AUTHOR’S RESPONSE

We would like to thank the editor for the thoughtful and interesting comments. Below you find our replies and respective changes made, as well as a marked-up version of chapter 4.3.4. for your consideration (other chapters remain the same as after first round of revisions; aside from the technical corrections of the quotations).

REPLY TO EDITOR REPORT

Comment:

Dear Authors,
after receiving one additional review, we may proceed with the publication. The reviewer suggested to accept the manuscript as it is. Thank you for the in-depth revision taking into account numerous reviewers' suggestions and comments.
Nevertheless, in this final stage, I would have a suggestion to extend the discussion related to debris flow events in year 1965 (events #6-10 in Table 2). These events all happened in one month (June 1965) - the first was attributed to Su (daily antecedent moisture content), the second one to P (daily precipitation), and the last three ones to M (melting).
I would suggest to get into more discussion specifically related to this month as it is worth explaining that triggering mechanisms can change rapidly, on a daily basis, following weather changes (raining and melting period).
Furthermore, it would be interesting explaining how is that this combination of 5 events in such a short time in 1965 has not repeated ever since till now (less snow since 1980's, high snow depths in 1965?). It think discussion of a time distribution of 25 debris events with regard to 1965 would be an added value, not just putting events into three distinctive groups of triggering mechanisms.

Reply & changes in manuscript:

We added a short discussion on the different triggers in June 1965 and that triggering mechanisms can change rapidly, following weather changes to the discussion (page 16, lines 15-20).
However, we would prefer not to add any further discussion on distribution of the 25 events in time as the dataset in our opinion is too small to allow any definite conclusions and also, because our **key point is on attributing trigger types to the documented debris flows, rather than defining probabilities for future debris flows** (and thereof, the distribution of debris flows in time is not of primary interest for us). As for the decrease in debris flows since the 1980’s this may be due to the effect of engineering mitigation measures (Braun, 2014), but we don’t have any conclusive data available for our study area to corroborate this hypothesis.

Comment:

Additionally, as the Handling Editor I may have a few minor technical issues:
1. Page 5, line 29: the quotation should read "Hargreaves and Samani (1985)"
2. Page 15, line 19: the quotation should read "Marchi et al., 2002;"
3. Page 5, line 29: the quotation should read "Aleotti, 2004;"

Reply & changes in manuscript:

We changed the corresponding quotations.

Comment:
I have checked the reference list and all references are used in the text, and vice versa.
Please, submit your revised manuscript at your earliest convenience to proceed to final publication.

Kind regards,
Matjaž Mikoš
Handling Editor

MARKED-UP DOCUMENT

4.3.4 Seasonally varying importance of the different trigger contributions

The above analysis illustrated quite clearly that water inputs originating from different individual "sources" can significantly contribute to generate trigger conditions in the study area. The data further suggest that the relative relevance of each these variables contributing to the actual trigger conditions does vary over time. Even more, there is some evidence that among the three tested variables, high-intensity and potentially short-duration precipitation P may be not the consistently most relevant (or "dominant") contributing factor for all events. Rather, it is not unlikely that also high-intensity snowmelt M and similarly, although with some lower degree of confidence, persistent, lower intensity water input, building up antecedent soil moisture content S_u and eventually causing saturated conditions, can generate the most relevant contributions to reach trigger conditions. More specifically, high-intensity precipitation was likely to be the dominant contributor to trigger debris flows on 17 out of 25 event days (68%). This corroborates previous studies that this type of precipitation is the prevalent trigger in such environments (e.g. Berti et al., 1999; Marchi et al. 2002; Berti and Simoni, 2005; Coe et al., 2008; Gregoretti and Fontana, 2008; Braun and Kaitna 2016; Ciavolella et al., 2016). In addition, however, high-intensity snowmelt was likely the dominant contributor on 6 days, corresponding to 24% of the observed events and antecedent soil moisture on 2 event days (8%), highlighting their critical individual contributions to debris flow initiation.

A somewhat different, more quantitative perspective is given by Fig. 7, showing the joint conditional posterior probabilities of a debris flow event E occurring, given the exceedance probability of each individual variable P, M and S_u, i.e. $p(E \mid P,M,S_u)$. Note that $p(E \mid P,M,S_u)$ is shown in classes of exceedance probabilities with an increment of 0.25 to allow a meaningful visualization of the clustering effects. High probabilities of debris flow events predominantly cluster at low exceedance probabilities of precipitation or in other words, on days with high precipitation totals which were exceeded only in 25% of all days in the study period (i.e. the right-most slice in Fig. 7). Under such conditions, additional contributions from snowmelt or antecedent soil moisture are not necessarily required to trigger debris flows (e.g. Aleotti 2004, Berti et al., 2012), which is also reflected in the elevated $p(E \mid P,M,S_u)$ for low M and Su in that class of precipitation exceedance probability. However, elevated event probabilities can also occur when little to no precipitation is observed, i.e. at exceedance probabilities of P >25%, which is roughly equivalent to $P<6$ mm d^{-1}, but when instead higher melt rates and/or, albeit to a lesser extent, antecedent moisture levels are likely to be present, as suggested by the model results. Although both, the relative proportions of the different dominant triggers as well as actual values of

$p(E \mid P,M,S_u)$ as shown in Fig. 7, may be subject to some change over time due to the relatively low absolute number of events with respect to the 60 year study period, the general pattern strongly underline the varying roles of the three variables under consideration as individual and potentially dominant contributors to debris flow trigger conditions in the study region.

Most debris flow events in the study area occur between mid- and late summer (Fig. 8), when spring precipitation and persistent snowmelt have developed above-average soil moisture levels and when the frequency of high-intensity, convective rain storms increases (Fig. 5, Supplementary Material Fig. S2). Further analysis also revealed a relatively clear pattern in the seasonally changing relative relevance of the three considered variables as contributors to debris flow trigger conditions. In general, three distinct seasonal debris flow trigger regimes emerge from the analysis, which to a high degree reflect both the seasonal cycle in the hydro-meteorological conditions and in debris flow occurrence, from snow melt to convective rainfall dominated debris flow triggers. While late spring and early summer events are mostly associated with snowmelt in combination with elevated soil moisture and only very minor contributions of high-intensity precipitation, the latter is, for the above reasons, the dominant trigger in summer and early autumn. While the former may be trivial given that significant snowmelt is less common from July onwards, it is interesting to observe that high-intensity precipitation may be, though also sometimes occurring in spring and early summer, less relevant for triggering debris flows in that time of the year. In our dataset event no. 7 occurring in early June 1965, which was attributed to high-intensity rainfall, while events no. 8-10, occurring in the same month, forms a clear exception from this general rule. Also, in the same month, triggering by elevated soil moisture conditions due to the combined effect of long-lasting rainfall and snowmelt has been observed (event no. 6). This shows how debris flows triggers can change very rapidly, following weather changes.~~This~~ The general pattern (high-intensity precipitation in summer vs. snowmelt in spring as dominant debris flow triggers) mostly arises from a combination of two factors, namely that in spring considerable proportions of precipitation observed at lower elevations (1) still fall as snow, in particular at higher elevations and (2) are, if falling as rain, intercepted by, transiently stored in and/or potentially refrozen in the snow pack, in particular if the snow pack has not yet reached isothermal conditions at 0°C throughout the region of interest. Although a mature snow pack later in the melt season may reverse the latter into a positive feedback, i.e. actually reinforcing intensive precipitation in rain-on-snow events (e.g. Harr, 1981; Conway and Raymond, 1993; Cohen et al., 2015), both factors above can, in principle, also cause an attenuation of the observed precipitation intensity as water will be released from the snow pack with some time lags and potentially over longer time, i.e. at lower rates than the observed ones. The immediate implications are then that thresholds for debris flow initiation estimated from traditional rainfall (but also precipitation) intensity-duration approaches may be suitable for some regions as for example demonstrated by Berti et al. (2012), who showed that antecedent soil moisture is of limited importance in their study region, but will be unreliable for certain hydrological conditions, in particular in snow dominated regions (cf. Decaulne et al., 2005), and thus insufficient for meaningful predictions of debris flows. As a step forward, it may therefore be beneficial to move towards understanding the problem in a more comprehensive and thus multivariate way, expressing and combining the varying relative relevance of different water "sources" in terms of *total liquid water availability* S_l (see Fig. 6e as example) in the source zone of debris flows, as recently also emphasized by Bogaard and Greco (2017).