Reply to referee F. Comiti (#3)

We thank Francesco Comiti for his constructive comments. Below we give detailed replies and outline the changes made to the manuscript.

General comments

a) The distinction between bedload- and debris flows-related damages is key in this paper, but in my opinion is not sufficiently explained. Please clarify what "clues" (descriptive characteristics) you relied on. Also, what about the intermediate type of process commonly labeled as "debris flood" ? Did you include it in the bedload category?

This issue was also brought up by reviewer no. 1 and is an important one. We added a paragraph in the methods sub-section 2.2 in which we provide information on our approach. It is important to stress that the decision whether a damage event was caused by bedload transport or a debris flow (or whether bedload transport was partly involved in the damage process) is based on the event description within the original Swiss flood and landslide database (description field of every entry). Please also see our response to comment [b] of reviewer no. 1.

We tried to only include bedload transport in the strict sense (during which sediment travels at slower velocities than the water). Unfortunately, the limitations in the event description did often not allow for finesse distinctions. Debris floods with a larger sediment concentration, if reported, were not included in the bedload category.

b) it would be extremely interesting to analyze the role of wood in the bedload event. I don't know whether this is feasible with existing database, but I suspect this could imply quite a work. Nonetheless, I think wood could have played a major role – in conjunction with channel aggradation – in bridge clogging, as evident from many floods elsewhere. The authors should at least present some qualitative discussion about it.

We agree that the assessment of the influence of large woody debris during bedload events would be very interesting. However, the data used in our study (Swiss flood and landslide database) is not detailed enough to allow for such an investigation. Especially small- and medium-sized events are often only shortly described in media reports and wood is scarcely mentioned, if at all.

We have added five sentences in the new third paragraph of section 2.2 (within the Methods section) where the role of wood during bedload carrying floods is discussed using an example that occurred during the major flood event of August 2005.

c) the methodology to determine the lower and the upper estimate for bedload damages remains a bit unclear. As this issue represents the core of the ms, please provide more details for the different types of objects. Also, a brief description/analysis of the characteristics of the events/areas featuring casualties would be useful.

We decided to introduce a lower and an upper bedload damage cost estimate for every object type within an entry of our final selection (3588 entries), because it was often difficult to determine a single sharp value. Thereby, we proceeded consistently for each object type. It is important to understand that the process of estimating bedload damage represents an interpretation and conversion of written information into damage figures.

Again, this has to do with the level of detail of our basic information in the Swiss flood and landslide database. The better an event is described and defined, the tighter we were able to keep the range of our estimation. For example, (1) if during a flood event a steep stream destroys streambank protection and subsequently causes considerable lateral erosion, we would take over the entire damage that is listed in the object types protection structures and agricultural land. In contrast, (2) if during another event a residential street was inundated by water from a stream that overflowed and deposited some coarse sediment, it is much more difficult to decide whether the flood water or the bedload caused the majority of the financial costs. In case just little material enters the buildings or covers parts of the adjacent lawn, we would take over only a small fraction of the listed damage in the object type “damaged buildings”.

In comparison to the process uncertainty index, which evaluates the *degree of confidence regarding the damage cause* the range between lower and upper bedload damage estimate represents an appraisal of the degree of confidence regarding the amount of damage. We have provided some additional information to describe the determination of the lower and upper bedload damage estimates in the second paragraph of section 2.2

d) The analysis of the “explicative” causes for variability in bedload costs (section 4.2) is in my opinion the weakest part of the ms. Rather than the average of the entire channel network within a basin, the average channel slope in the upstream proximity of the damaged areas (typically an alluvial fan or floodplain) should be used in my opinion. Otherwise high gradient values are obtained, well within the range of debris flows, with little significance to the actual process responsible for the damages.

*[…*additional points within comment (d), see below *…]*

All these additional variables should be analyzed statistically in more detail by means of multiple regression models, and possibly also by multivariate methods (e.g. PCA). This would greatly increase the international impact of the paper, otherwise too focused on the Swiss territory alone.

A main problem within our study is the fact that the analysis of the “explicative” causes for variability in bedload damage costs cannot be conducted in an ideal way, e.g. with the approach suggested by reviewer no. 3 (F. Comiti). There are two main reasons for this: (i) The coordinates indicated in the flood and landslide database are referring to the location of the main damage occurred during an event (if this location could be derived from the basic information, i.e. the media reports). This location is not necessarily identical with the location along a stream, where heavy bedload transport first took place. (ii) Quite often, however, the basic information is not accurate enough to pinpoint the center of damage, and sometimes it is not even possible to identify clearly the channel that was active in the event. In such cases we only know in which political municipality the damage occurred.

Thus, with the scarce spatial information comprised in a single database entry describing an event with bedload damage, it is generally impossible to accurately define the associated hydrological catchment where flood generation occurred. And as a consequence it is also not practical to determine the average channel slope in the upstream proximity of the damage location. This is why we had to carry out our analysis of controls on bedload damage costs at the municipal and regional level. We added a paragraph to the manuscript (section 2.3) that describes this problem and our procedure. We plan to make an attempt at deducing the upstream catchment of the damaged areas from the 3588 database entries including bedload damage. But this evaluation definitely goes beyond the scope of the present study. A first attempt could be carried out for a small selection events (e.g. within the framework of a master thesis). Moreover, the chances of success of such a try are questionable and subject to further uncertainties.

As to the *high gradient values that are obtained* (magnitude of the mean values for municipalities/subareas) that are *well within the range of debris flows*, they merely represent characteristic values for single municipalities or subareas and do not correspond to actual channel slopes observed upstream of damage locations. They are high because they include first order channels where much of the material is mobilized that will be carried as bedload transport further downstream. By altering the procedure to calculate mean channel gradients, lower values could be obtained for all subareas/municipalities. However, the correlation with damage data remains pretty much the same.

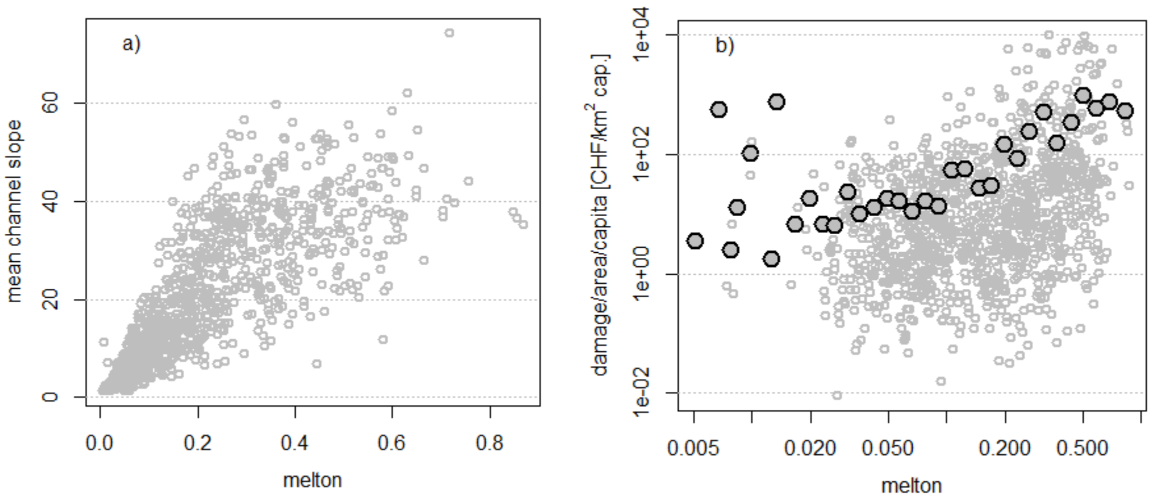
The issues brought up by the referee relating to the Melton number, geological settings, the influence of elevation are addressed below.

→ The information about the whole catchment steepness is better conveyed by the Melton number.

The Melton ratio is determined by dividing the height range of a hydrological catchment (difference of the max. elevation and the min. elevation) by the square root of the area of the catchment: [Melton ratio = $(Z_{max}-Z_{min})/area^{0.5}$]. Unfortunately, for our database it is generally impossible to derive the exact hydrological catchment associated with a given bedload damage point. We explicitly addressed this issue above (and also in our reply to comment [d] of referee no. 1).

However, we calculated the Melton number for each municipality. We thereby used the highest and lowest elevation and the area of the municipality. We are not sure if such an analysis even makes sense for areas that are not hydrological catchments. The relation between mean channel slope and the Melton ratio is shown below in figure (a). Most of the affected municipalities show a low Melton ratio and a low mean channel slope. The relation between municipal bedload damage costs normalized by area and population and the Melton ratio is given in the figure (b) below. The grey circles represent the individual municipalities affected by bedload transport damage between 1972 and 2011. The black circles represent binned means. We can see that higher damages per area and capita can be detected with higher ruggedness of the terrain.

We did not include these results in the manuscript since the Melton ratio is normally not calculated for politically defined areas such as a municipality (in contrast to topographically defined catchments).



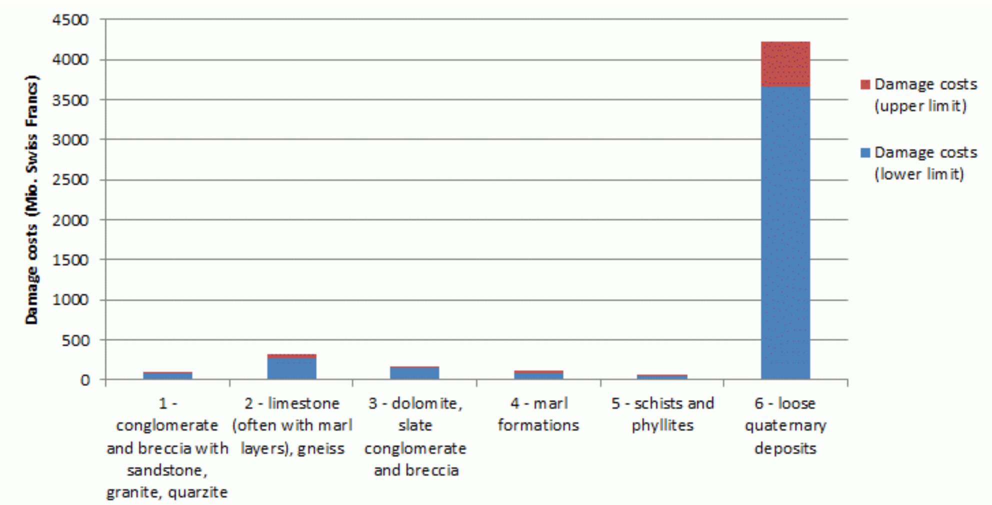
→ Also, some more discussion about the influence of elevation should be added, describing whether sediment supply from glacial or permafrost origin likely played a role or not.

We added some text to section 4.2.2 (Elevation) to address the influence of sediment supply from highly situated glacial/permafrost areas on the correlation of mean elevation and bedload damage costs.

→ *The geological setting of the different subareas is not consider at all, and I think it should.*

To give some basic information about the geological/geotechnical characteristics within the seven subareas, we added a column to table 1 in which the predominant lithology in the subareas is summarized. This description is based on the Geotechnical Map of Switzerland (BFS GEOSTAT/BUWAL).

In an additional step, we summarized the solid rock units of the Geotechnical Map of Switzerland into five lithological-geotechnical classes according to their susceptibility to mechanical weathering (according to their morphologic resistance, bedrock will yield different amounts of material to bedload transport in steep streams). While class 1 shows a very small susceptibility to weathering, class 5 is weathered rather easily. A sixth class contains the few different Geotechnical Map units of loose quaternary deposits that can be very easily mobilized. We then distributed the bedload damage costs (according to the spatial information in every single database entry) to the six lithological-geotechnical classes as shown below in the graph. The distribution of damage in classes 1 to 5 shows no obvious correlation with the vulnerability to mechanical weathering. Actually, most of the bedload damage costs fall into the loose quaternary deposits class (>83%). This can partly be explained by the fact that bedload damage occurs in settlements, along streets and rivers that are generally situated on alluvial deposits. Even in steep terrain in mountainous areas damage is going to result in the valley bottoms where goods and infrastructure are concentrated. We added a few sentences to the text to refer to this fact. However, because the underlying information provided in the database does not allow to define hydrological catchments, we are regrettably not able to investigate the upstream interaction between geological/geotechnical setting and the generation and transport of bedload. We thus refrained from including further investigations on the role of geology to our manuscript.



→ *The analysis of the role of precipitation should be enhanced by including parameters related to rainfall intensity for given recurrence intervals, possibly using regional depth-duration-frequency curves already available for Switzerland.*

We have the same problem here as described above. As it is not possible to define the hydrological catchments in which the flood events leading to bedload transport damage were generated, rainfall amounts were derived for municipalities and subareas. For this purpose, we used the RhiresD dataset of MeteoSwiss. RhiresD is a spatial analysis of daily precipitation covering the entire territory of Switzerland for the period from 1961 to the present (MeteoSwiss, 2013; Frei and Schär, 1998). It is based on daily precipitation totals measured at the rain-gauge network of MeteoSwiss and has a km-scale gridpoint spacing. The effective resolution of RhiresD is in the order of 15-20 km or larger (typical inter-station distance), and thus it is not really suitable to obtain statistics on local precipitation extremes.

However, we still determined 1-day rainfall values with a recurrence interval of 100 years for all the subareas and municipalities. As the RhiresD dataset has a temporal resolution of one day, we were not able to derive parameters related to rainfall intensity with a higher temporal resolution. The resulting graphs are given below, they show a rather poor relation between bedload transport damage and the 100 year daily rainfall. The graphs were added to Figs. 6, 7, 8 (subarea spatial resolution) and 9 (municipal spatial resolution) and discussed in section 4.2.3.

e) the section on bedload prediction in my opinion is not necessary in this paper, and I would delete it to make more room for the data analysis suggested above. It would only if contained an application of equations to some of the events with evaluation of their performance. Also, the relevance of macro-roughness correction discussed in the section bears limited benefit/sense (i.e. which boulders and bedforms would move and which not during a large flood ?) when predicting high magnitude flood events as the ones object of this paper.

Because of the limited possibilities to refine the analysis of the "explicative" causes for variability in bedload costs (as described in our detailed response to comment [d] above and due to the impossibility to link our damage events to catchments), we did not substantially lengthen section 4.2.

Hence, we would like to keep parts of the section 4.3 on bedload transport prediction. But we agree that the consideration of macro-roughness in the context of damaging flood events bears a rather limited benefit and thus deleted the third paragraph of this section.

<u>Technical corrections</u>

The term “torrent” in English suggests debris flow processes, whereas in the ms it is always used together with streams. I suggest to remove the term torrent and use “steep channels” or “steep streams”.

We removed the term “torrent” throughout the manuscript and mainly used the term “steep stream”. The only exception we made pertains to a sentence in the introduction that discusses both bedload transport and debris flows.

p. 1482, line 2: sediment erosion rather than bedload erosion. Also elsewhere in the bedload erosion should be removed. Also “fluvial bedload transport” could become “bedload transport” throughout the ms.

We agree and reformulated the sentence as follows: “In Alpine regions, floods are often associated with erosion, transport and deposition of coarse sediment along the streams.”

Furthermore, we removed the term “bedload erosion” throughout the manuscript as suggested by both J. Laronne (cf. specific comment [a] in review no. 2) and F. Comiti. Finally, we replaced “fluvial bedload transport” by “bedload transport” in the majority of the cases.

p. 1482, line 24: worldwide without hyphen.

Change made as suggested.

p. 1487, line 14: I don't think the term "certainty" is the best here. Better "Reliability" or "Degree of confidence".

We agree and replaced the term "certainty" by the term "reliability".

p. 1490: here or later it could be worth mentioning – even if it deals with a longer scale – the work by Schmocker-Fackel P, Naef F. 2010. Changes in flood frequencies in Switzerland since 1500. Hydrology and Earth System Sciences 14: 1581–1594.

We added the reference to Schmocker-Fackel and Naef (2010) a bit below, in section 4.3.

References:

MeteoSwiss (2013) Documentation of MeteoSwiss Grid-Data Products - Daily Precipitation (final analysis): RhiresD. Federal Office of Meteorology and Climatology MeteoSwiss, available at [http://www.meteoswiss.admin.ch/web/de/services/datenportal/gitterdaten/precip/rhiresd.Par.0007.DownloadFile.tmp/proddocrhiresd.pdf]

Frei C, Schär C (1998) A precipitation climatology of the Alps from high-resolution rain-gauge observations. Int. J. Climatol. 18(8), 873-900