consider replacing physically with directly.*
  Modified in the text using the term directly p. 7 l. 8.
- *p. 5 l. 9: Reference for the description of the earthflow.*
  Description of the earthflow is based on Schwab et al. (2008) and Clapuyt et al. (2017). References added p. 7 l. 10-11.
- *p. 6 l. 11: how are erosion and subsidence differentiated?*
  Net erosion of the earthflow as a whole occurs when the balance between surface subsidence and bulging is positive, i.e. there is a positive sediment flux from the earthflow to the Schimbrig river. We rephrased and added information on that throughout Section 3.2.
- *p. 6 l. 12: Isn't it only the rate of erosion that reflects the flux of sediment provided to the system?*
  Yes, we agree with your comment. It has been clarified at the beginning of Section 3.2 p. 8 l. 9-12.
- *p. 6 l. 17: reference?*
  Reference on uncertainties and precision on SfM method, i.e. James et al. (2017), added p. 9 l. 9.
- *p. 6 l. 17: "spatializing the error" I don't understand what this means.*
  It means that we used a spatially constant error value associated to topographic reconstructions. Precision made on p. 9 l. 8-9.
- *p. 6 l. 20: how were these loads measured?*
  Sediment loads are derived from measurements of suspended sediment concentrations in a gauging station in the Waldemme River. We added the information in the text p. 9 l. 12-13.
- *p. 7 l. 19: several CRN samples lie downstream of glacial deposits. I expect these deposits to yield a significant fraction of the sediment flux at these locations. The denudation rates derived from samples with an important recycled component would have lower concentrations and thereby higher rates. How is that taken into account?*
  We have addressed this point in Section 4.3. Data on ^{10}Be concentrations from glacial deposits published by Norton et al. (2008) support our argument that the decrease in ^{10}Be concentrations downstream is not primarily a result of admixture of glacial depostits.
- *p. 7 l. 22: Who is "we" Clapuyt et al. (2019) or Clapuyt et al. (2017), if it is the latter "they" would be clearer.*
  It is Clapuyt et al. (2017). We changed "we" to "Clapuyt et al" on p. 10 l. 23.

- *p. 7 l. 22: i.e. which part of the flow?*
  The active part of the earthflow surveyed by Clapuyt et al. (2017). We added the reference to Figure 4 where the extent is depicted.

- *p. 7 l. 22: across which gauge line is this flux constructed? i was expecting the sediment flux from the earth flow to correspond to its yield which has to be positive otherwise it would mean that sediment is climbing up from the river. so if this is flux corresponds to the overall budget of the active flow, it means that the flow has a stable volume through time. but for the question of sediment budget in the landscape, wouldn't the sediment throughput be the relevant value instead of the net balance?*
  The gauging line is the entire hillslope affected by the earthflow and surrounded by stable pastures. As stated above, our annual assessment of the sediment dynamics show that surface lowering is nearly equal to surface bulging. The mass balance of the earthflow is therefore roughly in equilibrium, meaning that the sediment mobilised by the earthflow is accumulating on the hillslope, indicating that the throughput flow is negligible during the short period 2013-2015. We have clarified this in Section 3.2 and 3.3.

- *p. 7 l. 23: It is either positive, null, or negative. There are no qualification of how positive a number is. It is or it is not. it can be simpler to say that the flux "can be considered null"*
  Thanks for the comment. We rephrased it on p. 10 l. 20-21.

- *p. 8 l. 3: should probably be m^2 only.*
  Thanks for the comment. We changed it in Table 1.

- *p. 8 l. 3: it is not a depth but a rate*
  Thanks for the comment. We changed it in Table 1.

- *p. 8 l. 16: what is the displaced mass? the throughput of the earth flow? needs more clarification about the origin of the percentage.*
  We now give details on p. 9 l. 17-20 about the two variables that are computed by Schwab et al. (2008) in order to understand what is measured. The displaced mass corresponds to surface lowering while the total sediment exported per year, i.e. the sediment flux entering the Rossloch river, is the balance between surface lowering and bulging. The ratio between both metrics indicates the percentage of sediment mass evacuated compared to the displaced mass.

- *p. 8 l. 19: maybe add a column for the value of displaced mass (even though it is already folded into the percentage) that would allow to clearly explain what this value is.*
  We added two columns in Table 2, i.e. total sediment displaced and exported (Schwab et al.,2008), in order to make everything clear and computable.

- *p. 10 l. 5: because of faster erosion or because of recycling?*
  p. 11 l. 1: higher rates due to recycling?
  p. 12 l. 7: strong suggestion that increased admixture of recycled material yields faster rates.
  We refer to our reply about your main comment above (this issue is now addressed in the text in Sections 4.3 and 5.1)

- *p. 11 l. 2: precision: from CRN*
  Precision done in the caption of Figure 6 (formerly Figure 3).

- *p. 12 l. 8: from CRN*
  Precision done in the caption of Figure 7 (formerly Figure 4).

- *p. 13 l. 26: Has the toe of the landslide moved down at 6 m/yr? Or is the toe simply swelling and not moving?*
  The entire earthflow is moving 6 m yr^{-1} downslope on average. But the toe of the landslide only

experienced a downslope movement of ca. 55 m between 2014 and 2015. We rephrased on p. 18 l. 16-17.

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- *p. 13 l. 29: there might be a need for precision here. shallow landslides are not "producing" sediment, they simply entrain them. Earthflows churn through bedrock effectively producing sediment. maybe this is actually a good way to frame the earthflow thoughput. I was confused by the meaningfulness of that value for sediment cascade but it could be defined in the intro that earthflows essentially produce colluvium/sediments. then question is what is the transport fate of that sediment.*
  Thanks for the comment. The earthflow has deep rotational structure that actually produce sediment by excavating and mobilizing them. It therefore acts as a pure sediment source. We emphasised the fact that the earthflow acts as a sediment factory in Section 3.1 on p. 7 l. 4-6. And we added the info on the landslide toe advance on p. 18 l. 16-17.

- *p. 13 l. 31: Where does the rest remain? In which form does it remain on the hill slope.*
  It is stored as colluvial fans at the foot of the earthflow, i.e. Figure 3 in Section 3.2. The sentence has been removed when reshaping the discussion.

- *p. 14 l. 3: this mechanism should be introduced earlier when the signification of an earthflow for the sediment cascade is explained.*
  Thanks for the comment. We moved this part after the introduction, in the "conceptual framework" section (Section 2).

- *p. 14 l. 6: All the paragraph: this type of information could be used at the beginning for a motivation of the study. it can help defining a knowledge gap.*
  Thanks for the comment. We moved this part after the introduction, in the "conceptual framework" section (Section 2).

- *p. 14 l. 11: can the actual data be plotted this way?*
  See next comment.

- *p. 14 l. 11: three timescales are compared here using mock-data. Wouldn't it be possible to plot the actual data produced and compiled in this manuscript to test the dependency of observed rate on the time window of measurement (Fig. 1 of Sadler, 1981). Or to complement this conceptual graph with the actual data in a plot next to it.*
  We have not enough data in this paper to implement a figure such as the one of Sadler (1981). However, we updated Figure 7 (formerly Figure 4) the sediment fluxes computed at the decadal scale, to enable the comparison for the Schimbrig catchment. We now emphasize in the text that Figure 8 is an extrapolation of our findings, in accordance with other studies about evacuation of sediments in landslide-prone environments.

- *p. 15 l. 2: What is compared here? total erosion rates? total denudation rate, total sediment flux?*
  We compare sediment fluxes. We rephrased on p. 18 l. 1-7.

- *p. 15 l. 9: the argument would be compelling if the actual data was plotted.*
  Thanks for the comment. We plotted it in Figure 7.

- *p. 15 l. 21: unclear. Because the system is transport-limited, or because the sediment pulse is diluted in a larger flux?*
  We have rephrased this sentence for clarification.

- *p. 15 l. 24: This seems to be an important element of the study. The upper reaches seem to be transport-limited. This is in part conflicting with an earlier statement about supply-limited upper reaches (p. 4 l. 24).*
  We rephrased the text in Section 3.1 as it was inaccurate. We agree with your observation that the upper reaches of the Entle catchment are transport-limited, as it is indeed suggested by our spatio-temporal database of sediment fluxes.

- *p. 15 l. 27: is it though? is there such a thing as a state of equilibrium in a situation like this? maybe when the earth flow scarp reaches the ridge and the slope can be in equilibrium again?*
  We agree with your statement, and have rephrased this part.

- *p. 15 l. 30: It might be opportune to frame it as a transport-limited system that delays and dilutes the propagation of the pulse*
  Done p. 19 l. 1-5 and p. 20 l. 4-6.

- *p. 16 l. 9: this again could be used in the intro to motivate the study. this is not inherently new stuff.*
  This sentence has been removed when restructuring the discussion and separating current knowledge and new findings of this paper.

- *p. 17 l. 5: but interestingly you have repeat observations suggesting that the system is transport-limited (p. 15, l. 21) elaborate!*
  We reworked the discussion part, as there was some repetitions between the different sections. We elaborated the idea of the transport-limited systems, and the geomorphic decoupling of slopes and channels in Sections 5.2 and 5.3.

- *p. 17 l. 10: of the hillslope or of the catchment?*
  Both on hillslopes and in the catchment. However, this sentence has been removed when restructuring the discussion and separating current knowledge and new findings of this paper.

- *p. 17 l. 17: ok but this is not new. what is new is that quantitative constraints are produced*

- We added our data in this section, to show the quantitative estimates of the sediment fluxes at the different spatial and temporal scales

- *p. 18 l. 13: average of what?*
  p. 18 l. 15: More so than if it was low magnitude, high frequency?
  p. 18 l. 22: does that mean that the total Qs doubles, or that the provenance fraction of a constant total Qs changes? If the total Qs does not change there is an interesting observation of transport-limited rates of sediment evacuation at the scale of the catchment.
  p. 18 l. 26: causality unclear to me. Why would the another catchment be affected ONCE the previous one ceases its activity?
  We have rephrased this part of the discussion, taking into account the previous comments that were related to poor wording.

Reviewer #2:

Different techniques of measuring sediment fluxes allow us to estimate average fluxes exported from catchments over different timescales. Our knowledge on the variability of sediment production on hillslopes and its supply to river channels however is still limited. As such, I consider the manuscript of Clapuyt et al. as a valuable scientific contribution. While I appreciate the presented datasets and their comparison, I have two major concerns regarding (1) the analyses and interpretation of the 10Be data as well as (2) the presentation of the concepts. In addition, I raise a few minor concerns and provide further line-by-line comments, which are mainly related to the clarity of the manuscript and should be considered as suggestions. I suggest the manuscript for publication once the main concerns have been addressed.

We thank Reviewer 2 for the challenging comments that helped us to improve the manuscript. Below, we provided a detailed reply to the issues raised.

Major comments

(1) The authors measure 10Be concentration in fluvial sediments, from which they calculate catchment average denudation rates as well as sediment fluxes by multiplying the denudation rates with the according catchment areas. When catchment-average denudation rates are calculated from detrital 10Be concentrations, one of the main assumptions is that each part of the catchment is equally represented in the sampled material. This assumption is violated when a sample is taken within or just downstream of a landslide deposit, because landslides are highly stochastic processes (as stated by the authors for example on p. 2 l. 3, p. 3 l. 10&12 or p. 13 l. 29). This is the case for the samples collected within the Schimbrig river. In such settings, the 10Be concentration in fluvial sediments collected at a certain moment in time is not necessarily representative of the long-term average and might be highly variable from year to year. Previous studies that have nicely demonstrated this are for example Dingle et al. (2018) or Lupker et al. (2012). For that reason, 10Be concentrations in fluvial sediments in landslide-prone areas are rather indicative of certain hillslope-erosion processes, but should be handled with care regarding the calculation of absolute values, such as denudation rates or sediment fluxes. This problem also becomes apparent when the 4 data points from the Schimbrig catchment are compared with each other (Fig. 2). The last row within each box gives the calculated sediment flux (in volume per year). The sample located highest up within the catchment (CH-ENT-3) indicates a total annual sediment flux of 900 m3. When moving down the channel, the total annual sediment flux must increase, as the sediment discharge includes at least 900 m3 from the upstream part and additional sediment from the newly added catchment area. The values downstream, however, are about two thirds lower. As such, a reduction of sediment flux in downstream direction, despite total sediment flux being a cumulative parameter, clearly indicates a bias in the method. For the reasons listed above, I recommend the authors to be more careful with any of their mass-balance analyses that are based on calculated denudation rates and sediment fluxes from the landslide/ earthflow affected catchment. In particular, I disagree with the statement given for the temporal upscaling (section 4.1, p. 15 l. 8-9). The disagreement between decadal and millennial sediment fluxes can be purely a methodological problem. This also includes the comparison between the two Rossloch sub-catchments (p. 13 l. 7-11). The authors mention in their manuscript that also the gorge area is affected by landslides (p. 4 l. 27-29). Consequently, also the sample taken at the catchment outlet (E-7a) might be biased by mixing with low 10Be concentrations from landslide material. If so, the mass-balance exercise within the spatial upscaling (section 4.2., p. 15 l. 16-20) might also be biased. To address the above challenges, I suggest the authors to carefully re-evaluate their denudation rate and sediment flux analyses and interpretations and include a new section to the discussion that critically discusses the potential biases of the applied 10Be method and how this would affect their presented results.

We acknowledge that landslides potentially dilute CRN concentrations and can introduce bias in the quantification of geomorphic processes. Therefore, in order to avoid overstatements using absolute values of denudation rates and sediment fluxes, we commented ^{10}Be concentrations only in the Results section, i.e. Section 4. Then, we opened the discussion section, i.e. Section 5.1, by acknowledging three potential caveats using ^{10}Be concentrations to quantify derived denudation rates and sediment fluxes in such geomorphologic settings, i.e. glacial sediment admixture and dilution of CRN concentrations. Regarding the latter caveat, we argue that dilution lead to a potential overestimation of CRN-derived denuation rates (see p. 14 l. 13-18 and p. 15 l. 1-16). Therefore, CRN-derived denudation rates and subsequent sediment fluxes presented hereunder should be taken as first order or maximum estimates of the actual values. Because the decadal sediment flux from the Schimbrig catchment is two order of magnitude higher than the one computed at the millennial scale, this overestimation does not eventually affect the conclusions drawn from the multi-temporal database of sediment fluxes.

The ^{10}Be concentration of sample CH-ENT-2 is in accordance with the decreasing linear trend when going downstream along the river network. Consequently, when entering the Kleine Entle river, i.e. a second-order river, the signal of the landslide is not captured over a timescale of ca. 2,000 yr. We added the apparent age of ^{10}Be measurements in Table 3.

However, as we are dealing with the sediment cascade of a mountainous environment, we do not necessarily agree with your statement that the total annual sediment flux must increase when going downstream, as it is a cumulative value. This is only true if the sediment transport rate is uniform over space and time. Mountainous river systems act as “jerky conveyor belts” (Ferguson, 1981) where sediment is transported episodically within catchments. Along the sediment cascade, sediment is sporadically deposited, eroded and transported, over different spatial and temporal scales (Fryirs, 2013). Here, the fact that the sediment flux is not cumulative when going downstream is precisely an indication of the capacity of the landscape to buffer sediment pulses, i.e. sediment mass from stochastic sediment pulses is trapped within first-order river catchments. These sediments are then progressively released further downstream over longer time scales. We see the same pattern in the landslide-affected catchment, over short time scales. A high landslide activity on the hillslopes does not necessarily lead to enhanced sediment fluxes at the outlet of the catchment.

(2) Secondly, I consider the discussion as largely under-cited. Although I really appreciate the detailed analysis of a single earthflow and the quantification of its contribution to the total sediment flux, the presented study is not the first study that has measured 10Be concentration in a landscape with stochastic sediment input, looked at evacuation timescales of stochastically supplied sediment or the potential alteration of sedimentary signals along sediment routing systems. None of the previous studies are cited in the discussion though. Rather, large parts of the discussion do not refer to any other studies at all. This includes most parts of the spatial upscaling (section 4.2) as well as large parts of the conceptual upscaling (section 4.3). To better highlight the novel findings of this work, the current study needs to be better embedded in the existing literature. A few suggestions for different topics are listed below, but many more are available. 10Be concentration in regions with stochastic sediment input: Puchol et al. (2014), Kober et al. (2012), West et al. (2014) Modification of sedimentary signals: van de Wiel and Coulthard (2010), Simpson and Castelltort (2012) Timescales of sediment removal provided by stochastic events: Hovius et al. (2000), Wang et al. (2015)

We agree with this comment. We indeed missed to cite a series of papers dealing with the topic. We added references to relevant literature in the discussion section.

Minor comments

To better understand the novel contribution of the presented study, I suggest a clearer statement of the knowledge gap/ open question that is addressed by this work. In the current version the according statement within the abstract is rather vague (p. 2 l. 5- 7). In the Introduction, the background knowledge *is built up, but no clear research question is formulated. A good opportunity would be to insert a sentence on p.3 after line 25. Maybe it would also help to move this explaining sentence (p. 3 l. 27-29) further up before stating the question, as it can be seen as a motivation.*

As also suggested by Reviewer 1, we have rewritten the last part of the introduction where we now introduce the research hypothesis that is addressed in our paper (p. 3 l. 30-32 and p. 4 l. 1-5): "In this study, we posit that sediment fluxes in landslide-prone alpine catchments can be highly variable in space and time, with long periods of quiescence during which sediment is temporarily stored on the hillslopes and short episodes of high sediment flux when hillslopes and channel are coupled through superimposed debris flows".

Please provide a more detailed characterization of the Schimbrig catchment, especially regarding the activity of hillslope processes apart from the earthflow itself (maybe add to p. 4 after l. 29). Could other processes within the catchment also affect the fluvial 10Be concentration? Along the same line, I would very much appreciate a photo of the Schimbrig earthflow. p. 6 l. 18-26 and p. 8 l. 10-22: Please provide a more detailed explanation of decadal sediment flux method, as it is done for the other two methods. In particular, please indicate the areal extend covered by this methods (for example in figure 2). If I understand correctly, the annual analysis only covers the earthflow itself, while the decadal analysis covers the entire catchment. To be able to compare the two, it would be interesting to know what other erosion processes are active in the catchment (see comment above) and what percentage of the catchment is affected/covered by the earth flow. Also, how is the displayed mass calculated (p. 8 l. 15-17)? I don't understand how this data is derived.

We added information on the different types of erosion processes in the Entle and Schimbrig catchments, respectively p. 6 l. 15-20 and p. 8 l. 1-4. We added pictures of the earthflow in Figure 3.

Regarding decadal sediment fluxes computation, we detailed the workflow and detailed how metrics presented in Table 2 are computed on p. 9 l. 17-20. In Figure 4 (formerly Figure 2), we added the outline of the Schimbrig catchment over which the decadal sediment fluxes are computed.

We added the importance of the Schimbrig earthflow within the catchment in Section 3.1 on p. 8 l. 3-4, i.e. 25% of the Schimbrig catchment in surface.

To ensure reproducibility of 10Be calculation and potential later re-analysis, please provide the raw data with the manuscript. This includes the original 10Be/9Be ratios from the AMS, as well as all the parameters needed to run the CAIRNs model. Also, was a correction for non-quartz containing areas within the catchments, as for example the carbonates, applied?

We added original measured ^{10}Be/^{9}Be ratios from the AMS in Table 3.

Line-by-line comments

- *p.3 l. 33-34: The sentence does not make sense as it is, please correct.*
  Sentence corrected p. 5 l. 18-19.
- *p. 4 l. 6-10: I suggest to number the analyses that are performed, as it makes it easier for the reader to follow the manuscript. However, I don't fully find the structure indicated here in the rest of the manuscript. Rather, the addressed topics are (i) temporal upscaling, (ii) spatial upscaling and (iii) conceptual upscaling. For clarification, I suggest to adapt this sentence, at least its order, or the way the data is later presented.*
  We restructured the entire paragraph to better highlight the focus of the paper.
- *p. 4 l. 6: Inconsistent use of tenses, stick to one: 'discuss' is present tense, 'quantified' in past tense.*
  Section rephrased but now tenses are correct.
- *p. 4 l. 16-19: As the 10Be concentration in fluvial quartz is measured later, it would help to provide information on the lithology/ quartz content in addition to the depositional types (molasse, flysch).*
  We added this information in the methodology section about CRN analyses p. 10 l. 3-4.
- *p. 4 l. 24-25: I don't follow the argument here. Why do differences in denudation rates point to a supply-limited system?*
  We have rephrased this part to avoid confusion.
- *p. 6 l. 19: Is 'sediment yield' the same as 'sediment flux'? If so, consider changing it to flux to be consistent. Otherwise please define yield.*
  We have rephrased this sentence: "… who assessed sediment transport by…
- *p. 6 l. 24: Was loose sediment or solid rock converted from tons per year into cubic meters per year? If it was converted from sediment, I would expect a lower density than 2.70 g/cm3.*
  We ignore the potential volumetric expansion of the earthflow material as we are interested in the general pattern of geomorphic responses rather than in the absolute magnitude of the responses.
- *p. 7 l. 1: In this sentence the authors state twice that their sample preparation was similar to other studies. What does 'similar' mean? Please be precise. Same accounts for the term 'several' in line 3.*
  We meant that the protocol followed is described in Vanacker et al. (2007) and has also been followed by Van den Berg et al. (2012). We rephrased on p. 9 l. 28-29.
  We replaced "several" by "up to 10" on p. 9 l. 31 as it is varying according to samples.
- *p. 7 l. 7: Change 'is' to 'was' to be consistent in tenses.*
  Correction done p. 10 l. 2.
- *p. 7 l. 27: What is meant by the term 'dynamic equilibrium'? Does it summarize what has been explained in the previous line, i.e. no net changes in volume? The way the sentence is written sounds to me like an interpretation, which would be miss-placed within the results sections.*
  "Dynamic equilibrium" reflects the fact that there is no net flux to the river, only a redistribution of sediments on the hillslope or a balance between surface lowering and bulging. To us, it is rather a summary of what is previously written than an interpretation that should go the discussion section.
- *p. 8 l. 22: I suggest to stick to one term, for instance earthflow when referring to the Schimbrig earthflow. In this sentence it is unclear if the 34%come from the earthflow or also from other landslides that are active within the catchment? This is what motivated my comment above regarding a more detailed characterization of the hillslopes in the Schimbrig catchment.*
  You are right about vocabulary consistency. We changed "landslide" to "earthflow" on p. 11 l. 14 and checked the entire document for similar mistakes.

The 34% of displaced material accounts only for the Schimbrig earthflow. We did not focus on other landslides in the Entle catchment, as stated in the Materiel and Methods section. Following your previous comment, we added more details on the erosion processes in Section 3.1 p. 8 l. 1-4.

- *p. 9 l. 15: It is unclear to which samples the term 'landslide-affected' refers to. For clarification, it would help to indicate in Table 3 which of the samples are considered as landslide-affected. I assume the term includes the 4 samples from the Schimbrig river. But why are 5 stars (= landslide-affected) displayed in the Fig. 3 and 4, but only 4 samples in that catchment? And is the Schimbrig earthflow the only landslide in the entire study-area, or could other samples also be considered as 'landslide-affected'?*

  Thanks for the comment. One star symbol in Figures 6 and 7 (formerly Figure 3 and 4) corresponded to knickpoint locations. We changed this symbol to a triangle to avoid confusion. We make the hypothesis that the Schimbrig catchment only affects the CRN concentrations of samples.

- *p. 10 l. 6-7: I don't follow this interpretation. An increase in denudation rates in downstream direction could also be related to different local uplift rates, changes in lithology or recycling of the glacial till material (and as such not give 'true' denudation rates). Also, as this phrase is rather interpretation than a description of the results, the authors could consider moving it to the 'Discussion' section of the manuscript.*

  We moved this interpretation into Section 5.1.

- *p. 10 l. 6-7: I don't understand the sentence. What is meant by 'Accounting for the drainage area: : :'? Is the data displayed in Fig. 4 normalized by catchment area? If not (and it doesn't seem so), wouldn't an increase in sediment flux in downstream direction be expected as the sediment flux gives the total volume of sediment evacuated from a certain area per time? Consequently, the larger the area, the higher the sediment flux, even if denudation rates were constant across the entire area. Along the same line, I don't follow the statement on p. 12 l. 2-3.*

  "Accounting for drainage area" means that we deal with sediment fluxes instead of denudation rates. We precised it on p. 15 l. 22-23. In Figure 7 (formerly Figure 4), we plot sediment fluxes (L^3 T^{-1}), i.e. the total volume of sediment evacuated from a catchment, which increase downstream. This actually supports your comment.

  We agree with you that the increase in sediment fluxes along the river network indicates that sediments are evactuated from the system. Our point is in fact that in the landslide-affected catchment, the opposite trend is observed, meaning that sediments are temporarily stored or deposited in this first-order catchment (see p. 17 l. 1-11), i.e. illustrating the buffering capacity of the landscape facing stochastic sediment pulses.

- *p. 12 l. 16 – p. 13 l. 2: This sentence is rather discussion than a description of the results. Regarding its content, another possible explanation is that the fluvial sediments gets mixed with other, high 10Be sediment from within the catchment. This depends on what other processes are active within the catchment (see earlier comment).*

  We agree with your comment and moved this interpretation to Section 5.1 (see p.15 l. 5-11). Besides, as precised in Section 3.1 (p. 8 l. 3-4), the Schimbrig earthflow occupies 25% of the catchment area and is the only active process.

- *p. 13 l. 6: Consider to also refer to Fig. 2 as this figure shows the variability in sediment fluxes across the entire study area. p. 13 l. 20: km-2 yr-1, is that the correct unit?*

  We added a reference to Figure 4 (formerly Figure 2) on p. 17 l. 14. It is the correct unit, i.e. the landslide rate as a number of landslides per square kilometre per year (see e.g. Hovius et al., 2000). To remove all doubts, we changed it to *events* km^{-2} yr^{-1}. See p. 18 l. 16.

- *p. 14 l. 18 – p. 15 l. 1: I suggest to replace 'the difference in denudations rates: : :' with 'the difference in 10Be concentration' as the denudation rates calculations are biased by the landslide and thus not reliable (see comment above).*
  As answered to your first main comment, we moved these interpretations to Section 5.1, after discussing their robustness.
- *p. 15 l. 2-3: What difference? The difference in sediment flux? And if it refers to the sediment flux, what about the other samples within the Schimbrig catchment? The uppermost sample (CH-ENT-3) already suggests an annual sediment evacuation of 900 m3, which is significantly higher than 230 m3 (CH-ENT-9). As such, I think the calculation of sediment flux from 10Be concentration in the earthflow affected catchments needs to be taken with care.*
  We refer to our detailed reply to major comment (1) above.
- *p. 15 l. 10: The importance OF landsliding: ?*
  We rephrased the title of Section 5.2 as "The stochastic nature of landsliding".
- *p. 15 l. 11-12: Or by a bias in the method, especially the 10Be derived sediment flux calculations (see comments above).*
  We refer to our detailed reply to major comment (1) above.
- *p. 15 l. 19-20: If a mass-balance analysis is done, how about the other tributaries? If the contribution of all catchments is summed up, does it result in 100%?*
  We refer to our reply to major comment (1) above.
- *p. 16 l. 6: Remove n from Entlen?*
  Removed as we restructured the discussion.
- *p.17 l. 15: 'pulses' instead of 'pulse'?*
  Not applicable anymore due to rephrasing.
- *p.18 l. 11: Redistribution on the hillslopes, or just within the earthflow affected area? Please clarify.*
  We have rephrased this sentence.
- *p. 18 l. 21: Where does the 90% come from? Is this calculated from the data?*
  Thank you for the comment. There was a mistake, and we made the necessary corrections in Section 5.3.
- *p. 18 l. 25-29: This statement is rather an interpretation about the evolution of such landscapes, which cannot directly be drawn from the presented data. Or if it can, I did not understand how it can be known from the presented dataset that once a sediment source is depleted, another landslide will be activated. Unless I missed something, I suggest reformulating the sentence to indicate it as an hypothesis that needs to be tested in the future.*
  We agree with the comment and rephrased the last part of the conclusion.
- *Fig. 1: The elevation as supposedly shown in grayscale (legend) cannot be seen in the figure. I suggest to have two maps: one showing the DEM, and one showing the geological map. Maybe include a photo of the earth flow. Fig. 3 and 4: The authors should consider to use different colors as red and green cannot be distinguished by a certain number of people.*
  Regarding the elevation displayed as grayscale on Figure 1, we agree that the superimposed hillshade nearly entirely overrides the DEM. We keep the scale bar in the legend to give an indication about the elevation range. Nevertheless, we do not think that a map displaying the DEM only is very relevant.
  Thank you for the comment about the readability of the figures by color-blind people. We reviewed

all the figures of the manuscript and adapted them accordingly.

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Spatio-temporal dynamics of sediment transfer systems in landslide-prone alpine catchments

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Abstract. Tectonic and geomorphic processes drive landscape evolution over different spatial and temporal scales. In mountainous environments, river incision sets the pace of landscape evolution, and hillslopes respond to channel incision by e.g. gully retreat, bank erosion and landslides. Sediment produced during stochastic landslide events leads to mobilisation of soil and regolith on the slopes that can later be transported by gravity and water to the river network during phases of hillslope-channel geomorphic coupling. The mechanisms and scales of sediment connectivity mitigate the propagation of sediment pulses throughout the landscape and eventually drive the contribution of landslides to the overall sediment budget of mountainous catchments. However, to constrain the timing of the sediment cascade, the inherent stochastic nature of sediment and transport through landsliding requires an integrated approach accounting for different space and time scales. In this paper, we examine the sediment production on hillslopes and evacuation to the river network of one landslide, i.e. the Schimbrig earthflow, affecting the Entle river catchment located in the foothills of the Central Swiss Alps. We quantified sediment fluxes over annual, decadal and millennial time scales using respectively UAV-SfM techniques, classic photogrammetry and in-situ produced cosmogenic radionuclides. At the decadal scale, sediment fluxes quantified for the period 1962-1998 are highly variable and are not directly linked to the intensity of sediment redistribution on the hillslope. At the millennial scale, landslide occurrence perturbs the regional positive linear relationship between sediment fluxes and downstream distance as the landslide-affected Schimbrig catchment is characterised by a decrease in sediment fluxes and a strong variability. Importantly, the average decadal sediment flux of the Schimbrig catchment is two orders of magnitude higher than millennial sediment fluxes computed over the same spatial extent. The discrepancy between decadal and millennial sediment fluxes, combined to the highly variable annual sediment evacuation from the hillslopes to the channel network suggest that phases of hillslope-channel geomorphic coupling are short and intermittent. During most of the time, the first-order catchments are transport-limited and sediment dynamics in the headwaters are uncoupled from the fluvial systems. In addition, our unique spatio-temporal database of sediment fluxes highlights the transient character of the intense geomorphic activity of the Schimbrig catchment in a regional context. Its decadal sediment flux is of the same order of magnitude than the background sediment flux going out of the entire Entle river catchment. Over the last 50 years, the Schimbrig catchment, which represents ca. 1% of the entire study area, provides 65 % of the sediments that the entire Entle catchment will supply over the millennial scale. These results suggest that episodic supply of sediment from landslides during intermittent phases of hillslope-channel geomorphic coupling are averaged out when considering sediment fluxes at longer time scales and larger spatial scales.

1 Introduction

The segmentation of the sediment pathway into distinct cascades is a widely used concept to describe the routing of sediment particles from sources to sinks throughout a landscape (Walling, 1983). Among other factors, e.g. topography, lithology, climate or tectonic activity (e.g. Aalto et al., 2006; Montgomery and Brandon, 2002; Whipple and Tucker, 1999), the geomorphic coupling and sediment connectivity control the efficiency of sediment transfer in geomorphic systems, and condition the pace at which landscapes evolve through time (Bracken et al., 2015; Fryirs, 2013; Harvey, 2001; Heckmann and Schwanghart, 2013). The *geomorphic coupling* between distinct landscape elements is commonly seen as a measure of how individual landforms are linked through sediment transport (e.g. Harvey, 2001; Heckmann and Schwanghart, 2013), while the term *sediment connectivity* has been employed for characterizing the transfer of sediments at a larger scale which includes potential sources and sinks within a geomorphic system (Bracken et al., 2015). Accordingly, a large connectivity requires an implicit geomorphic coupling between distinct landscape units (Bracken et al., 2015).

In this context, most research has focused on how the connectivity between landslides and trunk channels influences the overall sediment budget of a landscape. Because landslides are a dominant source of sediments in mountainous environments (Korup et al., 2010; Vanacker et al., 2003), one can expect that the magnitude and frequency of landsliding (e.g. Crozier and Glade, 1999; Hovius et al., 1997; Malamud et al., 2004) will directly impact the bulk sediment flux of a drainage basin. Nevertheless, the contribution of landslides to the overall sediment budget is still poorly constrained: landslides stochastically supply sediment to the river network, and their geomorphic efficiency varies according to the mechanisms and scales of sediment connectivity (Benda and Dunne, 1997; Bennett et al., 2014). Field studies have shown that the landscape capacity to buffer sediment fluxes from landslides can vary from several years (Berger et al., 2011; Fuller and Marden, 2010) to decades (e.g. Bennett et al., 2013; Schwab et al., 2008) and millennia (e.g. Wang et al., 2017). The inherent stochastic nature of sediment production and transport through landsliding prohibits linear upscaling of small-to-medium scale geomorphic process assessments, as well as extraction of a particular erosion mechanism from the entire sediment cascade using long-term/large-scale methods (Bennett et al., 2014; Bracken et al., 2015).

Although the analysis of spatio-temporal patterns of the sediment cascade can provide insights in sediment transfer mechanisms in landslide-affected catchments, few studies attempted to integrate different spatial and temporal scales to assess landscape response to landslide sediment supply and transport. Mackey et al. (2009) compared surface displacement velocities of an earthflow derived from historical airphotos with sediment transport rates derived from meteoric ^{10}Be inventories. Their study showed that the displacement rate of the Eel earthflow (northern California) was highly episodic in time, as the earthflow acted as a source of sediments over the last 150 years with an erosion rate that was more than 20 times faster than the millennial sediment transport rate. In a similar study, Delong et al. (2012) measured surface displacement rates of the Mill Gulch earthflow from light detection and ranging (LiDAR) data and compared this data with ^{10}Be-derived denudation rates of two adjacent catchments. These authors reported short-term denudation rates (2003 and 2007) that were similar to long-term ones. These two case studies show the assets of a spatio-temporal approach for unravelling the mechanisms of sediment connectivity in landslide-prone environments.

In this study, we examined the propagation of sediment pulses in landslide-prone environments, from sediment production at the hillslopes to sediment transport and delivery to the river network. By integrating geomorphic assessments at different spatio-temporal scales, and utilizing information on the propagation of sediment pulses along the sediment cascade, we considered the evacuation of landslide-derived sediment to the colluvial and fluvial domains. Sediment fluxes were assessed over annual, decadal and millennial time scales using respectively UAV-SfM techniques, classic photogrammetry and in-situ produced cosmogenic radionuclides. In this study, we posit that sediment fluxes in landslide-prone alpine catchments can be highly variable in space and time, with long periods of quiescence during which sediment is temporarily stored on the hillslopes and short episodes of high sediment flux when hillslopes and channel are coupled through superimposed debris flows.

2 Conceptual framework

Within the sediment cascade, landslides stochastically act as a major sediment source on hillslopes. Here, we propose a conceptual framework (Figure 1) that may facilitate the quantification of spatio-temporal patterns of sediment cascades in landslide-prone catchments. Landslides can mobilise soil and regolith material (Figure 1a) that can temporarily accumulate on the slopes (Figure 1b), and become available for further mobilisation and transport downslope. In decoupled hillslope-channel systems, sediments remain on hillslopes as landslide colluvial fans before being gradually depleted and transported to the river network by rainfall-induced and stochastic superimposed debris flows (e.g. Benda and Dunne, 1997b; Schwab et al., 2008). Therefore, the stochastic behaviour of sediment supply on the slopes and sediment transport in the river network gives the landscape a certain capacity to buffer sediment transfer within the sediment cascade (Gran and Czuba, 2017). The temporal scale of the buffering capacity can be highly variable, and vary from a number of years (e.g. Berger et al., 2011; Fuller and Marden, 2010; Sutherland et al., 2002), to decades (e.g. Bennett et al., 2013; Schwab et al., 2008), and millennia (e.g. Dingle et al., 2018; Wang et al., 2017; West et al., 2014). In configurations where hillslopes are physically linked to channels (Figure 1c), the material derived from landsliding is effectively evacuated by the fluvial system (e.g. Berger et al., 2011; Sutherland et al., 2002; Wang et al., 2017). The hillslope-channel geomorphic coupling controls the propagation of sediment pulses from landslides to the river network (Figure 1d). In catchments with strong hillslope-channel geomorphic coupling by e.g. debris flows entering the channel reach, we might expect to see rapid response of the fluvial system to geomorphic events, such as stochastic landslide events. In well-coupled systems, the landslide-derived sediment fluxes for the hillslopes should show good correspondence with the catchment-wide sediment flux.

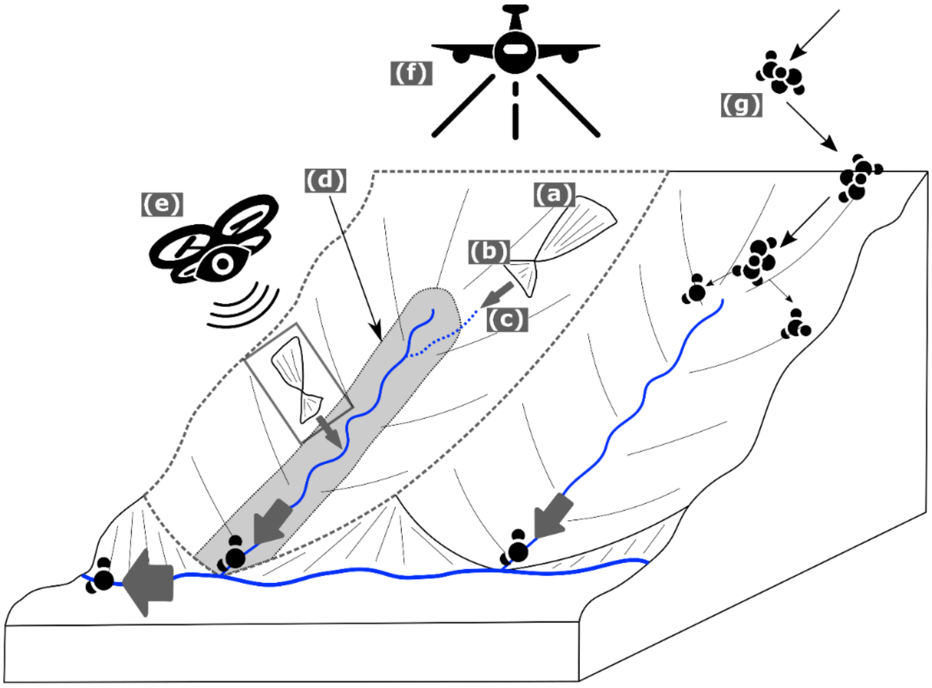

Figure 1: Conceptual framework of the sediment dynamics in alpine landslide-affected first-order catchments. (a) Landslides are a stochastic process that mobilise soil and regolith downslope. (b) Landslide-derived material can temporarily be stored on the slopes in landslide colluvial fans, (c) and/or be evacuated by debris flows to the fluvial system. (d) Hillslope-channel geomorphic coupling (by e.g. slope failures induced by river undercutting) is particularly

important for understanding the response of the geomorphic system to sediment pulses. The quantification of sediment fluxes is achieved using (e) UAV-SfM framework, (f) classic photogrammetry and (g) in-situ produced cosmogenic radionuclides.

The downslope propagation of sediment from the hillslopes sources, namely landslides, debris flows and colluvial fans, to the channel network can be constrained using a time-space approach. In this conceptual framework, we propose to combine information derived from UAV-SfM techniques, classic photogrammetry and in-situ produced cosmogenic radionuclides to quantify spatio-temporal patterns in denudation rates and sediment fluxes. Catchment-scale denudation rates quantify the surface lowering per unit of time (L T^{-1}) and are scale-invariant. Sediment fluxes record the volume of sediment exported or evacuated from a given surface area per unit of time (L^3 T^{-1}), and quantify the rate of sediment transfer between landscape units, i.e. between hillslopes and channels. At annual scale, the geomorphic processes in the hillslope domain (10^0-10^1 km^2) can be monitored using very high-resolution topographic reconstructions (Figure 1e). At the decadal scale, the sediment dynamics of first-order catchments can be quantified from time-series of digital elevation models using classic photogrammetry (Figure 1f). Catchment-averaged cosmogenic radionuclide (CRN)-derived denudation rates provide integrated geomorphic process rates over the millennial time scale (Figure 1g). In the discussion of the results of this study, we will refer to this conceptual framework (Figure 1) to contextualise the results.

3 Material and methods

3.1 The Entle and Schimbrig catchments

Our study area is located in the northern foothills of the Central Swiss Alps, between Bern and Lucerne (Figure 2). The Entle catchment has a drainage basin of 64 km^2, with an elevation ranging between 680 m a.s.l. at the outlet near Entlebuch village and 1,815 m on the Schimbrig summit. The study area lies on the intersection between the Swiss Plateau, i.e. the Molasse Basin, and the frontal thrusts of the Alpine orogeny. The Molasse unit, covering the lower reaches of the catchment, is composed of Late Oligocene conglomerate bedrock knobs, forming erosion-resistant low ridges. The intermediate part of the catchment is covered by the Subalpine Flysch, while the higher SW-NE-oriented ridge is composed of Cretaceous carbonate rocks of the Helvetic thrust sheet (Schlunegger et al., 2016a; Figure 2). The Entle catchment is dissected by a 7 km-long central inner gorge with two tributaries, i.e. the Grosse and the Kleine Entle, that are deeply incised into a more than 100 m thick unconsolidated glacial till. The glacial till was deposited during repetitive and extensive glaciations during the Pleistocene. Lateral and terminal moraines deposited by the Entle glacier during the Last Glacial Maximum (LGM) are dissected by the Grosse and Kleine Entle rivers up to the headwaters (Figure 2). The inner gorge contains knickzones in its longitudinal profile, and several cut terraces are visible. A ^{10}Be-based sediment budget, which covers the last ca. 2,000 years, highlighted that incision rates in the inner gorge are more than 4 times higher than in the non-incised reaches (Van den Berg et al., 2012). The study area experiences three types of mass movement processes over distinctive landscape units. Landslides categorised as earthflows mainly affect the flysch areas. This type of mass movement is very common in flysch sedimentary sequences, and represents more than 30% of all mass movements in Switzerland according to Lateltin et al (1997). Near the summits, rock falls are common phenomena; and the sidewalls of river valleys are subject to widespread rotational and translational landslides.

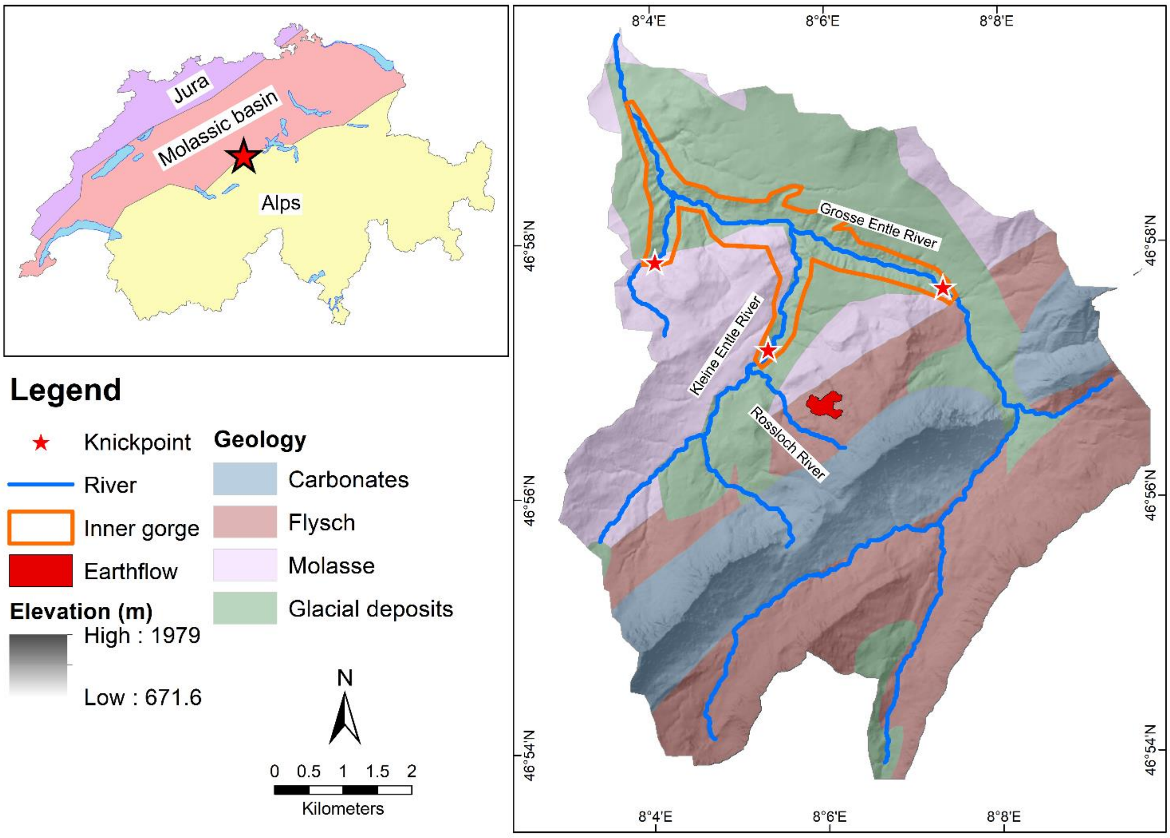

Figure 2: Simplified geological and geomorphological settings of the Entle river catchment (after Van den Berg et al., 2012; Schlunegger et al., 2016b). Inset: Location of the study area in Switzerland.

Within the Entle river catchment, an earthflow named Schimbrig has been particularly active over the last 150 years, acting as a sediment factory by excavating and mobilising sediments because of its deep rotational structure (Clapuyt et al., 2017; Lopez-Saez et al., 2017; Savi et al., 2013; Schwab et al., 2008). It is located in the first-order Schimbrig catchment, the latter draining successively into the Rossloch river and the Kleine Entle, before entering the trunk river, i.e. the Grosse Entle. The earthflow occurs on the hillslopes of the Schimbrig ridge and is not directly connected to the Schimbrig stream, except during short episodes when superimposed debris flows occur (Schwab et al., 2008). The Schimbrig earthflow consists of a fine-grained matrix of silt and mud, with centimetric to decimetric large clasts (Clapuyt et al., 2017). The internal structure of the earthflow is complex with nested rotational units (Clapuyt et al., 2017). Field observations revealed that a major earth slide with an up-to 12 m surface lowering occurred in the summer of 1994 after a succession of heavy precipitation events, followed by debris flows until March 1995 (Schwab et al., 2008). The intensity and spatial pattern of sediment redistribution, as well as the internal structure of the earthflow have rapidly evolved at the annual and decadal scale (Clapuyt et al., 2017; Schwab et al., 2008). The Schimbrig catchment also experiences scree slopes-like erosion processes in the upper part on the Schimbrig ridge. Eroded material is stored at foot of slope, above river sources. Within the Schimbrig catchment, the described earthflow affects ca. 25% of the area and is the only active process in the catchment.

3.2 Annual sediment fluxes

The annual sediment fluxes of the active part of the Schimbrig earthflow (Figure 3) were derived from time series of very high-resolution topographic datasets from Clapuyt et al. (2017). The earthflow has a rotational structure, and is the dominant source of sediment on the hillslopes. By quantitatively comparing topographic datasets, we assessed spatial patterns of surface *lowering*, i.e. a decrease in ground elevation, and *bulging*, i.e. an increase in ground elevation. The overall sediment budget of the area affected by the earthflow, i.e. the difference between surface lowering and bulging, is indicative of the change in sediment volume through time. The sediment flux is derived at the base of the hillslopes at the transition between the hillslope and fluvial domains, and represent the net flux of sediment from the earthflow to the Schimbrig river. The earthflow acts as a pure sediment source on the hillslope.

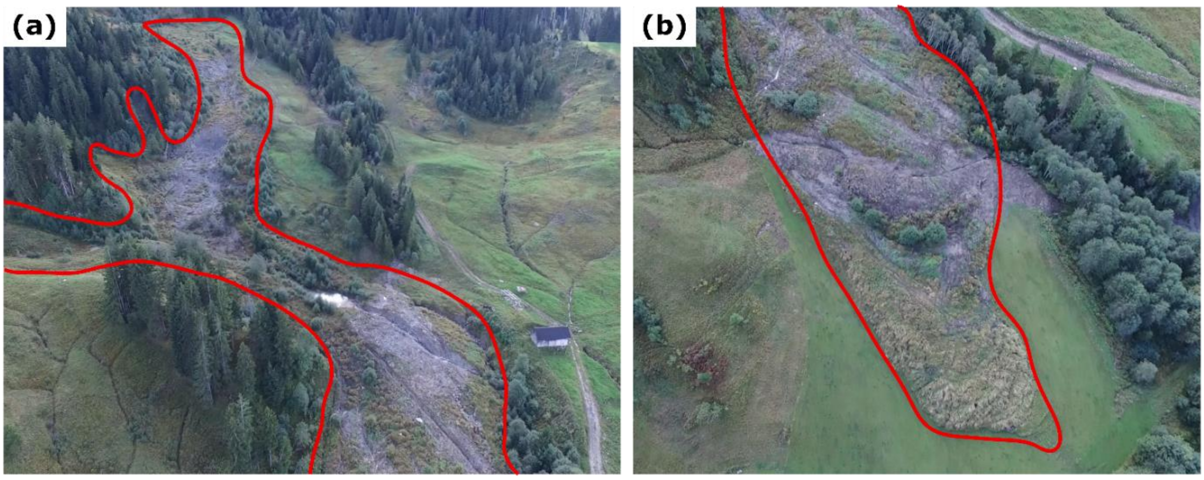

Figure 3: Illustration of the Schimbrig earthflow acting as a source of sediment in the river catchment. (a) Upper part with surface subsidence. (b) Toe of the earthflow with surface bulging.

The 3D topographic reconstructions were computed using the structure-from-motion algorithm (SfM) based on aerial photographs acquired by an unmanned aerial vehicle (UAV). Point clouds were subsequently interpolated into digital surface models (DSM) at a spatial resolution of 0.04 m, defined based on the density of the point clouds. The accuracy of the time series is ranging between 0.20 m and 0.24 m. Acquisition dates are October 2013, June 2014 and October 2015. As part of this sediment flux assessment, only the dataset of the 2014-2015 time interval was used because it covers the full spatial domain of the Schimbrig earthflow. The sediment budget was quantified from a digital elevation model of differences (DoD) between DSMs, using the Geomorphic Change Detection software (Wheaton et al., 2010). In this paper, values are eventually reported on an annual basis instead of over the entire period of interest (as in Clapuyt et al., 2017). Detailed information about the methodology and extended results are available in Clapuyt et al. (2017). Errors reported at the annual scale were computed based on a uniform limit-of-detection applied on each topographic surface. Therefore, the associated error to the annual sediment fluxes should be seen as a maximum value. It is likely that spatializing the error on very high-resolution topographic measurements, i.e. accounting for the spatial variation of photogrammetric and georeferencing precisions of the reconstructions, would lead to an increase of the signal-to-noise ratio as shown by James et al (2017).

3.3 Decadal sediment fluxes

The sediment fluxes at decadal scale were derived from Schwab et al. (2008), who assessed sediment transport by the Schimbrig earthflow and associated slopes, i.e. the *Schimbrig catchment* (Figure 4), and linked it with suspended sediment loads from a gauging station in the trunk stream, i.e. the *Waldemme river*. The authors based their analysis on a time series of DEMs derived from classic photogrammetry of aerial photographs acquired in 1962, 1986, 1993 and 1998. Each image of stereo-pairs was scanned with a ground resolution of 0.4 m and georeferenced using a differential GPS. Because of the scarcity of well-recognizable features through time, the associated volumetric errors of the photogrammetric workflow ranged between 2% for the 1986-1993 time interval and 29% for the 1962-1986 time interval. The sediment budget based on DEMs provides two metrics. The total sediment displaced corresponds to surface lowering while the total sediment exported per year, i.e. the sediment flux entering the Rossloch river, is the balance between surface lowering and bulging. The ratio between both metrics indicates the percentage of sediment mass evacuated compared to the displaced mass. For this study, we converted the average sediment fluxes that were expressed in tons per year into cubic metre per year, using a material density of 2.70 g cm^{-3} following a study by Gong (2005) on similar flysch units in Switzerland. Detailed methodology and results are available in the original paper of Schwab et al. (2008).

3.4 Millennial sediment fluxes

The geomorphic process rates at millennial scale were assessed from catchment-averaged denudation rates derived from in-situ produced cosmogenic radionuclides in fluvial sediments. In order to get a comprehensive dataset on the spatial variation in denudation rates in the Entle catchment, we collected river sand on eight locations in and around the Schimbrig catchment (Figure 4) and combined the resulting dataset with earlier work by Van den Berg et al. (2010). The new samples were processed following the protocol described in Vanacker et al. (2007), which is similar to the one followed by Van den Berg et al. (2010). After washing and sieving samples to the 0.25-1.00 mm fraction size, grains were separated using a Frantz Isodynamic Magnetic Separator. The remaining non-magnetic fraction was leached up to 10 times with 10% hydrochloric acid to remove organic, calcium and carbonate components. Then, samples were treated up to four times with 5% hydrofluoric acid in order to dissolve anything but quartz and also remove any meteoric ^{10}Be left. After the leaching step, 157.8 µg of ^{9}Be carrier was added to the clean quartz samples containing ca. 25 g of material. The purified quartz, i.e. ca. 10% of the original sample weight, was subsequently dissolved in concentrated HF, from which beryllium was stepwise extracted using anion/cation exchange column chemistry. Remaining precipitates were oxidized and pressed into copper targets. Finally, ^{10}Be/^{9}Be ratios were quantified using the 500 kV Tandy facility at ETH Zürich (Christl et al., 2013). These values were normalized with the in-house standard S2007N and corrected with a blank ^{10}Be/^{9}Be ratio of $4.06 \pm 0.23 \times 10^{-15}$. Catchment-wide denudation rates were then computed from the in-situ produced ^{10}Be concentrations, i.e. from this study and from earlier data published by Van den Berg et al. (2010), using the catchment-averaged denudation rates from cosmogenic nuclide (CAIRN) method (Mudd et al., 2016). This open source calculator uses the topography to weight the ^{10}Be production rate and shielding. A 1 m digital terrain model (DTM) resampled to 30 m resolution was used to compute topographic shielding. Snow shielding was averaged for each catchment individually. Snow cover is estimated using an elevation-dependent mean annual snow cover database for Switzerland (Auer, 2003). Following Jonas et al. (2009), an empirical relationship is used to derive the snow water equivalent thickness (SWE, g cm^{-2}).We kept the default parameters from Mudd et al. (2016) to run the CAIRN model, including the sea-level high-latitude production rate of 4.30 at g^{-1} yr^{-1} (based on Braucher et al., 2011). Long-term denudation rates obtained by the CAIRN calculator were converted into sediment fluxes (m^3 yr^{-1}), by multiplying them with the catchment area.

4 Results

4.1 Schimbrig earthflow sediment dynamics at the annual scale

When focusing on the active part of the Schimbrig earthflow (Figure 4), we obtained a net mass flux of 1,000 ± 4,000 m^3 yr^{-1} for the 2014-2015 period (Table 1; Clapuyt et al., 2017). Accounting for the associated error, the sediment flux is considered to be null. The sediment budget for the 2013-2014 time interval supports this finding. In the eroding sites, the average denudation was 0.8 ± 0.2 m yr^{-1}, and equivalent to the accumulation that was observed in the bulging areas (Table 1). For the Schimbrig earthflow, Clapuyt et al. (2017) reported a mean horizontal displacement of ca. 6.30 m yr^{-1} in the downslope direction. The UAV-SfM derived data suggest that the earthflow has been in a dynamic equilibrium over the 2014-2015 period, with earthflow-derived material being temporarily stored on the slopes during the period of interest.

Notwithstanding the state of dynamic equilibrium, the data suggest large internal movements with a complex pattern of sediment redistribution along the slope (Clapuyt et al., 2017). A succession of areas with terrain lowering and bulging characterised the earthflow along its longitudinal axis. The earthflow was re-adjusting to a new state of equilibrium after a massive failure that occurred in 1994. The sediment redistribution on the slopes was not associated with an increased sediment export downstream. Between 2013 and 2015, the hillslope domain was disconnected from the fluvial domain.

Table 1: Sediment fluxes for the 2014-2015 time interval from the Schimbrig earthflow (Modified from Clapuyt et al. (2017), to provide sediment fluxes reported on an annual basis).

	Estimate	Error (±)
Total area of surface bulging (m^2)	10763	-
Total area of surface lowering (m^2)	9730	-
Average rate of surface bulging (m yr^{-1})	0.8	0.2
Average rate of surface lowering (m yr^{-1})	0.8	0.2
Average net depth of difference (m yr^{-1})	0.05	0.15
Sediment flux (m^3 yr^{-1})	1,000	4,000

4.2 Sediment budget of the Schimbrig catchment at decadal scale

Sediment fluxes were computed from 1962 to 1998 over the first-order catchment affected by the earthflow, down to the confluence with the Rossloch river (Table 2; Figure 4; Schwab et al., 2008). The average sediment flux per year, evacuated from the catchment, is varying over time, from 14,000 ± 4,000 m^3 yr^{-1} for the 1962-1986 period, to 850 ± 20 m^3 yr^{-1} for 1986-1993 to 24,000 ± 4,000 m^3 yr^{-1} for the 1993-1998 time interval. The data from Schwab et al. (2008) indicate that there is no clear link between the sediment fluxes exported from the Schimbrig catchment and the earthflow dynamics on the hillslopes. This is evident from the fact that the proportion of the mass evacuated from the study area to the total displaced mass varies largely between 6% and 89% (Table 2).

Table 2: Sediment fluxes between 1962 and 1998 (after Schwab et al., 2008).

Time interval	Total sediment displaced (10^3 t)	Total sediment exported (10^3 t)	Average sediment flux evacuated (m^3 yr^{-1})	Error on sediment flux (m^3 yr^{-1})	Percentage of mass evacuated compared to the displaced mass (%)
1962-1986	1,003	892	14,000	4,000	89
1986-1993	272	16	850	20	6
1993-1998	946	322	24,000	4,000	34
1962-1998	1,581	1,229	13,000	2,000	78

During the 1962-1986 period, about 89% of the displaced mass was evacuated from the catchment, suggesting that sediment storage during this period was not significant. In contrast, during the following periods (1986-1993, 1993-1998) when the major earthflow event occurred in 1994, only up to 34% of the mobilised earthflow material was evacuated.

4.3 CRN concentrations in the Entle catchment

The ^{10}Be concentrations reported in this study are spatially and quantitatively consistent with earlier measurements by Norton et al (2008) and Van den Berg et al. (2010) (Figure 4). Overall, the ^{10}Be concentrations (Table 3; Figure 4; Van den Berg et al., 2010) range from 0.15 ± 0.53 ×10^3 at g^{-1} in the upper part of the Schimbrig earthflow (*CH-ENT-3*) to 5.28 ± 0.26 ×10^3 at g^{-1} in the upper part of the Entle catchment, i.e. the Rothbach river (*E-9*). As the ^{10}Be concentrations of the earthflow-affected area are low, relatively high errors are reported for the ^{10}Be concentrations of the earthflow-derived sediment (Table 3). The errors subsequently propagated on the denudation rates, particularly for the samples from the Schimbrig stream draining the earthflow, i.e. *CH-ENT-1*, *CH-ENT-5* and *CH-ENT-8*.

Table 3: ^{10}Be concentrations (at g^{-1}), CRN-derived denudation rates (mm kyr^{-1}) and sediment fluxes (m^3 yr^{-1}) for the Schimbrig catchment and other first-order rivers, i.e. samples CH-ENT-*, from this study and re-computed denudation rates and sediment fluxes for the Entle river catchment, i.e. samples Ent* and E-*, from Van den Berg et al. (2010).

Sample	Drainage area (km^2)	Altitude (m)	Latitude (dd)	Longitude (dd)	Measured $^{10}Be/^{9}Be$ ratio ($\times 10^{-14}$)	^{10}Be concentration ($\times 10^3$ at g^{-1})	Production scaling	Topographic shielding	Snow shielding	Denudation rate (mm ky^{-1})	Sediment flux (m^3 yr^{-1})	Apparent age (yr)
CH-ENT-1	0.20	1451	46.945	8.098	1.85	0.62 ± 0.45	3.306	0.954	0.904	1000 ± 2000	300 ± 400	650
CH-ENT-2	1.96	1264	46.951	8.086	7.52	2.94 ± 0.28	2.965	0.974	0.917	260 ± 60	500 ± 100	2500
CH-ENT-3	0.16	1500	46.943	8.104	1.17	0.15 ± 0.53	3.427	0.937	0.900	5000 ± 1000	900 ± 200	130
CH-ENT-5	0.35	1373	46.946	8.097	3.50	2.32 ± 0.58	3.208	0.961	0.909	300 ± 100	120 ± 40	2167
CH-ENT-6	3.25	1306	46.942	8.077	10.03	4.12 ± 0.28	3.069	0.950	0.914	180 ± 40	600 ± 100	3611
CH-ENT-7	4.54	1336	46.942	8.076	6.88	2.57 ± 0.27	3.112	0.960	0.912	300 ± 70	1400 ± 300	2167
CH-ENT-8	0.51	1325	46.947	8.092	4.07	1.34 ± 0.27	3.033	0.970	0.913	600 ± 200	290 ± 80	1083
CH-ENT-9	1.07	1287	46.946	8.092	8.80	3.53 ± 0.28	2.983	0.977	0.915	210 ± 50	230 ± 50	3095
Ent3-1	3.32	1076	46.9561	8.0621	-	1.94 ± 0.11	2.434	0.979	0.954	340 ± 70	1100 ± 200	1912
Ent4-1	54.6	1323	46.9367	8.1049	-	2.43 ± 0.12	3.007	0.965	0.948	320 ± 70	17000 ± 4000	2031
E-5	26.53	1482	46.9235	8.1157	-	3.11 ± 0.17	3.357	0.956	0.937	270 ± 60	7000 ± 1000	2407

E-7a	63.56	1274	46.9411	8.1	-	2.46 ± 0.13	2.922	0.967	0.951	310 ± 60	20000 ± 4000	2097
E-8	8.05	1547	46.9073	8.1074	-	4.60 ± 0.24	3.635	0.959	0.933	200 ± 40	1600 ± 300	3250
E-9	7.83	1537	46.9159	8.0881	-	5.28 ± 0.26	3.369	0.967	0.933	160 ± 30	1300 ± 300	4063
E-10	3.13	1445	46.9417	8.1527	-	4.70 ± 0.21	3.326	0.975	0.935	180 ± 40	600 ± 100	3611
E-11	16.01	1231	46.9393	8.0814	-	2.27 ± 0.13	2.871	0.969	0.949	330 ± 70	5000 ± 1000	1970
E-12	11.71	1280	46.934	8.0763	-	3.53 ± 0.25	2.989	0.964	0.946	220 ± 50	2500 ± 500	2955
E-13	16.64	1534	46.9125	8.0988	-	5.22 ± 0.24	3.511	0.960	0.934	170 ± 30	2800 ± 600	3824

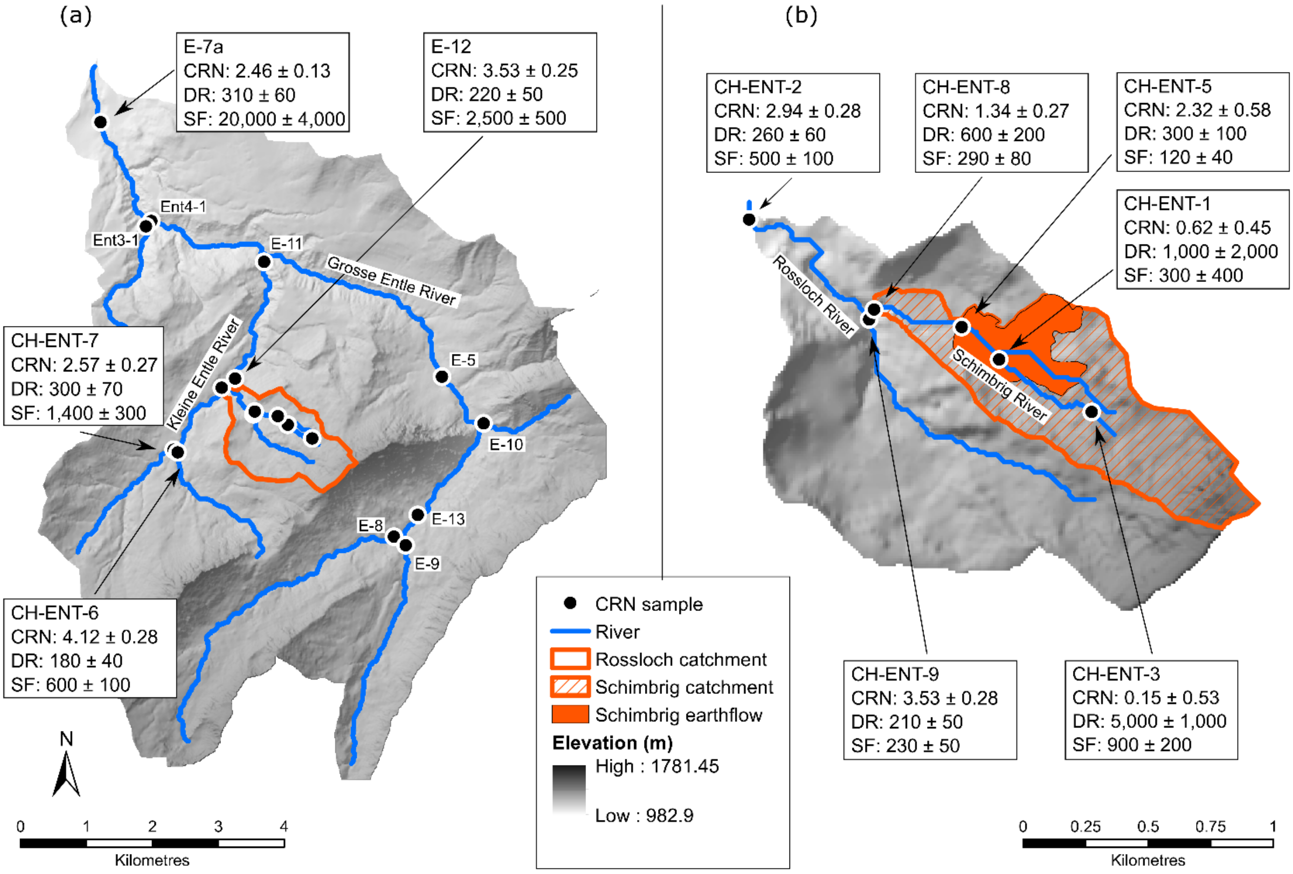

Figure 4: Location of CRN samples in the Entle catchment. CRN concentrations (CRN; ×10^3 at g^{-1}), denudation rates (DR; mm kyr^{-1}) and sediment fluxes (SF; m^3 yr^{-1}) values displayed are discussed in the text. Other values are available in Table 3. (a) Entle river and (b) Rossloch river catchments. The Schimbrig catchment is depicted by the hatched polygon within the Rossloch catchment in panel (b).

When analysing the ^{10}Be concentrations as a function of distance along the stream, we observe a clear and steady decrease in ^{10}Be concentrations with increasing downstream distance (and catchment area) for the catchments not affected by active mass movements (Figure 4; Figure 5). This decrease in CRN concentrations could, at least in part, results from an increase in erosion rates downstream, as suggested in earlier work by Korup and Schlunegger (2007) and Van den Berg et al. (2012), or from a recycling of buried glacial sediment as the river cuts through 100 m thick unconsolidated glacial deposits in the central part of the catchment (Figure 2).

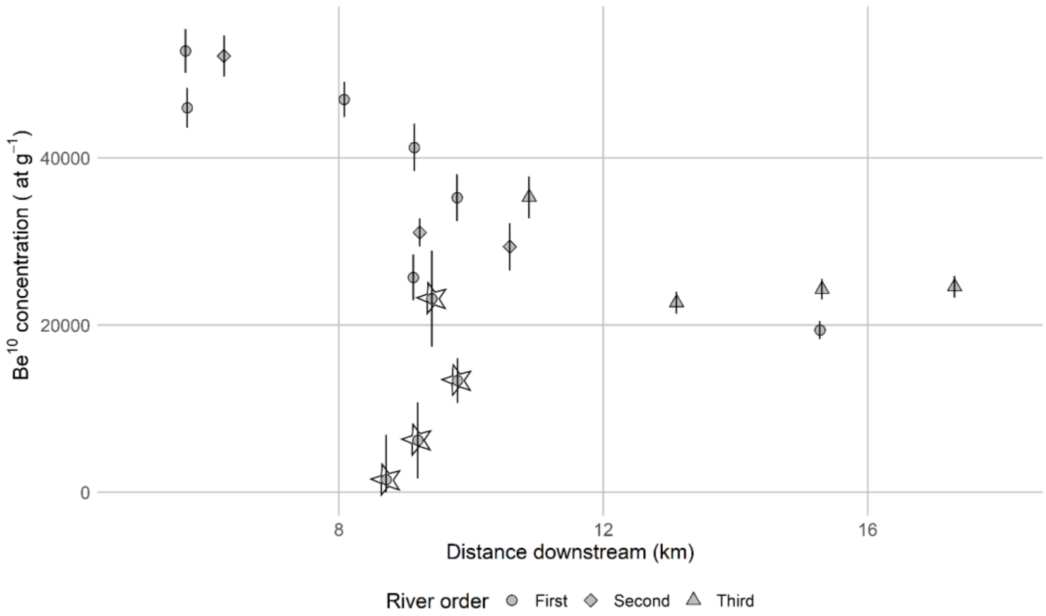

Figure 5: ^{10}Be concentrations (at g^{-1}) along the river network of the Entle catchment. Downstream distance is computed from the river source to the outlet of the Entle catchment. Samples from the earthflow-affected Schimbrig catchment are marked with a *star*.

Figure 5 illustrates the strong contrast in downstream change of ^{10}Be concentrations between the earthflow-affected Schimbrig and nearby catchments. Downslope of the Schimbrig earthflow, the river samples *CH-ENT-1*, *CH-ENT-5* and *CH-ENT-8* have systematically low CRN concentrations that increase downstream. The latter is likely to reflect poor sediment mixing, and long sediment residence time in the alluvial domain. At the confluence with the Rossloch river, the CRN concentration of the earthflow-affected catchment equals 1.34 ± 0.27 at g^{-1} (*CH-ENT-8*), which is at least two times lower than in the neighbouring catchment, i.e. 3.53 ± 0.28 at g^{-1} (*CH-ENT-9*).

5 Discussion

5.1 Sediment fluxes at the millennial scale

Any variation in sediment mixing capacity or delivery from shielded or reworked sediment to the river channel may dilute or increase the concentration in ^{10}Be in river sediments and lead to over- or under-estimation of the catchment-averaged denudation rates and sediment fluxes. Therefore, the geomorphological context of the Entle catchment potentially raises three caveats when using ^{10}Be concentrations measured in fluvial sediments to draw conclusions about the propagation of sediment pulses throughout the landscape. First, the admixture of buried glacial sediments due the incision of the Entle river in a 100 m thick layer of these deposits might lead to dilution of the ^{10}Be signal in the lower reaches. However, in glacial deposits of nearby sites (Trub river catchment, about 15 km to the West of our study site), Norton et al. (2008) reported ^{10}Be concentrations of glacial deposits reaching $0.76 \pm 0.13 \times 10^4$ at g^{-1} at 8.5 m depth, and $3.58 \pm 0.33 \times 10^4$ at g^{-1} at 1.5 m depth. As these values are about 15% to 50% higher than the catchment-wide CRN concentrations of nearby rivers, the incorporation of buried glacial material in the inner gorge is not the principal cause of the low ^{10}Be concentrations that decrease systematically along the Entle river. Second, along with its small size, the presence of an active earthflow in the Schimbrig catchment might violate the assumption of steady-state denudation and sufficient sediment mixing that are commonly assumed when converting ^{10}Be concentrations of river sediment into catchment-averaged ^{10}Be-derived denudation rates (e.g. Savi et al., 2014; Tofelde et al., 2018). We acknowledge that the dilution of ^{10}Be concentrations in river sediment due to stochastic inputs from landslides might lead to an overestimation of CRN-derived denudation rates (Niemi et al., 2005; Yanites et al., 2009). Therefore, CRN-derived denudation rates and subsequent sediment fluxes presented hereunder will be taken as first order or maximum estimates of the actual values (Puchol et al., 2014). Third, given that sediment production and delivery to the river network is typically stochastic in alpine environments, the ^{10}Be concentrations in river sediment might be highly variable in space and time as shown by Dingle et al., (2018) and West et al., (2014). Figure 5 illustrates the systematic variation in ^{10}Be concentrations in the Entle river basin, and the strong coherence between our dataset, and previously published data by Norton et al (2008) and Van den Berg et al. (2010). As such, the effect of the stochastic input of earthflow-derived sediment is likely to be buffered at the scale of the Schimbrig and Rossloch catchments.

Ignoring samples from the earthflow-affected catchment, the long-term denudation rates correlate positively with downstream distance (Table 3; Figure 4; Figure 6), with values ranging from 160 ± 30 mm kyr^{-1} (*E-9*) to 340 ± 70 mm kyr^{-1} (*Ent3-1*). Characterised by a low variability, these values are akin to ^{10}Be-derived denudation rates measured in similar alpine tectonic settings (e.g. Norton et al., 2008). The increase in denudation rates with downstream distance along the Entle river is triggered by the ongoing relief rejuvenation and incision of the inner gorge after the LGM (Van den Berg et al., 2012). The data also indicate that the river network effectively evacuates sediments supplied to the river channel. Accounting for the drainage area at each sampling location, the long-term sediment fluxes (Table 3; Figure 4; Figure 7) show the same positive correlation with downstream distance. The sediment fluxes range from 600 ± 100 m^{3} yr^{-1} in upper first-order catchments (*CH-ENT-6* and *E-10*) to 20,000 ± 4,000 mm kyr^{-1} at the outlet of the Grosse Entle river (*E-7a*). This two-order-of-magnitude increase in sediment fluxes downstream corroborates the efficient evacuation of sediment in the inner gorge.

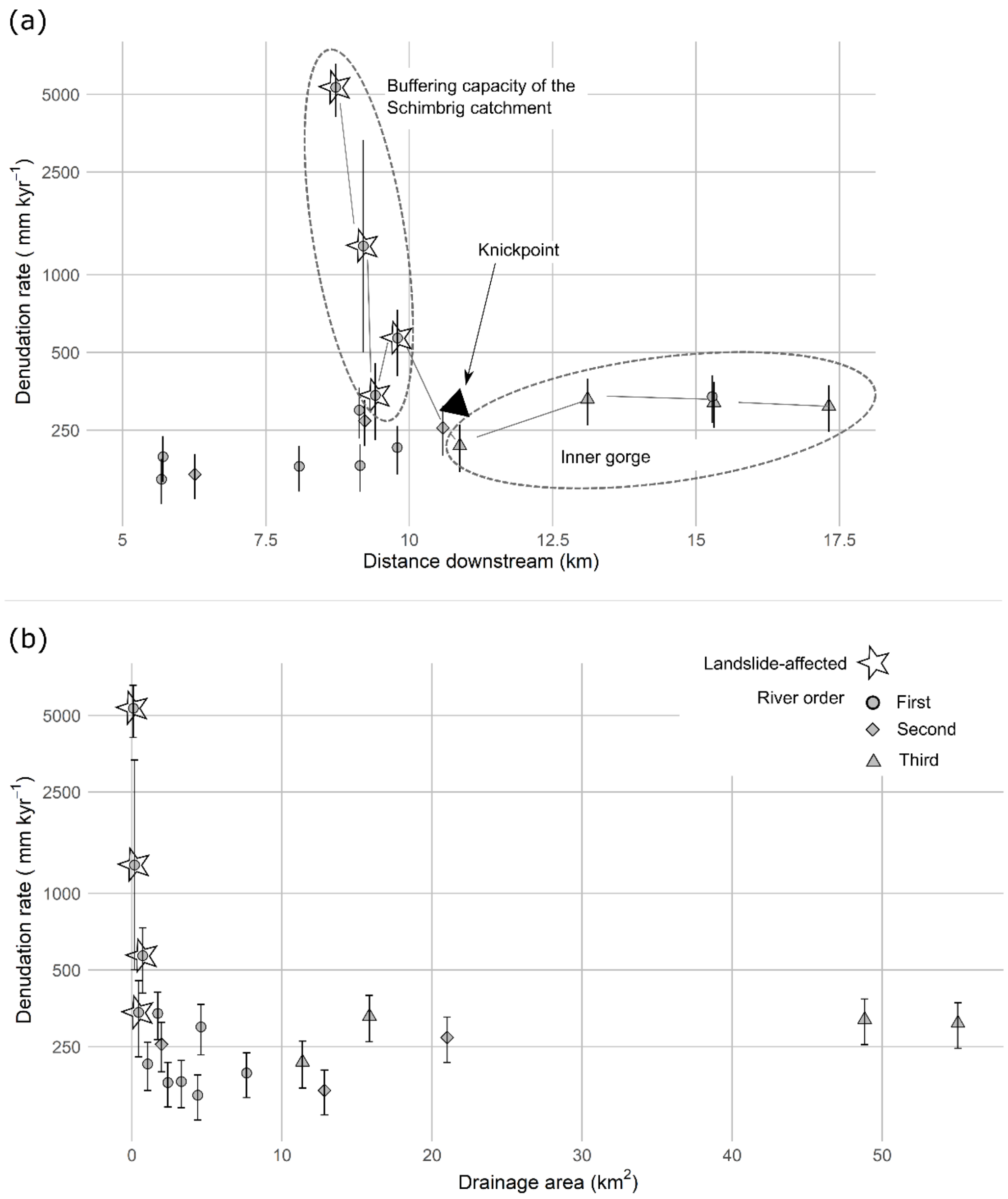

Figure 6: CRN-derived denudation rates (mm kyr^{-1}) in the Entle catchment against (a) downstream distance and (b) drainage area. Downstream distance is computed from the river source to the outlet of the Entle catchment. Samples from the earthflow-affected Schimbrig catchment are marked with a *star*. The grey line connects the points that are hydrologically connected, and part of the same fluvial system (Schimbrig, Rossloch, Kleine Entle and Grosse Entle rivers).

The earthflow-affected catchments show a different pattern that deviates from the overall trend of increasing denudation rates with distance downstream and catchment area. In the first-order Schimbrig catchment, long-term denudation rates correlate negatively with downstream distance (Table 3; Figure 4; Figure 6). The denudation rates of the earthflow-affected first-order catchment are up-to one order of magnitude higher than the rest of the Entle catchment, with values ranging between 300 ± 100 mm kyr^{-1} in the intermediate part (*CH-ENT-5*) and 5,000 ± 1,000 mm kyr^{-1} (*CH-ENT-3*) in the upper part of the Schimbrig catchment. The variability in denudation rates along the river is very high, with a one-order of magnitude difference between minimum and maximum values, and spatially highly variable. For example, the denudation rate in *CH-ENT-5* is lower than the sites directly up-and down-stream of this sampling location, reflecting the stochastic character of the sediment delivery from the earthflow. The decrease in denudation rates with catchment area suggests that material initially displaced by the earthflow is not directly evacuated to the river network but remains on the slopes, hence accumulating ^{10}Be atoms in the colluvial domain. Given that the catchment area of the first-order earthflow-affected catchments is small, the absolute sediment fluxes are low with values ranging between 120 ± 40 m^3 yr^{-1} and 900 ± 200 m^3 yr^{-1}. These long-term sediment fluxes computed for the Rossloch catchment, i.e. including the Schimbrig area, are one to two orders of magnitude lower than values computed in other parts of the Entle catchment (Figure 4; Figure 7).

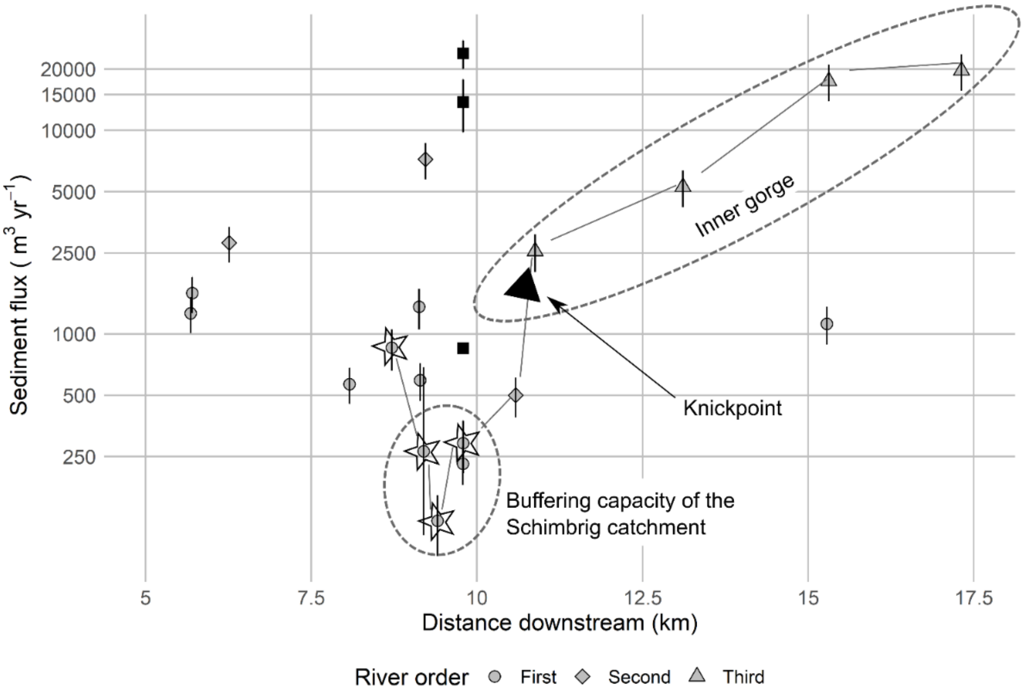

Figure 7: CRN-derived sediment fluxes (m^3 yr^{-1}) along the river network of the Entle catchment. Downstream distance is computed from the river source to the outlet of the Entle catchment. Samples from the earthflow-affected Schimbrig catchment are marked with a *star*. Black square marker represent the sediment flux computed by Schwab et al. (2008) for the period 1962-1998. Grey line presents the downstream sequence of denudation rates along the Schimbrig, Rossloch, Kleine Entle and Grosse Entle rivers.

The impact of landsliding on the long-term sediment dynamics can be evaluated by comparing the denudation rates of the two intersecting catchments at the confluence with the Rossloch river. At the outlet of the Schimbrig catchment, the denudation rate, i.e. 600 ± 200 mm kyr^{-1} (*CH-ENT-8*), is at least two times higher than in the neighbouring catchment, i.e. 210 ± 50 mm kyr^{-1} (*CH-ENT-9*). The difference in denudation rates between the two headwater catchments illustrates that the sediment dynamics of both catchments were probably very different over the last thousands of years as a function of the stochastic input of sediment from landslides (Figure 1). When accounting for their catchment area, the sediment fluxes are very similar though with values of respectively 290 ± 80 m^3 yr^{-1} (*CH-ENT-8*) and 230 ± 50 m^3 yr^{-1} (*CH-ENT-9*).

5.2 Temporal upscaling: The stochastic nature of landsliding

Characterised by a relatively gentle alpine topography, the millennial geomorphic activity of the study area is moderate in intensity. In comparison, the average CRN-derived denudation rate is 270 ± 140 mm kyr^{-1} in similar surrounding areas, i.e. in the Alpine foreland, but increases to 900 ± 300 mm kyr^{-1} in the high crystalline Alps

(Wittmann et al., 2007). Dendrogeomorphological data confirmed that the Entle river catchment was affected by an active earthflow at least over the past 150 years (Lopez-Saez et al., 2017; Savi et al., 2013). Given the extent of its active part, i.e. ca. 0.5 km^2, the Schimbrig earthflow is a larger-than-average landslide (Stark and Hovius, 2001). Therefore, according to the magnitude-frequency distribution of landslides (e.g. Hovius et al., 1997), this type of phenomena is generally relatively infrequent, i.e. between 10^{-2} and 10^{-3} events km^{-2} yr^{-1}. The mean annual horizontal displacements (Figure 1a) that we measured within the earthflow, i.e. ca. 6.30 m yr^{-1} for the period 2014-2015, are relatively high in comparison with decimetric displacements reported in the Western Slovakian Carpathians (Prokešová et al., 2014), submetric (< 2 m yr^{-1}) displacementrs reported for the Eel earthflow in California (Mackey et al., 2009), and metric to decametric displacements for the Super-Sauze landslide in Southern French Alps (Niethammer et al., 2012). The toe of the earthflow experienced a downslope movement of ca. 55 m between June 2014 and October 2015 (Figure 1b, Clapuyt et al., 2017). Although the important internal reorganisation of the Schimbrig earthflow, its net sediment budget is roughly in equilibrium: sediment transfer from the colluvial to the fluvial domain (Figure 1c) is minimal over the period 2013-2015. The sediment mobilised by the earthflow is buffered in the colluvial domain, due to decoupling of the hillslope-channel system (Figure 1d) over the annual timescale. In contrast to the limited annual sediment flux (period 2013-2015) of the Schimbrig catchment, its decadal sediment flux (period 1962-1998) equals 13,000 ± 2,000 m^3 yr^{-1} (Table 2; Figure 7). The decadal sediment flux is two orders of magnitude higher than the sediment fluxes computed at the millennial time scale over the same spatial extent, i.e. 290 ± 80 m^3 yr^{-1} (*CH-ENT-8*). We note here that the potential overestimation of ^{10}Be-derived denudation rates due to the addition of ^{10}Be-poor material from the earthflow (discussed in 5.1) does not affect our interpretation.

The sediment fluxes measured over different timescales reveal the episodic character of sediment production, delivery and transport out of first-order alpine catchments, such as the Schimbrig and Rossloch catchments (Figure 1). Landslides such as the Schimbrig earthflow generate sediment (Figure 1a) that is temporarily stored in the colluvial domain (Figure 1b), and continues to accumulate ^{10}Be nuclides during storage. During short phases when hillslope and channel systems are coupled, the colluvial deposits are evacuated out of the first-order sediment stores. The discrepancy between decadal and millennial sediment fluxes illustrates that these phases of hillslope-channel geomorphic coupling are short-lived and intermittent, and interrupt long periods of largely uncoupled colluvial and fluvial geomorphic systems (Figure 8). During most of the time, the first-order catchments are transport-limited, and sediment dynamics in the headwaters are uncoupled from the fluvial systems.

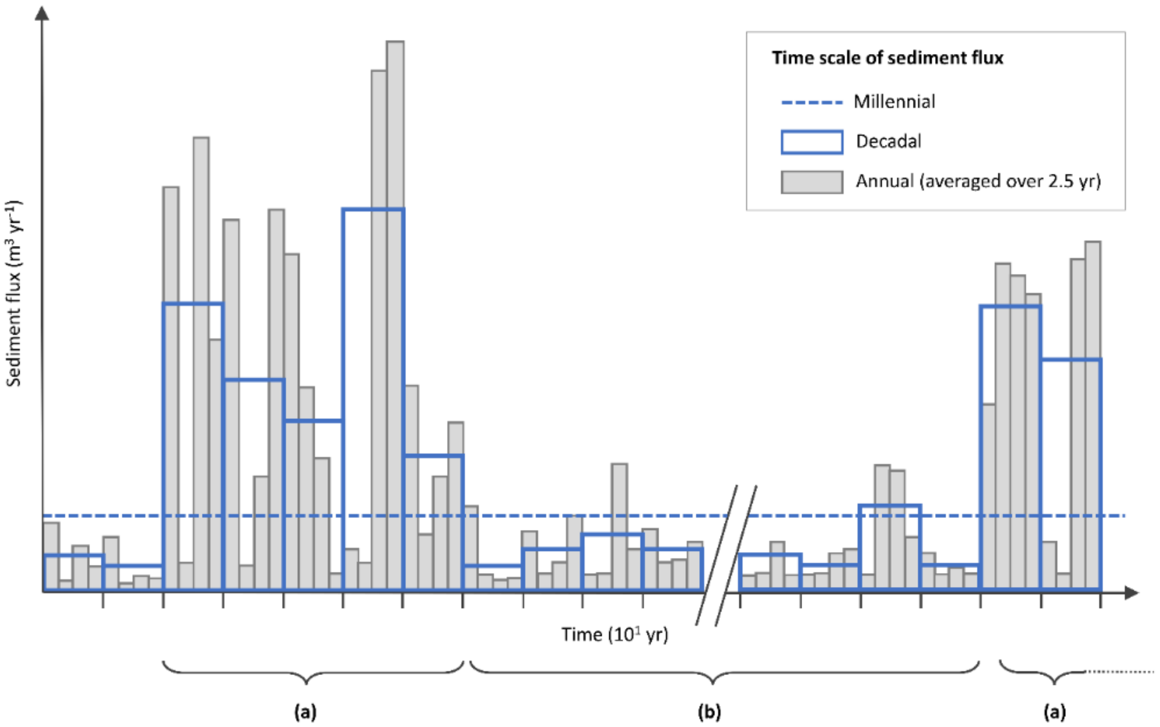

Figure 8: Conceptual representation of the sediment fluxes over different time scales at the outlet of a first-order river catchment. (a) Periods of high hillslope activity due to a landslide sediment pulse, resulting in intermittent hillslope-channel connections and in sediment export to the river network at the annual scale. (b) Periods of low hillslope activity both at the annual and decadal scales, due to poor sediment availability on slopes.

5.3 Spatial upscaling: The importance of landsliding for sediment budgets

Episodic landslides, such as the Schimbrig earthflow, have the potential to mobilise large quantities of sediment at annual or decadal time scale. The average sediment flux at the decadal scale (1962-1998) out of the Schimbrig catchment, i.e. 13,000 ± 2,000 m^3 yr^{-1} (Table 2; Figure 7), represents about 65 % of the average sediment flux out of the Entle catchment at the millennial scale, i.e. 20,000 ± 4,000 m^3 yr^{-1} (*E-7a*; Table 3; Figure 7). This illustrates that landslide-affected catchments can act as principal point sources of sediment, as a sub-catchment covering 1% of the area can provide 65% of the total sediment flux. The higher-order river network, i.e. the Kleine and Grosse Entle rivers, attenuates decadal sediment pulses through the sediment cascade, during which subsequent erosion and deposition occur over centennial time scales. The propagation of the sediment pulses (from e.g. landslides) across the channel network is largely controlled by the hillslope-channel geomorphic coupling, and the transport capacity of the fluvial systems. The latter act as nonlinear filters that smooth out spikes produced by episodic landslide disturbances as also suggested by Jerolmack and Paola (2010). In this sense, we can consider the episodic supply of sediment from landslides during intermittent phases of hillslope-channel coupling as noise that is averaged out when considering sediment fluxes at longer time scales and larger spatial scales. As our data show, one single disturbance (such as an earthflow) has not necessarily an impact on the long-term sediment budget of first-order catchments. Rather, it is the cumulated effect of multiple landslides, which are intermittently connected to the channel network at the decadal scale, along with sediment transport, that may regulate sediment fluxes at the regional spatial scale over the millennial time scale.

6 Conclusion

To better constrain the evacuation of sediment produced by landslides on hillslopes and their propagation in the channel network, we compiled geomorphic assessments at different spatio-temporal scales of the Entle river catchment located in the foothills of the Central Swiss Alps. This 64-km² mountainous river catchment is affected by the Schimbrig earthflow for more than 150 years. We quantified (or took benefit from previous studies of) sediment fluxes over annual, decadal and millennial time scales using respectively UAV-SfM-based 3D topographic reconstructions, classic photogrammetry and in-situ produced ^{10}Be cosmogenic radionuclides. Our unique spatio-temporal database of sediment fluxes highlights the episodic character of sediment production, delivery and transport out of first-order river catchments i.e. the Schimbrig and Rossloch catchments. A two-order of magnitude discrepancy is observed between annual, decadal and millennial sediment fluxes at the outlet of the Schimbrig catchment. It illustrates that phases of hillslope-channel geomorphic coupling are short-lived and intermittent, and interrupt long periods of largely uncoupled colluvial and fluvial geomorphic systems. During most of the time, the first-order catchments are transport-limited, and sediment dynamics in the headwaters are uncoupled from the fluvial systems.

Landslides such as the Schimbrig earthflow act as point sources of sediment. Although they represent only 1% of the total surface area, they can produce intermittently about 65% of the average regional sediment flux. The impact of a single sediment pulse is strongly attenuated at larger spatial and temporal scales by sediment transport mechanisms. The latter tend to smooth out the spikes in sediment flux delivered by episodic landslide events. Therefore, the accumulation of multiple sediment pulses, which are intermittently delivered to the channel network during phases of hillslope-channel geomorphic coupling, rather have a measurable impact on the regional pattern of sediment fluxes.

Data availability. All datasets and code are available upon request. Please contact the first author for details.

Competing interests. The authors declare that they have no conflict of interest.

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