Invited perspectives. A hydrological look to precipitation intensity duration thresholds for landslide initiation: proposing hydro-meteorological thresholds
Reply to Referee # 1

We thank the reviewer for the detailed and constructive review. Below we address and reply to the comments and questions. In Italic typesetting the original review is given, and in roman typesetting our replies.

Thom Bogaard and Roberto Greco

General comments
The paper offers a hydrological perspective of precipitation intensity-duration thresholds (hereafter, ID thresholds) for landslide triggering, useful in early warning systems. The ID threshold is a well established empirical model, as it is proposed in numerous studies. Several limitations affect these thresholds, as summarized in this paper. The authors with this paper propose to move away from this "conventional" path for future research, arguing that simple, even lumped, hydrological information should be introduced. They propose a general framework, where thresholds should represent both landslide causes (dynamic predisposing conditions) and landslide triggers. They argue that with ID thresholds only the latter are (conceptually) considered. Hydrological information is related to the former, and should be represented by something linked to soil water content.
I overall think that this is a good paper and well written. On the other hand, I also think that some improvements can be made.

We thank the reviewer for the detailed and constructive review. Actually, our conceptual approach is more general than only focusing on shallow landslide (then, it would be indeed soil moisture). Our point is that different hydrological information could be useful for landslide hazard assessment.

In particular, two main issues the authors should better discuss are:
1. How to separate between landslide "causes" and landslide "triggers" in practice?
In other words: at which instant/timescale one should think that there is a switch from causes to triggers?

This is an excellent point that we discussed at length ourselves. The reviewer is correct that categorizing landslides based on "cause" and "trigger" requires a kind of time scale to separate the two. The discussion on the timescale of trigger-cause is already half a century old (e.g. Sowers and Sowers, 1970). Wieczorek (1996) defined triggering as an "external stimulus (…) that causes a near-immediate response in the form of a landslide by rapidly increasing the stresses or by reducing the strength of slope materials.". In our own advanced review WIREs Water (Bogaard-Greco, 2015) we summarized the trigger-cause as: "A trigger is the last push for a slope to become unstable, whereas the cause is the underlying, often long term, change that occurred preparing the slope for failing.".
So we see the trigger as 'the last push' with near-immediate effect and consequently the hydrological cause is all before that. We agree that when adapting our proposed framework, to use the cause-trigger concept for defining regional landslide initiation thresholds, it becomes eminent to start defining timescale to distinguish between trigger and cause. This will be different for different landslides and slopes.
We agree with the reviewer we did not discuss this and we will add a short discussion on the definition of the timescale of the trigger event both in introduction and in conclusion section, as well as in the description of the discussed examples, which point out how the timescales of both trigger and cause are strongly related to the effective hydrological processes of a specific site.. However, for us, the more 'mathematical' or 'precise' defining of the trigger timescale in the various situations is out scope of this invited perspective and more for follow up work, when the community starts adapting the proposed concept.

2. How to manage the higher modeling freedom (respect to PID thresholds) that one can introduce by hydrological analyses?
The reviewer is correct that looking for variables different from rainfall to define thresholds gives in principle more freedom. However, the basic idea is that the choice of the most suitable variable should be guided not only by pure statistical analysis (that is, how the threshold performs), but also, and mainly, by the identification of the hydrological processes that, for the kind of landslide and geo-morphological context, are expected to be responsible for "causing" the conditions predisposing to a landslide. The statistical analysis could be regarded as a tool to confirm if the process identification is correct or not.

More details on these two points are given in the specific comments (comments to L253 and L 262-264). Finally, I recommend minor revisions for this manuscript.

Specific comments

L 20: "the conceptual idea is that precipitation information is a good proxy for bothmeteorological trigger and hydrological cause". It cannot be said that, in general, researchersderiving ID thresholds and their users have this conceptual idea in mind.This is a move of the authors which is not fully justified. So I think that this sentenceshould be rewritten, perhaps writing something on the fact that it is in general thoughtthat precipitation information can be linked by simple relationships to landslide occurrence,without explicitly taking into account hydrology.

The reviewer is correct we of course cannot speak for all researchers/groups who derived ID thresholds that this was the conceptual idea. They also could have other justifications, like: it gives (statistically) good/useful results. We will rephrase to make clear it is our interpretation, and that the practical background of precipitation ID is that often only meteorological information is available when analyzing (non-) occurrence of shallow landslides, and that, at the same time, the conceptual interpretation of their success could be that precipitation is sometimes a good proxy for both meteorological trigger and hydrological cause.

L 22: It is not fully clear what does "indistinct threshold" mean

Agree. We will delete these words as indeed indistinct threshold is not defined. We will rephrase: "this approach suffers from many false positives …."

L 36: "landslide is the most abundant hazard". Are the authors sure that "landsliding is the most abundant hazard"? Maybe say that it is "one of the most abundant naturalhazards", and add some references to literature (for instance: Sidle and Ochiai, 2013)Sidle, R. C. and Ochiai, H.: Landslides: Processes, Prediction, and Land Use, WaterResources Monograph, 2013.

Agree, we will rephrase and add the reference for this:"one of the most abundant natural hazards"

L 39 – 45: The three approaches listed by the authors are not all aimed to assess"landslide probability" in a strict sense (only number 3 is). In fact approach (1) leadsto an assessment of landslide "susceptibility", which is not exactly a probability, butan index of landslide proneness in a relative scale. Approach (2) does not provide ingeneral landslide probability, as most of the landslide triggering threshold schemes are"deterministic", and probability is in fact only in theory – but very seldom in practice– related to landslide triggering thresholds (Aleotti, 2004; Iiritano et al., 1998). Theauthors should clarify this point.
Aleotti, P.: A warning system for rainfall-induced shallow failures, Eng. Geol., 73, 247–265, 2004.
Iiritano, G., Versace, P., Sirangelo, B., 1998. Real time estimation of hazard for landslides triggered by rainfall. Environmental Geology 35 (2– 3), 175– 183.

In a strict sense the reviewer is correct. We will replace 'probability' with 'possibility'. (and see comment L46 below).

L 42: perhaps integrate literature on this, with other more recent papers (e.g. Peruccacci et al., 2017 and references therein)
Peruccacci, S., Brunetti, M. T., Gariano, S. L., Melillo, M., Rossi, M. and Guzzetti,F.: rainfall thresholds for possible landslide occurrence in Italy, Geomorphology, 290,39–57, doi:10.1016/j.geomorph.2017.03.031, 2017.

Thanks for pointing to more recent literature.

L 46: The term hazard may have a specific definition in the natural hazards field, related to the probability of the event to occur. So the authors should clarify that they refer to "hazard" in a broader sense. Perhaps in clarifying this they should cite a generally accepted definition of "landslide hazard". This comment is related to preceding one on L 39 - 45

We are using the term (landslide) hazard in a broader sense, not in a probabilistic way: A (landslide) hazard is a natural phenomenon that might have a negative effect on people or the environment. We will clarify this in the text by adding a definition.

L 63: the authors use both ID / PID when referring to precipitation intensity and durationthresholds. Only one way should be used

Correct, we will use: (precipitation) ID

L 63: "hazard" is perhaps not fully appropriate

We will replace with: 'landslide hazard"

L 70: add references to papers where a "probabilistic transition zone" is used

We refer to Berti et al (2012) which is detailed on from L80 onwards

L 88: It seems that authors are referring to works where antecedent precipitation isused (perhaps as a "measure of antecedent soil moisture content"). Here the authors should better clarify what they are referring to, and cite pertaining papers.

We refer to measures indicating the wetness state of the soil anteceding a precipitation event triggering a landslide event. These are listed further on in the paper (L245 onwards). We will put some of those references here as well.

L 88: It is unclear if antecedent precipitation should be seen in the authors' framework as an hydrological (cause) or meteorological (trigger) variable

Hydrological cause: we detail on that from L245 onwards. We will add clarification here as well.

L 90: again, here "hazard" is perhaps not fully appropriate

Landslide hazard

Figures 1 to 3: perhaps for a better comparison of the various curves it may be useful toplot in planes with the same axis range (e.g. x-axis of Fig. 1 goes from 0.1 to 100, whileFig. 2 from 0.1 to 1000). Also, it may be better that figures have the same appearance(e.g. no grid in the plot of Fig. 1; adjust font size in Fig. 3).

Good suggestion, we will make the figures appear more homogeneous

Figure 3: It is unclear how the dark grey area representing "landslide threshold" is derived from figure 2, as the area that it covers is narrower than that covered by thresholds in Fig. 2

It is a generalised threshold summarizing figure 2. We on purpose narrowed the range for discussion reasons (like looking through eyelashes).

L 171: It is unclear in which sense the ID threshold is "generalized"

Broadly summarizing indication of the threshold.

Figure 3: P is undefined (though its meaning can be easily understood from discussionin the text).

As the reviewer suspects, P denotes precipitation, we will add this to the figure caption

L 175: It is not clear why precipitation ID thresholds are "volumetric", as an infinitenumber of (I,D) or (H,D) pairs can be associated to a given event rainfall H.

We mean to say: Every point on the threshold line depicts a volume, as H=I×D

L 181: It is unclear why greater precipitation volumes should imply bigger landslides.Is this something reported in literature? I imagine that this is in general not true, asthe amount of rainfall gives little (or none) information on its spatial extension, and thusof that of the landslide. Also ID thresholds are derived using databases that usually report little information on landslide size, and to say that "the database consists for theoverwhelming majority of shallow landslides and debris flows" doesn't mean that the size of landslides is small.

Sorry for the confusion, we are referring to deeper seated landslides: the amount of rainfall refers to unit surface area, so it cannot be related to landslide size, but it can be related to landslide depth. We will clarify.

L 192 – 196: In this discussion the authors should mention that ID thresholds are sensitive to the way a rainfall event is defined, that is, mainly the maximum zero-precipitation interval within a rainfall event (See Vessia et al., 2014; Melillo et al; 2015). Cleary, the shorter this interval is, the shorter the length of rainfall

events will be. With long maximum dryness the events can be so long that different hydrological processes can takeplace. In this case rainfall events do not represent "the last push" but a mixture between "causes" and "triggers".

Vessia, G., Parise, M., Brunetti, M. T., Peruccacci, S., Rossi, M., Vennari, C. and Guzzetti, F.: Automated reconstruction of rainfall events responsible for shallow landslides, Nat. Hazards Earth Syst. Sci., 14(9), 2399–2408, doi:10.5194/nhess-14-2399-2014, 2014.

Melillo, M., Brunetti, M. T., Peruccacci, S., Gariano, S. L. and Guzzetti, F.: An algorithmfor the objective reconstruction of rainfall events responsible for landslides, Landslides, 12(2), 311–320, doi:10.1007/s10346-014-0471-3, 2015.

This is our point. We do discuss this point in L161-L165. However, we agree with the reviewer that this point should be highlighted here as well. Thanks.

L 253: The authors should discuss how to separate between the time scales of "causes" and those of the "triggers". In other words, how to switch, in practice, from the "cause" hydrological analysis (storage), to the "triggers" meteorological analysis (rainfall)? In other words, how does the framework the authors propose contribute in removing the subjectivity of identifying the rainfall that represents the "trigger"/"lastpush" (see comment on L 192 – 196)?

See reply with general comments

L 253: Another point is: hydrology may be in general important also during the "triggering" process, while in the authors' framework it is not explicitly taken into account. Arethe authors implicitly saying that "hydrology of the last push" can be taken into account without a significant processing of rainfall data?

The point we want to make here is that we propose that an effort is made to separate longer time scale causes with shorter time scale triggers. Of course we do not imply other mechanisms cannot take place, but processes evolving over shorter scales are more directly related to the characteristics of rainfall event (i.e. the intensity), while rainfall effects on long-term processes are smoothed.

L 262-264: "However there are several possible choices of hydrological variables to be plotted along the cause-axis, such as soil water content, catchment storage, representative regional groundwater level and similar". This implicitly reveals that a high degree of subjectivity follows from the framework that the authors propose. Researchers do generally agree that subjectivity of the ID threshold assessment is significant, in spite of his simplicity. For instance, one source of subjectivity in ID thresholds is related to the choice of the maximum zero-precipitation interval to define rainfall events (seecomment on L 192-196). This is known to impair comparisons between thresholds, which thus makes it difficult to search for general landslide triggering thresholds. The framework that the authors propose seems to possibly bring a higher heterogeneity of the analyses, and thus maybe can in practice represent a step backwards for finding unifying concepts. By introducing hydrological analysis, researchers may have more freedom in choosing models and parameters for estimating the "cause" variable (antecedent soil water content). This may represent a possible way to manipulate theresults so that the performances of the resulting hydro-meteorological thresholds appear to be higher than they actually are. Thus, the authors should discuss how one can prevent this, perhaps by highlighting the importance of always performing validation analyses, i.e. to test developed thresholds against a sub-dataset which is not used in calibration.

The point we make is that (hopefully) more process knowledge will be in the graphs and less statistics. Indeed there will be a higher degree of freedom from a statistical point of view, but we argue also higher causality. The reviewer is right that this subjectivity can be a problem, but we take the stand that searching for a hydrological cause will improve the physics behind the thresholds whereas now, we rely only on statistics.

L 319: "ID thresholds neglect the role of the hydrological processes" is a strong statement. Indeed it may be written that hydrological processes are too simplistically represented by ID thresholds. In other words, precipitation is the main cause of landslides, but the main problem is: how to process precipitation information to obtain thresholds that perform well in forecasting landslides? And, of course, ID thresholds certainly do not represent the best way to processes rainfall data.

We do not agree with the reviewer that this statement is too strong. There is no attempt to put hydrology into the threshold and only in case of relatively linear relationships between hydrology and precipitation this type of thresholds would hold. But hydrology (pore pressure built-up in the subsurface), is not linearly related to precipitation. So, yes, we can look at ID thresholds in terms of statistics, but we argue one could also look it from the point of "being right for the right reason".

L 332: I agree that one downside of spatially-distributed physically based models is that they require a "well calibration". However to estimate catchment storage (as in Ciavolella et al., 2016), requires a well calibrated model too. The authors should discussbetter this point.

Point well taken. Indeed, in practice also some of calibration will remain required, although to a lesser extend then calibration of a fully distributed model. We will add this in the discussion.

L 233: A sketch explaining the approach the authors propose can be useful for readers.
Good suggestion, we will try.

Technical corrections

We are thankful for these technical corrections. We will correct them in the revised version
L 42: Caine instead of Cain
L 45: maybe something is missing as citations finish with a ";"
L 71: "separation" instead of "separator"
L 78: remove "," after "conditions"
L 142: perhaps replace "for regions or areas not pertaining to this area" with "otherregions or areas"
L 147: "threshold" instead of "thresholds"
L 197: perhaps "phenomena" instead of "hazards"
L 198: "related" instead of "relate"
L 223: "thresholds" instead of "threshold"
L 255: perhaps "field" instead of "terrain"
L 283: "specific" instead of "particular"
L 318: "limitations" instead of "limitation"
L 326: "interpretations" instead of "interpretation"
L 331: "physically based" instead of "physically-based"

Reply to Referee # 2; Roy Sidle

We thank Roy Sidle for the detailed and constructive review. Also his insights in original literature is very valuable. Thanks so much. Below we address and reply to the comments and questions. In Italic typesetting the original review is given, and in roman typesetting our replies.

Thom Bogaard and Roberto Greco

This paper offers a refreshing and needed critique of the ID relationships commonly used in regional (and global) landslide predictions. Furthermore, it proposes an improved approach that includes metrics of predisposing 'causes' and 'triggers' of shallow landslides. As such, it should stimulate new research in this arena that will benefit landslide and hillslope debris flow prediction. It will be a valuable contribution to NHESS with some moderate revision.

I noted several times in my review that follows that ID relations (at least some previously published ones) have erroneously reported data as 'individual storms', which were obviously not individual events (i.e., very, very long durations). Additionally, on the opposite side of the ID 'x-axis' there are instances of very, very short storms of high intensity triggering landslides – these appear to be bursts of intensity on saturated soils as noted by the authors or they could in fact represent a totally different process, like channel bed mobilization causing a debris flow. My recollection of reading through some older reports in which data were used to develop ID thresholds is that in some cases the described mass failure was more of a within channel debris flow. Off the top of my head, I am thinking of some of Rapp's early papers that were included in Caine's threshold. In any event, these anomalies should be considered or mentioned herein.

The reviewer clearly indicates the importance of rainfall variation over a rain period. This indeed is extremely important as also discussed in our paper (L163-L166; L327). However, we agree, we should discuss this part more. We will add a new paragraph around L163 in which we detail on the effect of a) the uncertainty arising from precipitation measurements using gauges and b) the effect of using average intensities in the ID thresholds and that when moving from short to very long events it is not possible to have identical definitions of what an event is.

I have noted a number of editorial suggestions directly on the manuscript which I will attach for the authors.

Thanks, we are thankful for these and will benefit from them.

More scientific technical comments are noted as follows:

Title: I would say "Hydrological perspectives on precipitation intensity – duration thresholds. . ..."

The title starting with "Invited perspectives:" is a format of NHESS. We will discuss the title based on your suggestion (and of Ben Mirus) with the executive editors of NHESS.

Lines 28-29: reword – "discuss" based on "associated discussion"

OK

Lines 86-88: yes, we tried this in our 1985 Hillslope Stability and Land Use book using antecedent rainfall information, but the problem was the lack of documentation of such antecedent rainfall data in earlier studies. Overall, we felt that it did improve the ID thresholds (at least conceptually).

Thanks for sharing, we will make appropriate reference to it.

Line 109: The term 'stormwater management' implies to me more of an urban planning context; that may be my bias, but you may want to add 'flood prediction' (or something like this) as well.

We indeed use the term for urban stormwater management in this context. We will add the flood prediction.

Line 125-126: I think that this is a key difference between practical applications of IDF and ID curves; that is most (or at least many) shallow landslides respond to sort-term intensity bursts which are not articulated in typical IDF's. You may want to mention this.

Agree, indeed the rainfall durations considered for the derivation of IDF curves have nothing to do with the beginning or with the end of a rainfall event: they are time intervals of given duration during which some rainfall fell. And then, extreme observed values are considered (e.g. annual maxima). Shallow landslide tend to respond indeed to short term high intensity of rainfall which are often not visible anymore when averaging over larger time steps. We will include this aspect in our paper (see also below)

Line 144: Try not to start sentences with "Figure x shows. . ."; this can be seen in the Figure and caption. Just directly say what you wish to say about the data in the figure and cite the figure in parenthesis at the end of the sentence.

We will reformulate this.

Lines 155-157: rework this sentence – understandable, but a bit confusing. Maybe just put 'mostly debris flow and some shallow landslides' in parenthesis. Furthermore, I think there are some issues with such very short 'landslide producing storms' reported in the literature that are captured in these cited thresholds. As you note, they are probably mostly debris flows, and upon inspection of some earlier papers that reported such short-term events, it seemed that the authors were referring to possibly a different process – e.g., debris flows caused by channel bed mobilisation. I looking into this matter in our 2006 landslide book, we actually threw out some of these short-term rain events when constructing new ID curves because we were convinced that they represented different triggering processes.

We rephrase as follows: "For landslides triggered by short precipitation events (D ≤ 1 hr), the slopes of the IDF and ID curves substantially coincide (Figure 3). ".

Furthermore we will add it after line 161: "This is counter-intuitive, as during long-lasting wet periods landslides are usually more frequent, while many debris-flows triggered by very short and intense storm originate from channel bed mobilization rather than being (new) mass movements"

Lines 158-166: I agree that this is problematic, and I feel (as you state) that ignoring short-term peaks of rainfall in an otherwise long-duration, lower intensity event is the main reason for this problem. Based on my work and that of others, I always say that one common scenario for shallow rapid landslide initiation is a long storm of low to moderate intensity, with a peak intensity occurring near the end of the event. Another issue here, I agree that the longer return periods for landslides triggered by long-duration, low intensity storms is counterintuitive; however, when we looked into the actual data for some of these so-called long duration events that triggered landslides (in reviewing references for the 2006 AGU landslide book), it became apparent that some of the data included in these ID relationships were not strictly 'individual events', rather these were based on a longer period of rainfall leading up to the landslide. – thus, a direct comparison with some of these so-called long-duration landslide triggering 'events' with IDF curves for actual individual events may be a bit problematic. You probably should mention this potential discrepancy. My point is probably only relevant for the very long 'events', but it may be worth mentioning.

(See also reply after general comment at top and after Line 125-126) The importance of rainfall intensity variation should be elaborated on, and as stated before, we will add a paragraph discussing this in more detail.

Lines 185-188: This sentence is a bit confusing; it seems that you are referring to reported data when you saw the 'vast majority of empirical thresholds fall between . . .". Are you saying that for other studies most of the landslide reported would fall between thresholds of 10 to 100 mm? If so, you need to cite some references. But I am not sure that is what you are trying to say here. Anyway, please clarify. (and you overuse the expression 'vast majority' – just say most or the majority).

We reformulate: "Many of the reported empirical precipitation thresholds has between 10 and 100 mm of accumulated precipitation. However, also <10 mm and >1000 mm volumes needed for landslide initiation have been reported."

Lines 194-196 See my previous comment about data for very long duration 'events' that are likely not individual events.

Lines 209-210: In addition to my comment in the text, also see my previous comment about data for very long duration 'events' that are likely not individual events.

Agreed. See response above

Lines 227-231: Very complex sentence and a bit awkward. Can you rewrite this or try to break it up a bit?

We reformulate: "Hence, it was possible to define non-dimensional variables comparing the meteorological triggers with the infiltration and storage capacity of the soil cover. This non-dimensional hydro-meteorological threshold performed slightly better than the precipitation ID threshold in separating events resulting in factors of safety smaller and greater than 1.3."

Lines 240-241: I don't mean to be beating a 'dead horse' again, but such long events are obviously not 'events'; they were probably included in databases because this was the only precipitation record reported.

Agreed. See response above

Line 257: Why do you say 'was preferred'? by who?

We intended to express that in several studies another approach was followed, that of distributed physically-based modelling. We will change in: "This is a largely unexplored terrain, although we recognize that data availability can be cumbersome. " The discussion on the option of using physically-based distributed models is done elsewhere in the paper (In introduction and in conclusion L330).

Lines 258-260: Reword the first sentence to note that the trigger axis refers to the rainfall characteristics (intensity) responsible for initiating the landslide. When you say "depends on the local situation" – I think you mean both available data and the rainfall characteristics that are responsible for landslide initiation in that area.

Reformulated as: "Concerning the 'trigger'-axis, there is little debate; it is the rainfall intensity responsible for the short-term last push initiating a landslide."

Line 276: What do you mean by 'discharge intensity'? This is a rather unconventional term.

Reichenbach et al (1998) used: event intensity (in $m^3 sec^{-1} km^{-2}$). We will explain and use "specific discharge".

Line 282: What is low/high storage?

We mean to say how much water is stored in a catchment compared to its maximum storage capacity. We clarify.

Lines 286-287 (and the sentences that follow): I think this phenomena occurs for deep seated landslides like earthflows of slump-earthflows – maybe better to state this to avoid confusion, because you are mostly focussing on shallow landslides. There is some older work in Japan that has clearly showed such relationships with earthflow reactivation and a threshold groundwater depth. I believe mark Reid also published a paper on this from earlier work in Hawaii.

Thanks, indeed this mainly holds for deeper seated landslides. Thanks for the reference. We will rephrase: "In some cases, mainly deeper seated landslides, ….."

Line 322: Again, not all data in these ID relationships were for individual events.

Agree

Line 323: you mean even when they are developed for small areas?

Yes. Thanks

Line 338: These will be particularly valuable in developing countries.

True!

I really like the message in the last paragraph of the Conclusions! Well articulated.

Thank you

Reply to Referee # 3 Francesco Marra

We thank Francesco Marra for the insightful comment. Below we address and reply to the comments and questions. In Italic typesetting the original review is given, and in roman typesetting our replies.

Thom Bogaard and Roberto Greco

The authors analyze the concept of precipitation intensity-duration (ID) thresholds for shallow landslides and debris flows from a hydro-meteorological perspective to propose a new approach to the problem. The contribution is largely welcome since it suggests new approaches and perspectives to overcome important, but sometimes neglected, limitations of the commonly used methods.

Within the interesting analysis of the relationship between ID thresholds and IDF curves, the discussion so far neglects the impact of rainfall estimation uncertainty and its possible dependence on rainfall duration and return period (e.g., Krajewski et al., 2003, www.dx.doi.org/10.1623/hysj.48.2.151.44694; Ciach and Krajewski, 2006, www.dx.doi.org/10.1016/j.advwatres.2005.11.003). Recently, rainfall estimation uncertainty caused by the use of rain gauge measurements (still the most common source of rainfall estimates in this field) was shown to significantly affect the derived ID thresholds causing systematic bias (Nikolopoulos et al., 2014, www.dx.doi.org/10.1016/j.geomorph.2014.06.015). This systematic bias is caused by (i) systematic rainfall patterns observed around the triggering locations and (ii) the use of log-transformations within the derivation of the ID (Marra et al., 2016, www.dx.doi.org/10.1016/j.jhydrol.2015.10.010). At least for durations 2 days, these rainfall patterns were observed to be related to the return period of the triggering rainfall (Destro et al., 2017, www.dx.doi.org/10.1016/j.geomorph.2016.11.019). Consequently, the 'slope' of the ID threshold is affected by rain gauge sampling, and this potentially undermines the comparison between the slope of ID thresholds and IDF curves reported in the manuscript. In particular, I think this aspect should be discussed when the authors say [line 157 and following]: "On the other hand, for longer precipitation durations, ID thresholds have smaller slopes than IDF curves. This means that landslide initiation on the right side of the graph (lower precipitation intensity with longer duration) would occur with rapidly increasing return periods of precipitation events". In fact, the observed pattern could be caused/emphasized by the sampling issues discussed by Marra et al., (2016) and Destro et al. (2017).

To conclude, IDF curves are expected to vary within the examined region (generally a regional, if not global, scale); it is thus unclear to me how the idealized IDF curves in Fig. 3 have been drawn. The 'slope' of the curves (i.e. the dependence of I with D) at the regional scale may change so that the curves should be better represented as a shaded area – such as done for the ID thresholds.

This was a technical comment on an introductory aspect of the study; this being said, I repeat my compliments to the authors for the manuscript and the new proposed perspective.

With kind regards, Francesco Marra

Dear Francesco Marra

Thank you very much for you excellent comment. We strongly focus on the hydrology whereas you bring up the point of the effect rain patterns and rain measurements (rain gauge based precipitation observation, spatial organisation of rain and associated uncertainty) that so far we on purpose have left out of the article. We tried to keep the article brief as is requested for an "invited commentary". Our focus is that only using precipitation data for landslide hazard assessment is neglecting the importance of hydrological processes in landslide initiation. Hereto, we make a quite extensive 'problem' analysis showing the currently used ID thresholds have limited physical meaning, at the best they are statistically interesting to use. However, you are of course fully right that precipitation estimates and uncertainty can also be responsible for (part of) the observed low slopes of the ID thresholds. So, in hindsight we agree this is a too important aspect not to address, so we will add a short discussion on the effect of precipitation measurement uncertainty as depicted in your comment.

Your second point is about the (slope of the) IDF curve that we published in Figure 3. Yes, this is a somewhat arbitrary but representative, set of IDF curves (that is, the chosen slope is not far from those of the examples of IDF curves of Fig. 1, which refer to very different locations around the world). Like we write in the caption "Schematic" and in our opinion useful for the argumentation. It is however a good suggestion to show, also graphically, in Figure 3, that the IDF are schematic, so we will adapt the figure and explain it in the text as well.

Reply to Referee # 4; *B. Mirus,* bbmirus@usgs.gov

We thank Ben Mirus for this pro-active, stimulating and detailed review of our discussion paper. Below we address and reply to the comments and questions. In Italic typesetting the original review is given, and in roman typesetting our replies.

Thom Bogaard and Roberto Greco

The authors present a much needed discussion about some systematic problems with precipitation intensity-duration (ID) threshold approaches for predicting shallow landslides.In particular, they point out an unfortunate lack of reasonable constraints on the max/min duration of rainfall events, and also discuss how these unbounded events can affect the average intensity and predictive capabilities. Both issues are largely ignored in many studies focused on developing and testing ID thresholds, so it's a worthy discussion about some crucial sources of error. The authors also highlight the potential importance of hydrological information in addition to precipitation characteristics, which have not been systematically incorporated into landslide early warning criteria. In my opinion the most innovative contribution presented in the manuscript is the comparison of the rainfall intensity recurrence intervals and ID thresholds for landslide initiation from the literature, along with the contour lines of cumulative storm totals (Fig. 3). This is a new and intuitive way to broadly illustrate their point about some problems with the ID threshold concept.

We agree that Figure 3 is key in our argumentation of the issues linked to precipitation ID thresholds.

However, my primary concerns with the manuscript are twofold:
(1) Limited concrete guidance is provided on how to apply the proposed "cause-trigger" framework, so the potential novelty of the approach seems somewhat overstated.The general concept that both the predisposing factors (e.g. antecedent wetness) anda rainfall triggering event are needed to explain shallow landslide initiation is alreadygenerally accepted and has in fact been implemented in a number of landslide initiationthresholds. For example, two different rainfall thresholds developed for the Seattle area explicitly account for antecedent factors: (a) the recent-antecedent cumulative precipitation threshold compares the 3-day triggering rainfall to the 15-day antecedent rainfall (Chleborad et al, 2008), and (b) the Antecedent Water Index is used with an exponential ID threshold for events between 10min and 10days in duration, thoughstorms are generally less than 24hours (Godt et al., 2006). The authors also cite several other papers (including some of their own published work) that in various ways incorporate antecedent wetness as a measure for the predisposing factors prior to the triggering rainfall event using soil water balance modeling or catchment storage. As such it is not clear how the "cause-trigger" approach is truly novel, but rather seems to be a new term for a topic in need of further exploration. (As an aside, the term"predisposing factors" seems to be a more appropriate term: without context "cause" could be misleading since both predisposing factors and a triggering event are needed to cause a landslide.)

The objectives of this invited perspective are to: (a) critically analyse the precipitation ID thresholds for shallow landslides and debris flows from a hydro-meteorological point of view; and (b) propose a conceptual framework for lumped hydro-meteorological hazard assessment based on the concepts of trigger and cause.
We think we do not claim to be 'truly novel' in our paper. Obviously, as also discussed in the paper at length, we write this perspective-paper standing on shoulders of giants; the many colleagues who have shed light on this topic before us. In our article, we brought it into an overarching conceptual framework under which new research could (should) be done (L340-L350), also because many of the existing examples - like the two you point out - look for the causal relationship between antecedent precipitation and landslide occurrence merely by maximizing some measure of correlation, while our proposed framework invites to look at the most relevant hydrological process for the considered context. Only in the abstract (L27) we did write "novel trigger cause concept". Here we will reformulate in "we propose a trigger-cause conceptual framework"

The framing into 'trigger-cause' and then especially the "cause" is indeed debatable We defined the word "(hydrological) cause" as the predisposing (hydrological) condition of an area under study (L260, L320). We will define our use of the word "cause" earlier in the paper (section 3).

> *(2) The critical issue of data availability is understated.The topic of data availability is largely avoided until the very end of the conclusions, at which point it comes across as an afterthought instead of the main reason the precipitation ID threshold has been employed successfully for decades. Without continuous records of appropriate data during historic landsliding events it is challenging (if not impossible) to develop and test alternatives to the precipitation ID threshold. The reality is that rainfall data is widely available and has been for some time, which has facilitated useful, albeit somewhat flawed tools for assessing landslide potential for a number oflandslide-prone areas. Secondly, rainfall can be predicted in advance with considerable accuracy, so despite some errors in ID thresholds, the trade-off between appropriate lead-time using weather forecasts and threshold accuracy must at least be considered when arguing for alternative threshold approaches. Without a more balanced discussion of data availability it's not entirely clear whether the authors are arguing for better analysis of rainfall data that distinguished between the "causing" rainfall and the "triggering" rainfall or if the authors suggest that rainfall is not an appropriate data source for the "cause" variable and the ID threshold concept has been employed incorrectly for very long and very short duration storms. Although the Invited Perspective highlights both these problems with the ID threshold approach, it remains unclear how the"cause-trigger" approach can be used to solve these problems within the context oflimited data availability.*

Indeed, we decided to first set-up the problem, then the concept and lastly, the "afterthoughts". However, we do mention the issue of data availability several times (e.g. L255, relatively in the beginning of section 3). We do agree that the data availability is the issue (at the moment) and we agree to stress that in our paper also in writing why the traditional ID thresholds are often preferred/used. May we add that once the driving hydrological process is identified, modelling can supplement the lack of data, while this is impossible with rainfall alone?
The fact that rainfall data is widely available is, in our opinion, maybe one of the reasons for misuse of ID thresholds. I our opinion "somewhat flawed" seems an understatement. Could it not be that relying on rainfall records prevented us from digging deeper? Secondly, many papers address the issue of how representative this rainfall information is. By 'uncritically' linking landslide occurrence to the nearest precipitation record, we seem to prefer practical/statistical correlation over causal relation. In this perspective, this is one of the two aims.

> *After addressing these two issues regarding the novelty of the proposed approach and the availability of data for landslide initiation thresholds, the authors' hydrologic perspectives on the precipitation ID approach for landslide prediction will be a valuable contribution and will surely be of considerable interest to readers of NHESS. I suggest a number of general and specific revisions prior to publication, outlined in the sections below. Thank you for your consideration.*
> *Kind regards, Ben Mirus*

> *General Revisions:*
> *(a) Explain how the details of how the "cause-trigger" concept can be distinguished from prior contributions that consider antecedent conditions, or qualify the novelty ofthe proposed approach within the context of such prior work.*
> *(b) Provide more concrete guidance on how the "cause-trigger" framework could beapplied for future studies. In particular, how should researchers constrain the durationof storms to distinguish between "cause/predisposing factors" and "trigger"?*
> *(c) Include a more balanced discussion of what data could reasonably be obtained toinform the "cause" axis for any landslide early-warning threshold relative to the widelyavailable (and forecastable) input of rainfall.*

See above

> *Specific Edits:*
> *L1: I agree with the revision to the title suggested by Roy Sidle and would further suggest removing the second phrase since there no specific hydro-meteorological thresholds are proposed. Thus the suggested title is shorter and more precise: "Hydrological Perspectives on the Precipitation Intensity Duration Thresholds for Shallow Landslide Initiation"*

The format of the title is set by NHESS. We will discuss this with the editor in charge. We agree: Hydrological perspectives etc is to-the-point.

L13: Provide some citation or definitive evidence for the strong, yet disputable statements like "vast majority" and "never" . . . otherwise such pronouncements should be avoided in scientific writing. Furthermore, as is later argued in the manuscript, precipitation does not actually initiate the landslide. Suggest revising to: "Many shallow landslides and debris flows are rainfall induced."
The intention of an invited perspective is also to raise discussion and have sharp edges. We therefore allowed ourselves a writing style which is "less scientific" as generally seen in scientific articles. But as all reviewers bring this point on, we clearly 'overdone' it and we will discard such strong pronouncements.

L22: What does "indistinct" mean? Thresholds are by nature distinct. On the other hand, the errors resulting from application of distinct thresholds over broad areas reflects the heterogeneity of natural systems. In theory, each hillslope/hollow has a unique threshold that must be averaged over some area and some time to create auseful tool for landslide early warning.
Agree. We will delete these words as indeed indistinct threshold is not defined. We will rephrase: "this approach suffers from many false positives …."

L27: Again, calling this a novel conceptual framework is an overstatement. See general comments.
See reply above. Will change in: A conceptual framework

L36: References to support this claim? I was not aware landsliding is the MOST abundant hazard. At the very least it should be qualified as a natural hazard, sincemany health or other hazards could be considered more abundant and/or detriment also socio-economics.

Agree, we will rephrase and add reference for this: "one of the most abundant natural hazards"

L40-43: Unclear from the description provided here how 1) and 3) are different when applied to assessing landslide probability. Perhaps some example citations later in the paragraph could help distinguish between the two.
See also Reviewer #1: We will replace 'probability' with 'possibility'

L59: I recommend also citing Anagnostopoulos et al. 2015 when discussing model complexity.
Thanks for the suggestion.

L74-75: Perhaps include some more recent citations that are less than 10 years old?
You have a point here, we will add more recent references.

L78-79: Yes. Also there is considerable error introduced by the heterogeneity that must be "averaged out" for a PID threshold to be developed over an area of interest.
Yes

L86-88: Are you proposing something that is better than soil moisture? It seems that soil moisture would be better than the other variables suggested (albeit harder to measure),so it is seems counterintuitive to state that these studies are "limited" to measuresof antecedent moisture content.
Correct, "limited" should be removed: "however they were mainly including measures of antecedent soil moisture content, which may not represent the most suitable variable for any kind of landslide"

L88: Never say never. In general it is unwise use this word in scientific writing unless it can be rigorously confirmed, which is almost "never" possible. Suggest revising to"not" or "have not been the subject of"
As replied before we have been somewhat over-enthusiastic in our writing style. We agree to reduce the use of the strong pronouncements.

L106: Here and elsewhere the abbreviation switches from PID to ID. . . either is fine,but use only one consistently throughout.
Right, we will use ID

L149: What is an "absolute" value of a threshold? Do you mean, for example the xandy-intercept values? Revise for clarity.
L152: Again, what is the "absolute" precipitation ID?
We mean unscaled measured precipitation values

L153: At some point in this part of the discussion you should mention the novel use of duration-frequency curves by Fusco et al., 2017. They use this concept to examine temporal and spatial patterns of pressure head states that predispose slopes to recharge and/or landslide initiation. I think it is a nice example of how the "cause" concept you propose could be implemented practically.

Good suggestion. Thanks for pointing us to it. This is indeed a nice example.

L167: Yes. This also leads to questions about how storm durations are defined, particularly since longer storms are more likely to include actual breaks in precipitation where drainage and ET can be more effective in reducing landslide initiation potential.

L181-184: Revise these sentences for greater clarity. It seems like the main point is that if larger cumulative precipitations are needed to initiate landslides at lower intensities we would expect that to be reflected by the larger landslides in the inventory, but the inventory you reference is mostly small landslides, so an alternate interpretation is that the slope drains while it's raining? At least the last sentence is incomplete to communicate the message more clearly.
Sorry for the confusion. The amount of rainfall refers to unit surface area, so it cannot be related to landslide size, but it can be related to landslide depth. Indeed, we are referring to deeper seated landslides. We reformulate.

L186: Technically this (between <10 and >1000) is not a range, it is unbounded. Do you mean between >10 and <1000? Revise for accuracy.
We reformulate: "Many of the reported empirical precipitation thresholds has between 10 and 100 mm of accumulated precipitation. However, also <10 mm and >1000 mm volumes needed for landslide initiation have been reported."

L187: Again, such strong statements like "vast majority" should be supported by a number of independent citations or other evidence. Otherwise avoid this term.
Agree

L200: Not sure this is the most appropriate phrasing. The real utility of ID thresholds is that they are not at all cumbersome to use, but rather involve a very simple and easy interpretation: does the rainfall intensity and duration plot above or below the threshold line? Maybe more important point is that ID thresholds applied locally need a "calibrated range" for storm duration whereas regionally and globally they are misleading since there is too much spatial variability in rainfall and hillslope hydrologic responses for accurate predictions.
Good point, the ID thresholds are maybe too easy to use: We change the word "use" into "interpretation". This makes the interpretation of ID thresholds cumbersome.

L206: Napolitano et al., 2015 is another good reference to include here as they also used seasonal variations in antecedent soil wetness to identify different thresholds for winter vs. summer.
Thanks for the suggestion. We would also add some remark about the fact that, when this kind of thresholds accounting for previous precipitation (seasonal variation) have been proposed, then the considered antecedent duration is usually the mere result of a correlation analysis. By exploiting process knowledge, instead, you directly can look at the most appropriate physical cause-effect relationship (and thus variable).

L218-219: Indeed, this is the concept underlying the recent-antecedent cumulative rainfall threshold of Chleborad et al., 2008, except they use prescribed durations, which have since been statistically tested with receiver operator characteristics (Scheevel et al., 2017)
Thanks for this insight. We add this.

L229-231: The wording of this sentence is confusing. What is the significance of this separation between near-failure events at FS < 1.3? Without reading the papers listed before it's not really clear why this is relevant.
We reformulate: "Hence, it was possible to define non-dimensional variables comparing the meteorological triggers with the infiltration and storage capacity of the soil cover. This non-dimensional hydro-meteorological threshold performed slightly better than the precipitation ID threshold in separating events resulting in factors of safety smaller and greater than 1.3. The choice of referring to a factor of safety larger than 1.0 was dictated by the actually observed soil conditions during the monitoring period"

L247: Not exactly, for such studies soil water content is not usually measured directly. Suggest revising to "proxy" instead of "measure".
Good suggestion. We will use "proxy"

L261: Again, I much prefer the term "predisposing condition" (or factors) over "cause" since both the trigger and predisposing factors essentially conspire to "cause" the increased pore pressures and reduced strength that initiates a landslide.

Although we see your point we prefer the word "cause" (defined as "predisposing (hydrological) condition"), because it is a way to highlight that we are looking for the identification of the causal hydrological process.

L263: Although perhaps beyond the scope of this paper, the "cause-triggers" approach ought to be more universally applicable to landslides, including those triggered by earthquakes or erosion. For example, an earthquake may trigger more landslides in wet vs. dry soils. Similarly, erosion at the toe of a slope may allow it to become more predisposed to failure during a rainfall event. Perhaps worth considering as you explore and develop this framework in the future.
Yes, this is indeed an outlook we have. And yes, your examples are excellent. I think this is a very good suggestion for future work.

L264: What kind of "storage" is this? Do you mean how much water is stored in the catchment (e.g. an effective saturation)? Or do you mean how much water the catchment can store (i.e. storage capacity)?
We mean to say how much water is stored in a catchment compared to it maximum storage capacity. We clarify

L286: How is a catchment itself more or less permeable? Bedrock permeability is clearly a measure you could consider, but very permeable bedrock would result in all groundwater recharge and no runoff (or landslides?). Perhaps more relevant would be the thickness and hydraulic conductivity of the soil, which ultimately are reflected byhow quickly the catchment drains.
Indeed not well formulated, it indeed links to soil hydraulic characteristics. Chitu et al found that two catchment with low infiltration capacity and thus larger direct runoff fraction links to landslides whereas in the other catchment the underlying hydrological process was infiltration and pore pressure build-up. We will reformulate.

L290-291: There are a lot of things mixed up in here, which makes it difficult to relate to the primary topics of the article. First, this is not a shallow landslide, so perhaps this is a bit of a tangential argument for this paper, but it seems that the main point is mobility for a large, slow moving landslide can be related to groundwater levels. That's fine.However, it's not clear groundwater levels would be a good proxy for conditions favouring shallow landslides, particularly since deeper groundwater levels might not respond until after shallow soils on hillslopes have drained and are no longer susceptible to failure.
Yes, you are completely right here, this example is not a shallow landslide, but indeed a deeper-seated, reactivating, coastal bluff type of landslide. This will be explicitly mentioned, and yes, regional GW does not need to be a good proxy for shallow landslides but we also did not claim that either. But we agree this was not clear. Thanks for pointing to this.

L310-314: OK. This makes sense, but can you provide more concrete guidance or framework for evaluating the appropriate "cause" variable? Also, can you provide some balanced perspective of how readily available those types of data may be relative to rainfall? An example Figure 4 might be helpful.
In this perspective we aim to give direction to future research by providing a problem analysis and an overarching framework. Cautiously, we also give some examples, and we later on discuss that the approach will (currently) suffer from data availability. In my own experience, we ran into this problem as well when searching for hydrological information to use. However with more and more data coming available, we argue the community could try to make the step from "statistical/practical' threshold to "causal relationships".

L322-323: This is a somewhat subjective (i.e. value) judgment, which is tangential to the discussion presented here. The perceived or tangible value of predicting even 1/100 landslide events correctly at the expense of many false alarms is an entirely different question. Probably "predictive accuracy" would be more appropriate.
Thanks for the suggestion. We will change into "predictive accuracy"

L340-349: I completely agree with these statements and don't wish to argue with the sentiment, but at the same time the conclusions are rather wordy and not particularly satisfying or informative. Another (shorter) way of saying this is that hydrologic information could improve individual thresholds for shallow landslide initiation, but the type of hydrologic information that is most appropriate will vary based on location and data availability. So then how do we go about addressing this issue?
Indeed the last paragraph is somewhat wordy. One reviewer likes it a lot, the other one a bit less. We will try to use shorter sentences in the last paragraph to increase readability.

L350: The last-minute mention of remote sensing comes across as a bit of an afterthought and it is not clear how this very broad suite of information products can be used to constrain hillslope water balance. Why not soil moisture monitoring?

Indeed is the explicit mentioning of RS unnecessary and an "afterthought". We will replace by mentioning the increasing hydrological data that become available (without specifying).

References Cited:
Anagnostopoulos, G.G., S. Fatichi, P. Burlando, 2015, An advanced process-based distributed model for the investigation of rainfall-induced landslides: The effect of process representation and boundary conditions, Water Resources Research,doi:10.1002/2015WR016909
Chleborad, A.F., R.L. Baum, J.W. Godt, P.S. Powers, 2008, A prototype for forecasting landslides in the Seattle, Washington, Area, Reviews in Engineering Geology, doi:10.1130/2008.4020(06).
Fusco, F., V. Allocca, and P. De Vita, 2017, Hydro-geomorphological modelling of ashfall pyroclastic soils for debris flow initiation and groundwater recharge in Campania(southern Italy), Catena, doi:10.1016/j.catena.2017.07.010.
Godt, J.W., R. L. Baum, A.F. Chleborad, 2006, Rainfall characteristics for shallow landsliding in Seattle, Washington, USA, Earth Surface Processes and Landforms, doi:10.1002/esp.1237.
Napolitano, E., F. Fusco, R. L. Baum, J.W. Godt, P. De Vita. 2015, Effect of antecedent hydrological conditions on rainfall triggering of debris flows in ash-fall pyroclastic mantled slopes of Campania (southern Italy), Landslides, doi:10.1007/s10346-015-0647-5)
Scheevel, C.R., R.L. Baum, B.B. Mirus, J.B. Smith, 2017, Precipitation thresholds for landslide occurrence near Seattle, Mukilteo, and Everett, Washington: U.S. GeologicalSurvey Open-File Report 2017–1039, doi:10.3133/ofr20171039.

1 ~~Invited~~Hydrological perspectives. ~~A hydrological look to~~ on precipitation

2 intensity duration thresholds for landslide initiation: proposing hydro-

3 meteorological thresholds

4

5 Thom.Bogaard[1] and Roberto Greco[2]

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7 [1] Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of

8 Technology, Delft, the Netherlands: t.a.bogaard@tudelft.nl

9

10 [2] Dipartimento di Ingegneria Civile Design Edilizia e Ambiente, Università degli Studi della

11 Campania Luigi Vanvitelli, Aversa (CE), Italy

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12

13 ABSTRACT

14 ~~The vast majority of~~Many shallow landslides and debris flows are precipitation initiated.

15 Therefore, regional landslide hazard assessment is often based on empirically derived

16 precipitation-intensity-duration (~~PID~~ID) thresholds and landslide inventories. Generally, two

17 features of precipitation events are plotted and labelled with (shallow) landslide occurrence or

18 non-occurrence. Hereafter, a separation line or zone is drawn, mostly in logarithmic space.

19 The practical background of ~~PID~~ID is that often only meteorological information is available

20 when analyzing (non-) occurrence of shallow landslides and, at the same time, ~~the conceptual~~

21 ~~idea is~~it could be that precipitation information is a good proxy for both meteorological

22 trigger and hydrological cause. Although applied in many case studies, this approach suffers

23 from ~~indistinct threshold,~~ many false positives as well as limited physical process

24 understanding. Some first steps towards a more hydrologically based approach have been

25 proposed in the past, but these efforts received limited follow-up.

26   Therefore, the objective of our paper is to: a) critically analyse the concept of

27 ~~PID~~precipitation ID thresholds for shallow landslides and debris flows from a hydro-

28 meteorological point of view, and b) propose a ~~novel~~ trigger-cause conceptual framework for

29 lumped regional hydro-meteorological hazard assessment. ~~We will discuss this~~ based on ~~the~~

30 published examples and associated discussion. We discuss the ~~PID~~ID thresholds in relation to

31 return periods of precipitation, soil physics and slope and catchment water balance. With this

32 paper, we aim to contribute to the development of a stronger conceptual model for regional

33 landslide hazard assessment based on physical process understanding and empirical data.

34

1 INTRODUCTION

Landsliding is one of the most abundant ~~hazard~~hazards having massive influence on socio-economic functioning of society. Continuous development in mountain areas increases the exposure of people and properties to the landslide hazards, with precipitation-initiated landslides being the most common. On regional scale, the ~~probability~~possibility of a landslide to occur can be assessed in different ways (Chacon et al, 2006, for review): 1) heuristic, via susceptibility modelling; 2) empirical, lumped-statistical, by relating rainfall information to the observed occurrence (e.g. ~~Cain~~Caine, 1980; Wieczorek and Glade, 2005; Guzzetti et al, 2007; Guzzetti et al, 2008, and reference therein); 3) by spatially distributed physical-deterministic modelling (e.g. Anderson and Lloyd, 1991; Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Borga et al, 1998; Pack et al, 1998; Burton and Bathurst, 1998; Van Beek, 2002~~;~~; Baum et al, 2008~~;).~~).. The heuristic models are mainly used in first assessments of ~~hazard~~(landslide) hazards for regional planning. They are based on readily available static information, like topography, lithology and land use, and then empirically related to historical landslide database (if available). The dynamic predisposing factors, like actual wetness state of the potentially unstable slopes, are not taken into account. The physical process-based models can take into account the dynamics of regional hazard assessment. Most of these models run spatially distributed hydrology – slope stability calculations, with different conceptualization and degrees of complexity for the representation of the physical processes. Typically, the hydrology in these models at catchment scale is not calibrated, or the calibration is restricted to the infiltration process or local groundwater levels (if monitored). In such case, the correctness of the modelling is assessed from how well local displacements or possible failure areas can be predicted. With the increased ~~data~~ availability of data and computational power, a range of these models has been published with increased levels of complexity and applicability (e.g. Frattini et al, 2004; Arnone et al, 2011; von Ruette et al, 2013; Lepore et al, 2013; Anagnostopoulos et al, 2015; Aristizábal et al, 2016; Fan et al, 2016). However, the practical application of such deterministic models, especially in terms of early warning systems, is still limited to specific studies, due to the time effort and data demand.

The precipitation intensity-duration (ID) thresholds for landslide hazard assessment, however, see widespread application in early warning systems, both at local and regional scale. They are based on analysis of the dynamic variables precipitation and landslide occurrence, and require a high quality spatiotemporal landslide inventory and precipitation

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69 time series. Empirical-statistical precipitation thresholds are derived by plotting two

70 characteristics of precipitation, usually intensity (mm/hr or mm/day) and duration (hr or

71 days), that have or have not resulted in landslides in a given area. The separation line, a

72 deterministic threshold or a probabilistic transition zone, between precipitation events

73 inducing landslides and events without hazards, is then drawn visually or by

74 ~~separator~~separation techniques. Due to the spread of information over several orders of

75 magnitude, it is usually plotted in bi-logarithmic scale. Various precipitation ID thresholds for

76 landslide initiation have been derived for different ~~physio geographical~~physiographic settings

77 and at various spatial scales (e.g. Wieczorek and Glade, 2005; Guzzetti et al, 2007; Guzzetti et

78 al, 2008; ~~Wieczorek and Glade, 2005, and references therein~~Peruccacci et al, 2017; Rossi et

79 al, 2017). The global and regional landslide precipitation ID thresholds encompass different

80 types of landslides and a distinct variety of geological and environmental factors, such as

81 lithology, soil depths and land use. The local ID thresholds are restricted more often to

82 relatively homogeneous conditions~~,~~ and mass movement types.

83 However, several shortcomings are frequently recognized and discussed. For example,

84 Berti et al (2012) recognized the problem of looking at landslide occurrence and disregarding

85 non-occurrence when applying the ID threshold. They used a Bayesian probability approach

86 to derive the probabilistic transition explicitly taking into account landslide occurrence and

87 non-occurrence. Also the role of hydrology in landslide initiation, although often

88 acknowledged to be of key importance, is usually not included in the statistical precipitation

89 ID threshold approach. ~~Some~~Several attempts to more explicitly include

90 ~~hydrology~~hydrological predisposing factors have been proposed~~, but however they were~~

91 mainly ~~limited to include~~including measures for antecedent soil moisture content~~.~~ (e.g.

92 Crozier and Eyles, 1980; Glade et al, 2000; Godt et al, 2006; Ponziani et al, 2012) or by

93 splitting data sets in physiographic units like lithology, soil type, land use or season (e.g. Sidle

94 and Ochiai, 2006; Baum and Godt, 2010; Napolitano et al 2016; Peruccacci et al, 2017).

95 These approaches improved the predictive accuracy of the ID thresholds. However, to the

96 authors' knowledge, ~~these~~such studies have ~~never~~not been subject to a more thorough analysis

97 of the specific hydrological information needed for reliable local and regional hazard

98 prediction.

99 Therefore, the objectives of this invited perspective are to: (a) critically analyse the

100 precipitation ID thresholds for shallow landslides and debris flows from a hydro-

101 meteorological point of view; and (b) propose a conceptual framework for lumped *hydro-*

102 *meteorological* hazard assessment based on the concepts of trigger and cause. We will frame

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103   in this perspective some published examples and associated discussions, making reference to

104   work ~~made~~ by colleagues who have already explored this avenue. ~~Aim~~The aim of this paper is

105   to contribute to the development of a stronger conceptual model for regional landslide hazard

106   assessment based on physical process understanding ~~and~~. not only on empirical data.

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110   2 HYDROMETEOROLOGICAL ANALYSIS OF ID THRESHOLDS

111

112   COMPARING ID THRESHOLDS WITH IDF CURVES

113

114   Both precipitation intensity-duration thresholds (ID) and precipitation intensity-duration-

115   frequency curves (IDF) are empirical relationships linking the duration of a precipitation

116   event, D, with its average intensity, I=H/D, H being the precipitation depth ~~fallen~~ during the

117   event. IDF curves are routinely used in stormwater <u>and flood</u> management design

118   ~~problems~~<u>and predictions</u>, as they describe the relationship linking duration and mean intensity

119   of precipitation events characterized by the same return period (Chow et al., 1988). Several

120   functional expressions can be used to describe such a relationship (Bernard, 1932; Wenzel,

121   1982; Koutsoyiannis, 1998), most of which can be approximated, especially for durations

122   longer than 1 hr, as a power law:

123                     $$I = A \times D^B \qquad\qquad (1)$$

124

125   with B [-] being the slope of the log-plotted straight line and A [~~mm/hr~~<u>L/T</u>] a measure of the

126   rain intensity of a rain event of unit duration.

127   Equation (1) is also adopted to describe precipitation ID thresholds, the difference

128   being that the IDF curves are isolines of cumulative probability of precipitation events,

129   whereas the ID plots are empirical thresholds for shallow landslides and debris flow

130   occurrence. Figure 1 gives examples of IDF curves with a return period of 10 years from

131   different places around the world. A common feature of the curves is that, regardless of

132   geographic location, B ranges from -0.8 to -0.65 for rain durations longer than ~1 hour, while

133   it levels off to around -0.5 for D ≤ 1 hr for most IDF curves. Note that IDF curves are mostly

134   determined for rain durations up to 24 hrs. In the same graph, the upper envelope of the

135   largest precipitation values ever observed (World Meteorological Organization, 1986), is

136   plotted using the equation proposed by Brutsaert (2005), which has a smaller slope with B
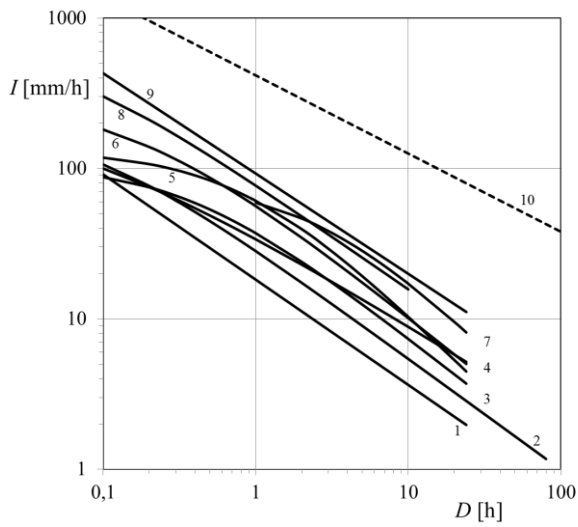
137   equal to -0.52.

138

Figure 1. Examples of intensity-duration-frequency curves for 10 ~~years~~year return period (1-9) and curve of the maximum observed precipitations (10). Location and source: 1 Najran region, Saudi Arabia (Elsebaie, 2012); 2 Uccle, Belgium (Van de Vyver, 2015); 3 Naples, Italy (Rossi and Villani, 1993); 4 Los Angeles, California (Wenzel, 1982); 5 Pelotas, Brazil (Damé et al., 2016); 7 Hamada, Japan (Iida, 2004)); 8 Selangor, Malaysia (Chang et al., 2015); 9 Sylhet, Bangladesh (Rasel and Hossain, 2015); 10 Greatest known observed point rainfall (Brutsaert, 2005).
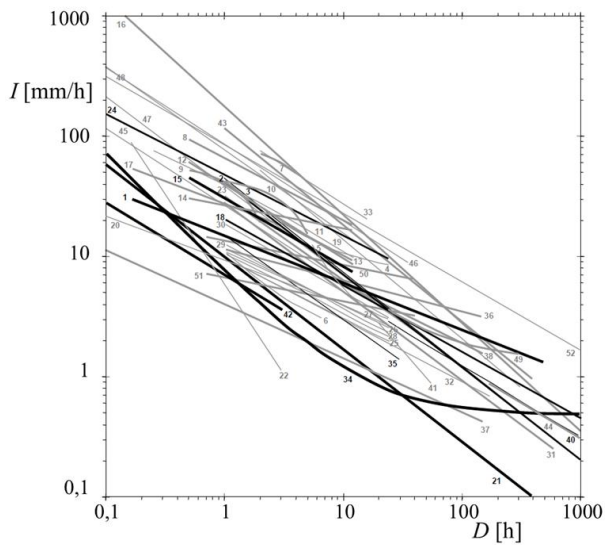
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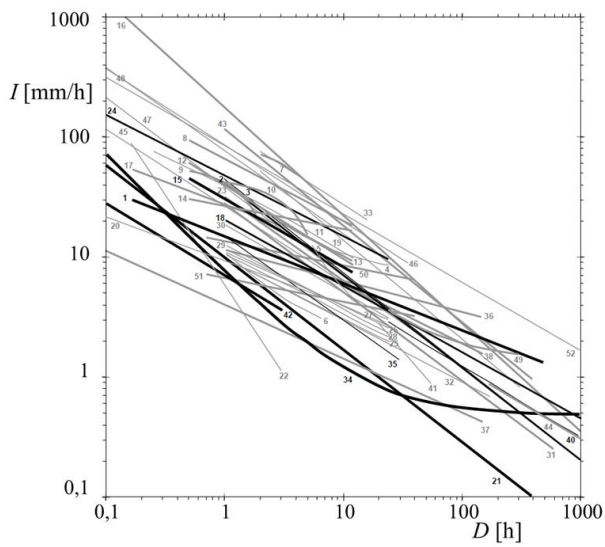
Figure 2. Rainfall intensity-duration (ID) thresholds. Numbers refer to case studies (Guzzetti et al, 2007). Very
thick lines are global thresholds; thick lines are regional thresholds and thin lines are local thresholds. Black
lines show global thresholds and thresholds determined for regions or areas pertaining to the Central to Eastern
European region. Grey lines show thresholds determined for other regions or areas not pertaining to this area.

~~Figure 2 shows~~ More than 90% of the ~~thresholds that come from a global dataset of~~
landslides~~, more than 90% of which~~ in the global data set are shallow landslides and debris
flows (Figure 2, Guzzetti et al, 2007). Note that the ~~thresholds are~~threshold is usually obtained
as lower envelope of the events resulting in landslide initiation, although also other
~~thresholds~~threshold definitions exist (e.g. Staley et al., 2013; Ciavolella et al, 2016; Peres and
Cancelliere, 2016~~, Ciavolella et al, 2016~~). Obviously, ID thresholds differ greatly between
climate and physiographic regions, especially in absolute values. Therefore, scaled
representations have been proposed for the thresholds, such as dividing precipitation intensity
by the mean annual precipitation ~~(Guzzetti et al, 2007),~~ in order to better compare the
thresholds~~.~~ (Guzzetti et al, 2007). However, in our analysis the focus ~~will be~~is on the
~~absolute~~unscaled measured precipitation ID representation, as it is a convenient way to
compare with IDF ~~and for the following discussion~~. The exponent of most of the reported
thresholds for initiation of landslides range between -0.2 and -0.6. ~~By overlaying IDF and ID
curves (Figure 3), for~~For landslides triggered by short precipitation events (D ≤ 1 hr), ~~mostly
debris flows and some shallow landslides,~~ the slopes of ~~ID~~the IDF and ~~IDF~~ID curves
substantially coincide~~.~~ (Figure 3).. On the other hand, for longer precipitation durations, ID
thresholds have smaller slopes than IDF curves. This means that landslide initiation on the

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170 right side of the graph (lower precipitation intensity with longer duration) would occur with

171 rapidly increasing return periods of precipitation events. This is counter-intuitive, as during a

172 long-lasting wet ~~periods~~period landslides are usually more frequent, while many debris-flows

173 triggered by very short and intense storm originate from channel bed mobilization rather than

174 being (new) mass movements. This shows that the method used to derive ID thresholds for

175 landslide initiation based on landslide and precipitation reports leads to troublesome

176 interpretations. ~~Several~~Owing to the high spatial variability of rainfall at scales smaller than 5

177 km (e.g. Krajewski et al., 2003; Ciach and Krajewski, 2006) and the limited density of

178 operational rain gauge networks, the rainfall intensity observed by rain gauges systematically

179 underestimates the actual triggering rainfall intensity at debris flow initiation locations (Marra

180 et al., 2016), especially for short rain duration and high return period (Destro et al., 2017).

181 This issue has been shown to significantly affect the obtained ID thresholds for debris flow

182 initiation (Nikolopoulos et al., 2015; Marra et al., 2017). Additionally, different methods

183 adopted to define the dry period separating rain events have been shown to strongly affect the

184 ID threshold (e.g. Vessia et al., 2014; Melillo et al; 2015). Furthermore, several authors

185 already pointed out that characterizing a storm with its mean intensity, thus neglecting peaks

186 and underestimating actual intensity, affects the estimated probability of landslide occurrence

187 (e.g. D'Odorico et al., 2005; Peres and Cancelliere, 2016), and such an issue is obviously

188 more significant for long storm durations. In fact, for the rainfall depth data used to derive

189 IDF curves, the considered duration is simply a moving interval along the rainfall time series,

190 regardless from the actual beginning and end of a rainfall event. So, the corresponding mean

191 intensity usually refers, especially for short durations, to the heaviest part of a longer rainfall

192 event. Conversely, whatever the criterion adopted for the definition of a rainfall event, in the

193 case of ID threshold curves, the plotted mean intensity refers to the entire rainfall event. Thus,

194 within very long events leading to landslide triggering, there is very likely an intensity peak,

195 which is the "real" landslide trigger, preceded by a period of rain which contributes to

196 predispose the slope to failure. In the (D, I) plane, the point corresponding to the peak would

197 be shifted left- and upwards, compared to the point of the entire event. Given the typical

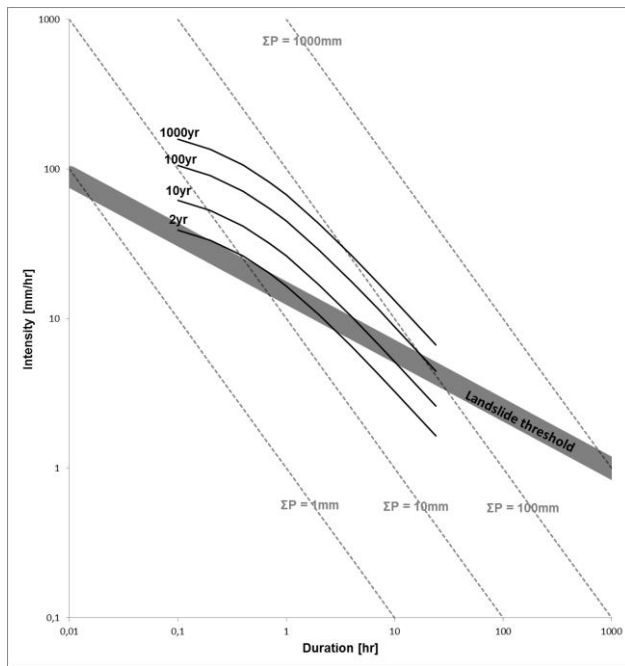198 slopes of IDF and ID threshold curves, this shift likely corresponds to a smaller return period.

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202 Figure 3. Schematic representation of precipitation IDF curves, isolines of accumulated precipitation (ΣP) and
203 ~~generalised~~ ID threshold for shallow landslides and debris flows (~~derived~~simplified from Figure 2).
204

HYDROLOGICAL INTERPRETATION OF ID THRESHOLDS

206

207 The precipitation ID thresholds are *"volumetric"*, i.e. ~~they depict the~~every point depicts a
208 total, cumulative amount of precipitation. In Figure 3 the global summary of ID thresholds for
209 shallow landslides and debris flows (Guzzetti et al, 2007) is schematically represented by the
210 dark grey area, but, added to it, are isolines of accumulated precipitation volume (1, 10, 100
211 and 1000 mm). The first observation is that the regional and global landslide thresholds
212 clearly follow a slope different from isolines, meaning that longer duration landslide
213 triggering thresholds require larger water volume. This is understandable if ~~landslide size~~
214 ~~increases.~~landslides will be deeper seated. However, the database ~~consists for the~~
215 ~~overwhelming majority of~~contains mainly shallow landslides and debris flows (Guzzetti et al,
216 2007). Clearly, this indicates the role of hydrology, or, to be precise, the balance between
217 infiltration, storage and drainage capacity of a slope (Bogaard and Greco, 2015).
218 ~~If we take a closer look at~~ Many of the ~~volumes needed for landslide initiation, we see~~
219 ~~a spread in landslide triggers between the roughly <10 mm and >1000 mm of accumulated~~

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220 ~~precipitation, with the vast majority of the~~ reported empirical precipitation thresholds ~~being~~

221 ~~reported~~ range between 10 and 100 mm of accumulated precipitation. However, also <10 mm

222 and >1000 mm volumes needed for landslide initiation have been reported (e.g. as

223 summarized in Guzzetti et al 2007). Under 'normal' antecedent wetness conditions (that is,

224 soil field capacity), an accumulated precipitation of < 10 mm is generally not capable of

225 triggering a landslide or debris flow. Of course, such an accumulated precipitation volume can

226 trigger a shallow landslide or debris flow in case of nearly saturated antecedent conditions. In

227 this latter case, the reported precipitation event is really the last 'push', the so-called trigger

228 (see next section). On the other hand, precipitation volumes ~~over 1 meter~~> 1000 mm and/or

229 durations of over 100 or even 1000 hours (> 1 month) are difficult to interpret in terms of

230 average precipitation intensities and triggering thresholds for shallow landslides and debris

231 flows. ~~The~~Our point ~~we want to make~~ here is that the current ID concept ~~combines a~~

232 ~~too~~incorporates an unacceptable wide range of information with different types of hazards

233 (debris flows and landslides ~~relate~~related to different hydrological processes), different

234 temporal meteorological information (from minutes to several days). This makes the use of ID

235 thresholds cumbersome or even misleading.

236 Additionally, ID thresholds have been derived by applying physically-based models of

237 infiltration and slope stability evaluation, which ~~allow taking into~~account for soil hydraulic

238 properties, different initial moisture conditions and the boundary conditions through which

239 the slope exchanges water with the surrounding hydrological system (e.g. Terlien, 1998;

240 Rosso et al., 2006; Salciarini et al., 2006; Frattini et al., 2009; Papa et al., 2013; Peres and

241 Cancelliere, 2014). Such physically-based thresholds often do not follow equation 1,

242 generally adopted for ID thresholds. For long precipitation durations, the physically-based ID

243 curves tend to flatten (e.g. Rosso et al., 2006; Salciarini et al., 2006), indicating that landslide

244 initiation thresholds become less sensitive to (average) precipitation intensity, which

245 ~~consequently~~ is ~~not anymore~~counter-intuitive and a ~~good~~poor explanatory variable for

246 landslide initiation.

247 Interestingly, Frattini et al. (2009) followed an inverse approach and obtained

248 estimates of the probability of the precipitation characteristics leading to shallow landslide

249 initiation by also considering ~~also~~ antecedent precipitation. In particular, they showed how the

250 exponent of the IDF curves of their study area (a catchment located on the east side of the

251 Lake Como, in Lombardy, northern Italy) changed from -0.65, for unconditional probability

252 of triggering events, to -0.43, when ~~only events preceded by 300mm fallen~~300 mm of rainfall

253 in the ~~antecedent~~previous four days ~~were considered~~was included, thus approaching the slope

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254   of the observed ID thresholds. Antecedent precipitation can be seen as an indirect means to
255   ~~take into~~ account for the moisture conditions of the soil cover before a triggering event.
256   Therefore, the results of Frattini et al. (2009) can also be interpreted as an indirect
257   confirmation that considering the ~~involved~~integral hydrological processes would improve the
258   performance of landslide initiation thresholds.

259   Greco and Bogaard (2016) give an example of the possible inclusion of slope
260   hydrological processes in the definition of landslide initiation ~~threshold~~thresholds for the case
261   of a slope covered by loose granular volcanoclastic deposits ~~laying upon~~overlying a fractured
262   limestone bedrock. The hydraulic characteristic curves of the volcanic ashes constituting the
263   majority of the soil cover were known (Damiano et al., 2012; Greco et al., 2013), as well as
264   the moisture state of the cover before all 78 observed rainfall events (Comegna et al., 2016).
265   Hence, it was possible to define non-dimensional variables comparing the meteorological
266   triggers with the infiltration and storage capacity of the soil cover~~, showing that a~~. This non-
267   dimensional hydro-meteorological threshold performed slightly better than the precipitation
268   ID threshold in separating events resulting in factors of safety smaller and greater than 1.3.
269   The choice of referring to a factor of safety larger than 1.0 was dictated by the actually
270   observed soil conditions during the monitoring period.
271
272   3   TRIGGER - CAUSE   CONCEPT: PROPOSING   HYDROMETEOROLOGICAL
273   LANDSLIDE THRESHOLDS
274
275   In the strict sense, the precipitation ID threshold is an empirical-statistical threshold drawn to
276   separate failure and non-failure conditions based on observed landslides and precipitation
277   records. Precipitation is described in terms of average intensity and duration. The main
278   assumption is that there is an underlying causal relation between the recorded precipitation
279   event and the landslide occurrence. However, by including durations up to e.g. 1 month, the
280   direct causal relationship is weak and the method implicitly includes the wetness state of a
281   region. This limitation has been recognized from the start of using ID thresholds. For several
282   regional hazard assessment analyses, research groups have extended the ID threshold method
283   by replacing the duration of a precipitation event on the x-axis with an antecedent
284   precipitation index or accumulated rainfall over a certain time interval (e.g. Crozier and Eyles,
285   1980; Glade et al, 2000; Chleoborad et al, 2006; Chleoborad et al, 2008; Scheevel et al, 2017).
286   This, however, leads to limited added information as still only precipitation information is
287   used. On the contrary, by replacing the x-axis with a direct measure or proxy for antecedent

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288 soil water content, physically relevant information is added (e.g. Crozier and Eyles, 1980;
289 Wilson 1989; Wilson and Wieczorek, 1995; Crozier, 1999; Glade, 2000; Chirico et al. 2000;
290 Gabet et al, 2004; Godt et al, 2006; Ponziani et al, 2012). Interestingly, by including a water
291 balance of the potentially unstable soil, a statistical ID threshold evolves conceptually from a
292 plot with one prevalent driver and data source (precipitation) into a plot containing two
293 predominant drivers with two distinct time-scales: the antecedent hydrological 'cause' and the
294 precipitation 'trigger'. Besides soil water balance calculations, different sources of
295 hydrological information can be used to quantify the hydrological 'cause' of landslides. This
296 is a largely unexplored terrainground, partly as data availability can be cumbersome and
297 partly because physically-based, (semi-) distributed modelling was preferred.

298   Concerning the 'trigger'-axis, there is little debate; it is the rainfall intensity
299 responsible for the short-term last push forinitiating a landslide. The time-scale for local and
300 regional assessment of course depends on the local situation, but hourly or daily time-scales
301 are the most common. The 'cause'-axis should represent the predisposing condition of anthe
302 area under study. For hydrologically triggered landslides, it should be related to the
303 antecedent wetness state of the area. However, there are several possible choices of
304 hydrological variables to be plotted along the 'cause'-axis, such as (effective) soil water
305 content, relative catchment storage, and representative regional groundwater level and similar.
306 The choice for the 'trigger' and 'cause' also implies a definition of the time-scale separating
307 trigger from cause, which should be related to the characteristics of the triggered landslide,
308 but is in practice often limited by the (temporal resolution of the) available data.

309   As mentioned before, there are – besides the soil moisture storage calculations
310 previously described above- various examples of hydrological information added to landslide
311 thresholds. Hashino and Murota (1971) published in 1971 an analysis of landslide triggers in a
312 catchment, related to debris production, using measured river discharge data to link itthe
313 landslide triggers to the water balance of the catchment. They identified that the landslides in
314 their study area took place inoccurred during above average antecedent conditions of
315 catchment storage above average. This is one of the earliest reported studies we know of
316 explicitly looking at catchment water balance as an important source of information on the
317 antecedent hydrological condition of an area in relation to landslide occurrence. Reichenbach
318 et al (1998) made a combined flood and landslide hazard analysis of the Tiber river catchment
319 using 72 years of historical daily discharge data from different gauging stations where
320 hydrological parameters were calculated, such as maximum mean daily discharge, specific
321 discharge intensity and flood volume and duration. Probability of occurrence of landslides and

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322   floods was based on the ranking of the events. Combining maximum mean daily discharge
323   and discharge intensity, regional hydrological thresholds for landslide and flood hazard
324   (individually or combined) could be drawn. Chitu et al (2016) followed a somewhat similar
325   approach, analyzing the river discharge in several catchments in the Ialomita Subcarpathians
326   in Romania for landslide events ~~occurred~~ in 2014. The catchments could be characterized as
327   having low/high relative storage. Additionally, a calibrated regional rainfall-runoff model was
328   used for hydrological analysis of landslides in ~~particular~~specific catchments. Detailed analysis
329   of the (modelled) hydrological response indicated that in two catchments with low
330   ~~permeability~~infiltration capacity the direct runoff was strongly related to landslide occurrence,
331   whereas it ~~was~~could be linked to modeled soil infiltration flux in ~~the more permeable~~another
332   catchment. ~~In some cases,~~Extending the above to deep-seated landslides, the connected
333   regional groundwater level could be informative. Bogaard et al (2013) studied the hydro-
334   meteorological triggering threshold of the re-activating coastal Villerville–Cricqueboeuf
335   landslide, Normandy, France. In this situation the hinterland of the coastal cliff consists of a
336   well-defined regional groundwater level. Landslide reactivation was seen to take place only
337   when water level was in the upper, more permeable top layer. The triggering rain event
338   together with surpassing a certain regional groundwater threshold could explain 3 of the 4 re-
339   activations. Note that these groundwater levels were not taken in the active landslide area but
340   several kilometers inland.

341   Recently, further attempts have been made to use river discharge and lumped water
342   storage in a catchment as a proxy for the predisposing conditions for landslides along its
343   slopes. Following Hashino and Murota (1971), the basic idea is that when 'more-than-
344   average' water is stored in the catchment, it is more likely that a rainfall event triggers
345   landslides. The disadvantage of using catchment wide storage is the relatively low spatial
346   resolution, and the difficulty of having (reliable and homogeneous) discharge time series in
347   catchments. Moreover, catchment storage assessment needs information on evaporation which
348   can have significant uncertainties. Of course, such an approach works only if the causes of the
349   predisposing conditions for landslides are somewhat related to catchment scale hydrological
350   processes. Ciavolella et al. (2016) defined a cause-trigger hydro-meteorological threshold in
351   the catchment of river Scoltenna, in Emilia Romagna (Italy), linking catchment storage and
352   event rainfall intensity, and compared its performance with that of a statistical ID
353   precipitation threshold. The two thresholds performed similarly, with the hydro-
354   meteorological thresholds ~~resulting~~being more accurate ~~in the identification of~~for identifying
355   landslides, but giving a somewhat larger number of false positives.

356 ~~The above~~These examples indicate that considering hydrological causes could be
357 useful for a better identification of landslide initiation, but, at the same time, they show that
358 the correct identification of the hydrological processes involved in the establishment of the
359 predisposing conditions for landslides ~~in a considered area~~ is mandatory for choosing the most
360 informative hydrological variable to be plotted along the x-'cause'-axis.

361

362 4 CONCLUDING REMARKS AND OUTLOOK

363

364 The intrinsic ~~limitation~~limitations of precipitation ID thresholds for the identification of
365 landslide initiation conditions has been ~~pointed out long since~~noted for some time. Indeed,
366 such thresholds neglect the role of the hydrological processes occurring along slopes, which
367 ~~lead~~predispose hillslopes to ~~the predisposing conditions for~~ failure (causes~~),~~) and focus
368 predominately on the characteristics of the last rainfall ~~event~~events leading to slope failure
369 (triggers). As a consequence, the predictive ~~value~~accuracy of the ID thresholds is often low,
370 even when they refer to small areas. We argue that the threshold values for rainfall intensity
371 of short and long duration (the far left and right side of the graphs) have limited physical
372 meaning and, consequently, that the use of precipitation ID thresholds can lead to misleading
373 ~~interpretation~~interpretations of initiation conditions, as important antecedent conditions and
374 rainfall intensity variations are not taken into account. For this reason, we here advocate to be
375 very careful in uncritically using the precipitation ID thresholds as kind of regional
376 characteristic of (shallow) landslide occurrence.

377 Equally, for this and several other reasons, many colleagues advocate the use of
378 spatially-distributed physically- based models for assessing landslide probability. The obvious
379 downside is that large data input and a well calibrated model are required. However, it is fair
380 to say, data are becoming more and more available and even precipitation predictions are
381 improving rapidly, especially with short lead-time. The use of high quality rainfall prediction
382 with very short lead time (e.g. 3 hours) requires efficient numerical models combined with
383 high computational power, especially if predictions are used for early warning purposes. This,
384 in practice, is still easier said than done. Therefore, we believe, that lumped, empirical (or
385 semi-empirical) thresholds will continue having a practical value, which still justifies
386 scientific attention.

387 We propose to use the cause-trigger concept for defining regional landslide initiation
388 thresholds. This, we agree, is challenging, but, in our opinion, not impossible. First of all, it is
389 needed to define the characteristic time-scale separating the (dynamic) long-term predisposing

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390 hydrological cause from the short 'final' landslide hazard triggering. This obviously depends
391 on the landslide type and physiographic characteristics. Looking at the discussed examples, it
392 becomes clear that the choice of the most informative hydrological variable to be used as a
393 proxy for landslide predisposing conditions strictly depends on site-specific geomorphological
394 characteristics, and that accurate analysis of the boundaries through which the potentially
395 unstable area exchanges water with the surrounding hydrological systems is mandatory. In
396 other words, for the assessment of landslide predisposing conditions, the water balance of the
397 slope should be assessed, but getting the information about the ~~involved~~inherent hydrological
398 processes (e.g. evaporation, runoff, groundwater recharge) at the required spatial-temporal
399 resolution is often ~~still a challenge, although remote sensing could help increasing the~~
400 ~~reliability of catchment water storage estimates~~a challenge and could require some kind of
401 calculations or modelling. However, rapidly more and higher resolution hydrological data
402 become available which can be used in assessing the hydrological predisposing condition.

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413 REFERENCES
414
415 .
416 Anagnostopoulos, G.G., Fatichi, S., Burlando, P.: An advanced process-based distributed
417   model for the investigation of rainfall-induced landslides: The effect of process
418   representation   and   boundary   conditions,   Water   Resources
419   Research,doi:10.1002/2015WR016909, 2015
420 Anderson, M.G. and Lloyd, D.M.: Using a combined hydrology stability model to develop cut
421   slope design charts. Proceedings of the Institution of Civil Engineers, 91, 705–718,
422   https://doi.org/10.1680/iicep.1991.17486, 1991.
423 Aristizábal, E., Ignacio Vélez, J. Martínez, H.E. and Jaboyedoff, M.: SHIA_Landslide: a
424   distributed conceptual and physically based model to forecast the temporal and spatial
425   occurrence of shallow landslides triggered by rainfall in tropical and mountainous basins.
426   Landslides 13, 3, 497, 2016.
427 Anderson, M.G. and Lloyd, D.M.: Using a combined hydrology stability model to develop cut
428   slope design charts. Proceedings of the Institution of Civil Engineers, 91, 705–718,
429   https://doi.org/10.1680/iicep.1991.17486, 1991.
430 Arnone, E., Noto, L.V., Lepore, C., and Bras, R.L.: Physically-based and distributed approach
431   to analyze rainfall-triggered landslides at watershed scale, Geomorphology, 133, 121–131,
432   2011.
433 Baum, R.L., Savage, W.Z., and Godt, J.W.: TRIGRS—A FORTRAN program for transient
434   rainfall infiltration and grid—based regional slope—stability analysis, version 2.0. US
435   Geological   Survey   Open—File   Rep   2008—1159.
436   http://pubs.er.usgs.gov/publication/ofr20081159, 2008
437 Bernard M.M.: Formulas for rainfall intensities of long duration, A,.Soc.Civil Eng.,Trans.
438   Vol.96,p.592, 1932.
439 Berti, M., Martina, M.L.V., Franceschini, S., Pignone, S., Simoni, A. and Pizziolo, M.:
440   Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach, J.
441   Geophys.Res., 117, F04006, doi:10.1029/2012JF002367, 2012.
442 Bogaard, T.A., Laxmi Devi Maharjan, Maquaire, O., Lissak, C., and Malet, J.-P.:
443   Identification of hydro-meteorological triggers for Villerville coastal landslide. pp. 141-
444   145, Vol.5 of Landslide Science and Practice, C. Margottini, P. Canuti, K. Sassa (Eds),
445   ISBN: 978-3-642-31309-7 (Print) 978-3-642-31310-3 (Online), Springer, Berlin
446   Proceedings of the Second World Landslide Forum, 3-7 October 2011, Rome, Italy, 2013.
447 Bogaard, T.A. and Greco R.: Landslide hydrology: from hydrology to pore pressure. WIREs
448   Water 2015. doi: 10.1002/wat2.1126, 2015.
449 Borga, M., Dalla Fontana, G., Da Ros, and Machi, D.L.: Shallow landslide hazard assessment
450   using a physically based model and digital elevation data. Env. Geol. 35: 81.
451   doi:10.1007/s002540050295. 1998.
452 Brutsaert, W.: Hydrology—An introduction, Cambridge Univ. Press, Cambridge, UK. 2005.
453 Burton, A. and Bathurst, J.: Physically based modelling of shallow landslide sediment yield at
454   a catchment scale. Environmental Geology, 35: 89. doi:10.1007/s002540050296, 1998.
455 Caine, N: The rainfall intensity: duration control of shallow landslides and debris flows.
456   Geogr Ann A 62:23–27, 1980.

Chacón, J, Irigaray, C, Fernández, T., and El Hamdouni, R.: Engineering geology maps: landslides and geographical information systems, Bull Eng Geol Environ 65:341–411, DOI 10.1007/s10064-006-0064-z, 2006.

Chang, K.B., Lai, S.H., and Othman, F.: Comparison of Annual Maximum and Partial Duration Series for Derivation of Rainfall Intensity-Duration-Frequency Relationships in Peninsular Malaysia. Journal of Hydrologic Engineering 21(1):05015013 , DOI: 10.1061/(ASCE)HE.1943-5584.0001262, 2015.

Chirico, G.B., Claps, P., Rossi, F., and Villani, P.: Hydrological condition leading to debris-flow initiation in the Campanian volcanoclastic soils. In: P. Claps and F. Siccardi (eds). Mediterranean Storms: proceedings of the EGS Plinius conference, Maratea, Italy. Oct 1999. Pp.473-484. Editoriale Bios, Cosenza, Italy, 2000.

Chitu, Z., Bogaard, T.A., Busuioc, A., Burcea, S., Sandric, I., and Adler, M-J.: Identifying hydrological pre-conditions and rainfall triggers of slope failures at catchment scale for 2014 storm events in the Ialomita Subcarpathians, Romania. Landslides. DOI 10.1007/s10346-016-0740-4, 2016.

Chleborad, A.F., Baum, R.L., Godt, J.W.: Rainfall Thresholds for Forecasting Landslides in the Seattle, Washington, Area—Exceedance and Probability. Geological Survey Open-File Report 2006–1064, http://pubs.er.usgs.gov/publication/ofr20061064, 2006

Chleborad, A.F., Baum, R.L., Godt, J.W., Powers, P.S.: A prototype for forecasting landslides in the Seattle, Washington, Area, Reviews in Engineering Geology, doi:10.1130/2008.4020(06), 2008.

Chow V.T, Maidment D.R. and Mays L.W.: Applied Hydrology. McGraw-Hill Publishing Company. ISBN: 0071001743, 1988.

Ciavolella, M., Bogaard, T.A., Gargano, R., and Greco, R.: Is there ~~Predictive Power in Hydrological Catchment Information for Regional Landslide Hazard Assessment?~~predictive power in hydrological catchment information for regional landslide hazard assessment? Procedia Earth and Planetary Science 16, 195-203. http://dx.doi.org/10.1016/j.proeps.2016.10.021, 2016.

Ciach, G.J., and Krajewski, W.F.: Analysis and modeling of spatial correlation structure in small-scale rainfall in Central Oklahoma, Advances in Water Resources, 29: 1450–1463, https://doi.org/10.1016/j.advwatres.2005.11.003, 2006.

Comegna, L., Damiano, E., Greco, R., Guida, A., Olivares, L., and Picarelli, L.: Field hydrological monitoring of a sloping shallow pyroclastic deposit. Canadian Geotechnical Journal, 53(7): 1125-1137, https://doi.org/10.1139/cgj-2015-0344, 2016.

Crozier, M. J. and Eyles, R. J.: Assessing the probability of rapid mass movement, Proceedings of the Third Australia-New Zealand Conference on Geomechanics, New Zealand Institute of Engineers, Proceedings of Technical Groups, 6, 47-53, 1980.

Crozier, M.J.: Prediction of rainfall-triggered landslides: a test of the antecedent water status model. ESPL, 24, 825-833, 1999.

~~Chitu, Z., Bogaard, T.A., Busuioc, A., Burcea, S., Sandric, I., and Adler, M-J.: Identifying hydrological pre-conditions and rainfall triggers of slope failures at catchment scale for 2014 storm events in the Ialomita Subcarpathians, Romania. Landslides. DOI 10.1007/s10346-016-0740-4, 2016.~~

18

500 D'Odorico, P., Fagherazzi, S., and Rigon, R.: Potential for landsliding: Dependence on
501 hyetograph characteristics, J. Geophys. Res., 110, F01007, doi:10.1029/2004JF000127,
502 2005.

503 Damé, de R.C.F., Teixeira-Gandra, C.F.A., Guedes, H. A. S., da Silva, G.M. and da Silveira,
504 S.C.R.: Intensity-Duration-Frequency relationships: stochastic modeling and
505 disaggregation of daily rainfall in the lagoa Mirim watershed, Rio Grande do Sul, Brazil.
506 Engenharia Agrícola, 36(3), 492-502. https://dx.doi.org/10.1590/1809-4430-
507 Eng.Agric.v36n3p492-502/2016, 2016.

508 Damiano, E., Olivares, L., and Picarelli, L.: Steep-slope monitoring in unsaturated pyroclastic
509 soils. Eng. Geol. 137-138, 1-12, 2012.

510 Destro, E., Marra F., Nikolopoulos, E.I., Zoccatelli, D. Creutin, J.D., and Borga, M.: Spatial
511 estimation of debris flows-triggering rainfall and its dependence on rainfall return period.
512 Geomorphology, 278: 269-279, https://dx.doi.org/10.1016/j.geomorph.2016.11.019, 2017.

513 Elsebaie, I.H.: Developing rainfall intensity–duration–frequency relationship for two regions
514 in Saudi Arabia. Journal of King Saud University-Engineering Sciences 24.2: 131-140.
515 2012.

516 Fan, L., Lehmann, P., and Or, D.: Effects of Soil Spatial Variability at the Hillslope and
517 Catchment Scales on Characteristics of Rainfall-Induced Landslides, Water Resources
518 Research, 52,doi:10.1002/2015WR017758, 2016.

519 Frattini, P., Crosta, G.B., Fusi, N., and Dal Negro, P.: Shallow landslides in pyroclastic soils:
520 a distributed modelling approach for hazard assessment. Engineering Geology 73(3–4):
521 277–295, 2004.

522 Frattini, P., Crosta, G. and Sosio, R..:. Approaches for defining thresholds and return periods
523 for rainfall-triggered shallow landslides. Hydrol. Process. 23, 1444–1460 (2009), DOI:
524 10.1002/hyp.7269, 2009.

525 Gabet, E.J., Burbank, D.W., Putkonen, J.K., Pratt-Sitaula, .B.A.,and Ojha, T.: Rainfall
526 thresholds for landsliding in the Himalayas of Nepal. Geomorphology 63, 131-143.
527 DOI:10.1016/j.geomorph.2004.03.011, 2004.

528 Glade, T.: Modelling landslide-triggering rainfalls in different regions in New Zealand - the
529 soil water status model. Zeitschrift für Geomorphologie 122:63-84, 2000.

530 Glade, T., Crozier, M., Smith, P.: Applying probability determination to refine landslide-
531 triggering rainfall thresholds using an empirical " antecedent daily rainfall model". Pure
532 and Applied Geophysics. 157: 1059-1079, 2000.

533 Godt, J.W., Baum, R.L., and Chleborad, A.F.: Rainfall characteristics for shallow landsliding
534 in Seattle, Washington, USA. Earth Surface Processes and Landforms 31, 97-110.
535 DOI:10.1002/esp.1237, 2006.

536 Greco, R., and Bogaard, T.A.: The influence of non-linear hydraulic behavior of slope soil
537 covers on rainfall intensity-duration thresholds. Landslides and Engineered Slopes.
538 Experience, Theory and Practice – Aversa et al. (Eds). © 2016 Associazione Geotecnica
539 Italiana, Rome, Italy, ISBN 978-1-138-02988-0, 2016.

540 Greco, R., Comegna, L., Damiano, E., Guida, A., Olivares, L., and Picarelli, L.: Hydrological
541 modelling of a slope covered with shallow pyroclastic deposits from field monitoring data.
542 Hydrology and Earth System Sciences 17:4001-4013, 2013.

543 Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C.P.: Rainfall thresholds for the initiation of
544   landslides in central and southern Europe, Meteorol. Atmos. Phys., 98, 239–267, 2007.
545 Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C.P.: The rainfall intensity-duration control
546   of shallow landslides and debris flows: an update, Landslides, 5, 3–17, 2008.
547 Hashino, M.. and Murota, A.: A stochastic study on debris production in the form of landslide
548   due to heavy rainfall. Proceedings of the Japan Society of Civil Engineers. No. 188 P 33-
549   43. http://doi.org/10.2208/jscej1969.1971.188_33, 1971.
550 Iida, T.: Theoretical research on the relationship between return period of rainfall and shallow
551   landslides. Hydrol. Process. 18, 739–756. DOI: 10.1002/hyp.1264, 2004.
552 Jakob, M., Holm, K., Lange, O., and Schwab, J.W.: Hydrometeorological thresholds for
553   landslide initiation and forest operation shutdowns on the north coast of British Columbia.
554   Landslides. DOI: 10.1007/s10346-006-0044-1, 2006.
555 Koutsoyiannis, D., Demosthenes, K. and Manetas, A.: A Mathematical Framework for
556   Studying the Rainfall Intensity-Duration-Frequency Relationships. Journal of Hydrology,
557   303, 215-230, 1998.
558 Krajewski W.F., Ciach G.J., and Habib, E.: An analysis of small-scale rainfall variability in
559   different climatic regimes, Hydrological Sciences Journal, 48(2): 151-162,
560   https://dx.doi.org/10.1623/hysj.48.2.151.44694, 2003.
561 Lepore, C., Arnone, E., Noto, L.V., Sivandran, G., and Bras, R.L.: Physically based modeling
562   of rainfall-triggered landslides: a case study in the Luquillo forest, Puerto Rico., Hydrol.
563   Earth Syst. Sci., 17, 3371–3387, https://dx.doi.org/10.5194/hess-17-3371-2013, 2013.
564 Marra, F., Nikolopoulos, E.I., Creutin, J.D., and Borga, M.: Space–time organization of
565   debris flows-triggering rainfall and its effect on the identification of the rainfall threshold
566   relationship, Journal of Hydrology, 541: 246–255,
567   https://dx.doi.org/10.1016/j.jhydrol.2015.10.010, 2016.
568 Marra, F., Destro, E., Nikolopoulos, E.I., Zoccatelli, D., Creutin, J.D., Guzzetti, F., and
569   Borga, M.: Impact of rainfall spatial aggregation on the identification of debris flow
570   occurrence thresholds, Hydrol. Earth Syst. Sci., 21: 4525–4532,
571   https://doi.org/10.5194/hess-21-4525-2017, 2017.
572 Melillo, M., Brunetti, M. T., Peruccacci, S., Gariano, S. L. and Guzzetti, F.: An algorithmfor
573   the objective reconstruction of rainfall events responsible for landslides, Landslides, 12(2),
574   311–320, doi:10.1007/s10346-014-0471-3, 2015.
575 Montgomery, D.R. and Dietrich, W.E.: A physically based modelfor the topographic control
576   on shallow landsliding, Water Resour. Res., 30, 1153–1171, 1994.
577 Nikolopoulos, E.I., Borga, M., Creutin, J.D., and Marra, F.: Estimation of debris flow
578   triggering rainfall: Influence of rain gauge density and interpolation methods,
579   Geomorphology 243: 40–50, https://dx.doi.org/10.1016/j.geomorph.2015.04.028, 2015.
580 Pack, R.T., Tarboton, D.G., and Goodwin, C.N.: The SINMAP approach to terrain stability
581   mapping. 8th congress of the international association of engineering geology, Vancouver,
582   British Columbia, Canada. Vol. 21. 1998.
583 Papa, M.N., Medina, V., Ciervo, F., and Bateman, A.: Derivation of critical rainfall thresholds
584   for shallow landslides as a tool for debris flow early warning systems, Hydrol. Earth Syst.
585   Sci., 17, 4095-4107, doi:10.5194/hess-17-4095-2013, 2013.

586 Peres, D.J. and Cancelliere, A.: Derivation and evaluation of landslide-triggering thresholds
587   by a Monte Carlo approach, Hydrol. Earth Syst. Sci.2014, 18, 4913-4931,
588   doi:10.5194/hess-18-4913-2014, 2014.
589 Peres, D.J. and Cancelliere, A.: Estimating return period of landslide triggering by Monte
590   Carlo simulation. J. Hydrol., http://dx.doi.org/10.1016/j.jhydrol.2016.03.036, 2016.
591 Ponziani, F., Pandolfo, C., Stelluti, M., Berni, N., Brocca, L., and Moramarco, T.: Assessment
592   of rainfall thresholds and soil moisture modelling for operational hydrogeological risk
593   prevention in Umbria region (central Italy). Landslides. 9:229-237. DOI 10.1007/s10346-
594   011-0287-3, 2012.
595 Rasel, M.M., and Hossain, S.M.:. Development of rainfall intensity duration frequency (R-
596   IDF) equations and curves for seven divisions in Bangladesh." International Journal of
597   Scientific & Engineering Research 6.5, 96-101, 2015.
598 Reichenbach, P., Cardinali, M., De Vita, P., and Guzzetti, F.: Regional hydrological
599   thresholds for landslides and floods in the Tiber River Basin (central Italy). Environmental
600   Geology 35 (2–3) 1998.
601 Rossi, F., and Villani, P.: Regional methods for flood estimation. Coping with floods, edited
602   by: Rossi G., Harmancioglu, N., and Yevjevich, V., NATO-ASI Series, Kluwer Academic
603   Publ , 135-169, 1992.
604 Rossi, M., Luciani, S., Valigi, D., Kirschbaum, D., Brunetti, M.T., Peruccacci, S., Guzzetti,
605   F.: Statistical approaches for the definition of landslide rainfall thresholds and their
606   uncertainty using rain gauge and satellite data. Geomorphology 285, 16-27,
607   https://doi.org/10.1016/j.geomorph.2017.02.001., 2017.
608 Rosso, R., Rulli, M.C., and Vannucchi, G.: A physically based model for the hydrologic
609   control on shallow landsliding. Water Resources Research 42. 6, 2006.
610 Salciarini, D., Godt, J.W., Savage, W.Z., Conversini, P., Baum, R.L., and Michael, J.A.:
611   Modeling regional initiation of rainfall-induced shallow landslides in the eastern Umbria
612   Region of central Italy. Landslides, 3(3), 181-194, 2006.
613 Scheevel, C.R., Baum, R.L., Mirus, B.B., Smith, J.B.: Precipitation thresholds for landslide
614   occurrence near Seattle, Mukilteo, and Everett, Washington: U.S. Geological Survey
615   Open-File Report 2017–1039, doi:10.3133/ofr20171039, 2017.
616 Sidle, R.C., Ochiai, H.: Landslides: Processes, Prediction, and Land Use. Am. Geophys.
617   Union Water Resour. Monogr. Vol. 18. American Geophysical Union, Washington, D.C.,
618   p. 312. 2006.
619 Staley, D.M., Kean, J.W. Cannon, S.H., Schmidt, K.M., and Laber, J.L.: Objective definition
620   of rainfall intensity–duration thresholds for the initiation of post-fire debris flows in
621   southern California, Landslides (2013) 10:547–562 DOI 10.1007/s10346-012-0341-9,
622   2013.
623 Terlien, M.T.J.: The determination of statistical and deterministic hydrological landslide-
624   triggering thresholds. Environmental Geology, 35(2-3):124-130, 1998.
625 Van Beek, L.P.H.: Assessment of the influence of changes in climate and land use on
626   landslide activity in a Mediterranean environment. Doctoral Thesis, Netherlands
627   Geographical Studies 294, Utrecht, 2002.
628 Van de Vyver, H.: Bayesian estimation of rainfall intensity–duration–frequency relationships.
629   J. Hydrol. 529, 1451–1463, 2015.

630 Vessia, G., Parise, M., Brunetti, M. T., Peruccacci, S., Rossi, M., Vennari, C. and Guzzetti, F.:
631 Automated reconstruction of rainfall events responsible for shallow landslides, Nat.
632 Hazards Earth Syst. Sci., 14(9), 2399–2408, doi:10.5194/nhess-14-2399-2014, 2014.
633 von Ruette, J., Lehmann, P., and Or, D.: Rainfall-triggered shallow landslides at catchment
634 scale: Threshold mechanics-based modeling for abruptness and localization, Water Resour.
635 Res., 49, 6266–6285, doi:10.1002/wrcr.20418, 2013.
636 Wenzel, H.G.: Rainfall for Urban Stormwater Design. In Urban Storm Water Hydrology.
637 Kibler, D.F. (editor). Washington, DC: Water Resources Monograph, 7, AGU, 1982.
638 Wilson, R.C.: Rainstorms, pore pressure and debris flows: a theoretical framework. In: PM
639 Sadler and DM Morton (eds). Landslides in semi-arid environment (pub.no.2,pp.101-117)
640 Inland Geological Society, Riverside, USA, 1989.
641 Wilson, R.C. and Wieczorek, G.F.: Rainfall thresholds for the initiation of debris flows at La
642 Honda, California. Environmental and Engineering Geoscience, 1(1), 11-27, 1995.
643 Wieczorek, G.F. and Glade, T.: Climatic factors influencing occurrence of debris flows. In:
644 Jakob M, Hungr O (eds) Debris-flow hazards and related phenomena. Praxis and Springer,
645 Berlin Heidelberg New York, pp 325–362, 2005.
646 Wu, W. and Sidle, R.C.: A distributed slope stability model for steep forested basins, Water
647 Resour. Res., 31, 2097–2110, 1995.
648