# Hydrological perspectives on precipitation intensity duration thresholds for landslide initiation: proposing hydro-meteorological thresholds

Thom Bogaard[1] and Roberto Greco[2]

[1] Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands: t.a.bogaard@tudelft.nl

[2] Dipartimento di Ingegneria Civile Design Edilizia e Ambiente, Università degli Studi della Campania Luigi Vanvitelli, Aversa (CE), Italy

## ABSTRACT

Many shallow landslides and debris flows are precipitation initiated. Therefore, regional landslide hazard assessment is often based on empirically derived precipitation-intensity-duration (ID) thresholds and landslide inventories. Generally, two features of precipitation events are plotted and labelled with (shallow) landslide occurrence or non-occurrence. Hereafter, a separation line or zone is drawn, mostly in logarithmic space. The practical background of ID is that often only meteorological information is available when analyzing (non-) occurrence of shallow landslides and, at the same time, it could be that precipitation information is a good proxy for both meteorological trigger and hydrological cause. Although applied in many case studies, this approach suffers from many false positives as well as limited physical process understanding. Some first steps towards a more hydrologically based approach have been proposed in the past, but these efforts received limited follow-up.

Therefore, the objective of our paper is to: a) critically analyse the concept of precipitation ID thresholds for shallow landslides and debris flows from a hydro-meteorological point of view, and b) propose a trigger-cause conceptual framework for lumped regional hydro-meteorological hazard assessment based on published examples and associated discussion. We discuss the ID thresholds in relation to return periods of precipitation, soil physics and slope and catchment water balance. With this paper, we aim to contribute to the development of a stronger conceptual model for regional landslide hazard assessment based on physical process understanding and empirical data.

## 1 INTRODUCTION

Landsliding is one of the most abundant 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 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. 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 (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 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 time series. Empirical-statistical precipitation thresholds are derived by plotting two characteristics of precipitation, usually intensity (mm/hr or mm/day) and duration (hr or days), that have or have not resulted in landslides in a given area. The separation line, a deterministic threshold or a probabilistic transition zone, between precipitation events inducing landslides and events without hazards, is then drawn visually or by separation techniques. Due to the spread of information over several orders of magnitude, it is usually plotted in bi-logarithmic scale. Various precipitation ID thresholds for landslide initiation have been derived for different physiographic settings and at various spatial scales (e.g. Wieczorek and Glade, 2005; Guzzetti et al, 2007; Guzzetti et al, 2008; Peruccacci et al, 2017; Rossi et al, 2017). The global and regional landslide precipitation ID thresholds encompass different types of landslides and a distinct variety of geological and environmental factors, such as lithology, soil depths and land use. The local ID thresholds are restricted more often to relatively homogeneous conditions and mass movement types.

However, several shortcomings are frequently recognized and discussed. For example, Berti et al (2012) recognized the problem of looking at landslide occurrence and disregarding non-occurrence when applying the ID threshold. They used a Bayesian probability approach to derive the probabilistic transition explicitly taking into account landslide occurrence and non-occurrence. Also the role of hydrology in landslide initiation, although often acknowledged to be of key importance, is usually not included in the statistical precipitation ID threshold approach. Several attempts to more explicitly include hydrological predisposing factors have been proposed mainly including measures for antecedent soil moisture content (e.g. Crozier and Eyles, 1980; Glade et al, 2000; Godt et al, 2006; Ponziani et al, 2012) or by splitting data sets in physiographic units like lithology, soil type, land use or season (e.g. Sidle and Ochiai, 2006; Baum and Godt, 2010; Napolitano et al 2016; Peruccacci et al, 2017). These approaches improved the predictive accuracy of the ID thresholds. However, to the authors' knowledge, such studies have not been subject to a more thorough analysis of the specific hydrological information needed for reliable local and regional hazard prediction.

Therefore, 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 will frame in this perspective some published examples and associated discussions, making reference to work by colleagues who have already explored this avenue. The aim of this paper is to contribute to the development of a stronger conceptual model for regional landslide hazard assessment based on physical process understanding, not only on empirical data.

## 2 HYDROMETEOROLOGICAL ANALYSIS OF ID THRESHOLDS

### COMPARING ID THRESHOLDS WITH IDF CURVES

Both precipitation intensity-duration thresholds (ID) and precipitation intensity-duration-frequency curves (IDF) are empirical relationships linking the duration of a precipitation event, D, with its average intensity, I=H/D, H being the precipitation depth during the event. IDF curves are routinely used in stormwater and flood management design and predictions, as they describe the relationship linking duration and mean intensity of precipitation events characterized by the same return period (Chow et al., 1988). Several functional expressions can be used to describe such a relationship (Bernard, 1932; Wenzel, 1982; Koutsoyiannis, 1998), most of which can be approximated, especially for durations longer than 1 hr, as a power law:

$$I = A \times D^{B} \tag{1}$$

with B [-] being the slope of the log-plotted straight line and A [L/T] a measure of the rain intensity of a rain event of unit duration.

Equation (1) is also adopted to describe precipitation ID thresholds, the difference being that the IDF curves are isolines of cumulative probability of precipitation events, whereas the ID plots are empirical thresholds for shallow landslides and debris flow occurrence. Figure 1 gives examples of IDF curves with a return period of 10 years from different places around the world. A common feature of the curves is that, regardless of geographic location, B ranges from -0.8 to -0.65 for rain durations longer than ~1 hour, while it levels off to around -0.5 for $D \leq 1$ hr for most IDF curves. Note that IDF curves are mostly determined for rain durations up to 24 hrs. In the same graph, the upper envelope of the largest precipitation values ever observed (World Meteorological Organization, 1986), is plotted using the equation proposed by Brutsaert (2005), which has a smaller slope with B equal to -0.52.

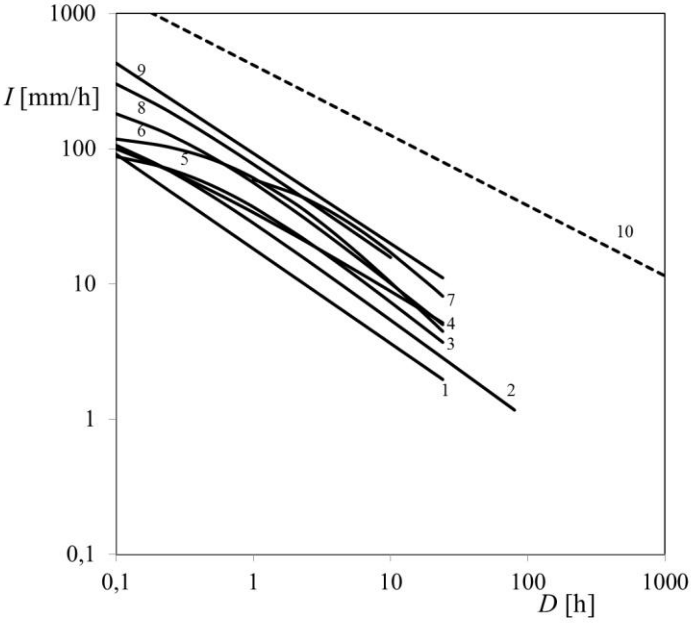


Figure 1. Examples of intensity-duration-frequency curves for 10 year return period (1-9) and curve of the maximum observed precipitations (10). Location and source: 1 Najran region, Saudi Arabia (Elsebaie, 2012); 2 Uccle, Belgium (Van de Vyver, 2015); 3 Naples, Italy (Rossi and Villani, 1993); 4 Los 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).

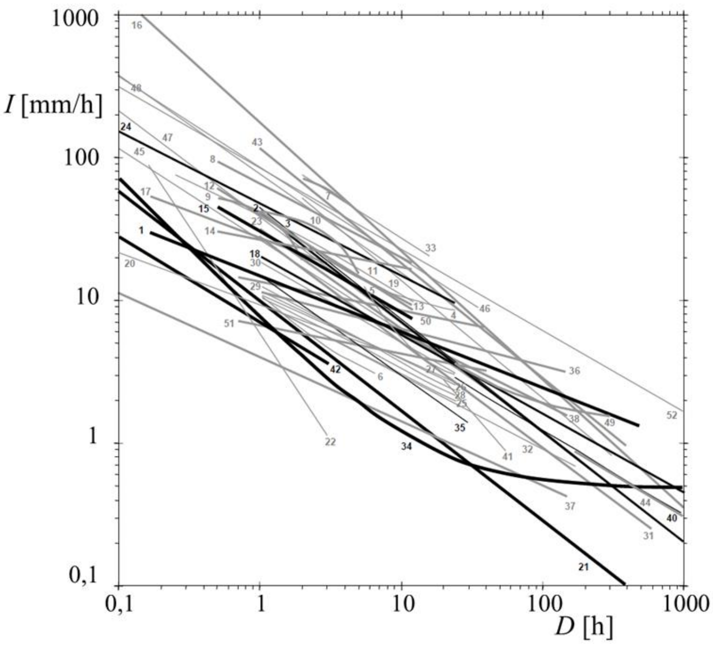


Figure 2. Rainfall intensity-duration (ID) thresholds. Numbers refer to case studies (Guzzetti et al, 2007). Very thick lines are global thresholds; thick lines are regional thresholds and thin lines are local thresholds. Black lines show global thresholds and thresholds determined for regions or areas pertaining to the Central to Eastern European region. Grey lines show thresholds determined for other regions or areas.

More than 90% of the landslides in the global data set are shallow landslides and debris flows (Figure 2, Guzzetti et al, 2007). Note that the threshold is usually obtained as lower envelope of the events resulting in landslide initiation, although also other threshold definitions exist (e.g. Staley et al., 2013; Ciavolella et al, 2016; Peres and Cancelliere, 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 in order to better compare the thresholds (Guzzetti et al, 2007). However, in our analysis the focus is on the unscaled measured precipitation ID representation, as it is a convenient way to compare with IDF. The exponent of most of the reported thresholds for initiation of landslides range between -0.2 and -0.6. For landslides triggered by short precipitation events ($D \leq 1$ hr), the slopes of the IDF and 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 right side of the graph (lower precipitation intensity with longer duration) would occur with rapidly increasing return periods of precipitation events. This is counter-intuitive, as during a long-lasting wet period 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. This shows that the method used to derive ID thresholds for landslide initiation based on landslide and precipitation reports leads to troublesome interpretations. Owing to the high spatial variability of rainfall at scales smaller than 5 km (e.g. Krajewski et al., 2003; Ciach and Krajewski, 2006) and the limited density of operational rain gauge networks, the rainfall intensity observed by rain gauges systematically underestimates the actual triggering rainfall intensity at debris flow initiation locations (Marra et al., 2016), especially for short rain duration and high return period (Destro et al., 2017). This issue has been shown to significantly affect the obtained ID thresholds for debris flow initiation (Nikolopoulos et al., 2015; Marra et al., 2017). Additionally, different methods adopted to define the dry period separating rain events have been shown to strongly affect the ID threshold (e.g. Vessia et al., 2014; Melillo et al; 2015). Furthermore, several authors already pointed out that characterizing a storm with its mean intensity, thus neglecting peaks and underestimating actual intensity, affects the estimated probability of landslide occurrence (e.g. D'Odorico et al., 2005; Peres and Cancelliere, 2016), and such an issue is obviously more significant for long storm durations. In fact, for the rainfall depth data used to derive IDF curves, the considered duration is simply a moving interval along the rainfall time series, regardless from the actual beginning and end of a rainfall event. So, the corresponding mean intensity usually refers, especially for short durations, to the heaviest part of a longer rainfall event. Conversely, whatever the criterion adopted for the definition of a rainfall event, in the case of ID threshold curves, the plotted mean intensity refers to the entire rainfall event. Thus, within very long events leading to landslide triggering, there is very likely an intensity peak, which is the "real" landslide trigger, preceded by a period of rain which contributes to predispose the slope to failure. In the (D, I) plane, the point corresponding to the peak would be shifted left- and upwards, compared to the point of the entire event. Given the typical slopes of IDF and ID threshold curves, this shift likely corresponds to a smaller return period.

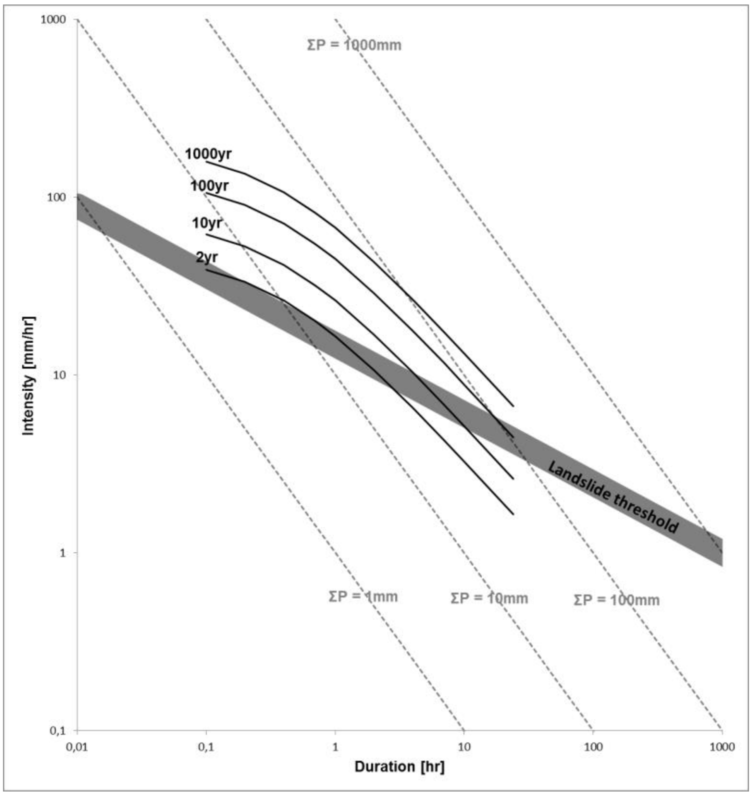


Figure 3. Schematic representation of precipitation IDF curves, isolines of accumulated precipitation (ΣP) and ID threshold for shallow landslides and debris flows (simplified from Figure 2).

HYDROLOGICAL INTERPRETATION OF ID THRESHOLDS

The precipitation ID thresholds are *“volumetric’*, i.e. every point depicts a total, cumulative amount of precipitation. In Figure 3 the global summary of ID thresholds for shallow landslides and debris flows (Guzzetti et al, 2007) is schematically represented by the dark grey area, but, added to it, are isolines of accumulated precipitation volume (1, 10, 100 and

1000 mm). The first observation is that the regional and global landslide thresholds clearly follow a slope different from isolines, meaning that longer duration landslide triggering thresholds require larger water volume. This is understandable if landslides will be deeper seated. However, the database contains mainly shallow landslides and debris flows (Guzzetti et al, 2007). Clearly, this indicates the role of hydrology, or, to be precise, the balance between infiltration, storage and drainage capacity of a slope (Bogaard and Greco, 2015).

Many of the reported empirical precipitation thresholds range between 10 and 100 mm of accumulated precipitation. However, also <10 mm and >1000 mm volumes needed for landslide initiation have been reported (e.g. as summarized in Guzzetti et al 2007). Under ‘normal’ antecedent wetness conditions (that is, soil field capacity), an accumulated precipitation of < 10 mm is generally not capable of triggering a landslide or debris flow. Of course, such an accumulated precipitation volume can trigger a shallow landslide or debris flow in case of nearly saturated antecedent conditions. In this latter case, the reported precipitation event is really the last ‘push’, the so-called trigger (see next section). On the other hand, precipitation volumes > 1000 mm and/or durations of over 100 or even 1000 hours (> 1 month) are difficult to interpret in terms of average precipitation intensities and triggering thresholds for shallow landslides and debris flows. Our point here is that the current ID concept incorporates an unacceptable wide range of information with different types of hazards (debris flows and landslides related to different hydrological processes), different temporal meteorological information (from minutes to several days). This makes the use of ID thresholds cumbersome or even misleading.

Additionally, ID thresholds have been derived by applying physically-based models of infiltration and slope stability evaluation, which account for soil hydraulic properties, different initial moisture conditions and the boundary conditions through which the slope exchanges water with the surrounding hydrological system (e.g. Terlien, 1998; Rosso et al., 2006; Salciarini et al., 2006; Frattini et al., 2009; Papa et al., 2013; Peres and Cancelliere, 2014). Such physically-based thresholds often do not follow equation 1, generally adopted for ID thresholds. For long precipitation durations, the physically-based ID curves tend to flatten (e.g. Rosso et al., 2006; Salciarini et al., 2006), indicating that landslide initiation thresholds become less sensitive to (average) precipitation intensity, which is counter-intuitive and a poor explanatory variable for landslide initiation.

Interestingly, Frattini et al. (2009) followed an inverse approach and obtained estimates of the probability of the precipitation characteristics leading to shallow landslide initiation by also considering antecedent precipitation. In particular, they showed how the exponent of the IDF curves of their study area (a catchment located on the east side of the Lake Como, in Lombardy, northern Italy) changed from -0.65, for unconditional probability of triggering events, to -0.43, when 300 mm of rainfall in the previous four days was included, thus approaching the slope of the observed ID thresholds. Antecedent precipitation can be seen as an indirect means to account for the moisture conditions of the soil cover before a triggering event. Therefore, the results of Frattini et al. (2009) can also be interpreted as an indirect confirmation that considering the integral hydrological processes would improve the performance of landslide initiation thresholds.

Greco and Bogaard (2016) give an example of the possible inclusion of slope hydrological processes in the definition of landslide initiation thresholds for the case of a slope covered by loose granular volcanoclastic deposits overlying a fractured limestone bedrock. The hydraulic characteristic curves of the volcanic ashes constituting the majority of the soil cover were known (Damiano et al., 2012; Greco et al., 2013), as well as the moisture state of the cover before all 78 observed rainfall events (Comegna et al., 2016). 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.

## 3 TRIGGER - CAUSE CONCEPT: PROPOSING HYDROMETEOROLOGICAL LANDSLIDE THRESHOLDS

In the strict sense, the precipitation ID threshold is an empirical-statistical threshold drawn to separate failure and non-failure conditions based on observed landslides and precipitation records. Precipitation is described in terms of average intensity and duration. The main assumption is that there is an underlying causal relation between the recorded precipitation event and the landslide occurrence. However, by including durations up to e.g. 1 month, the direct causal relationship is weak and the method implicitly includes the wetness state of a region. This limitation has been recognized from the start of using ID thresholds. For several regional hazard assessment analyses, research groups have extended the ID threshold method by replacing the duration of a precipitation event on the x-axis with an antecedent precipitation index or accumulated rainfall over a certain time interval (e.g. Crozier and Eyles, 1980; Glade et al, 2000; Chleoborad et al, 2006; Chleoborad et al, 2008; Scheevel et al, 2017). This, however, leads to limited added information as still only precipitation information is used. On the contrary, by replacing the x-axis with a direct measure or proxy for antecedent soil water content, physically relevant information is added (e.g. Crozier and Eyles, 1980; Wilson 1989; Wilson and Wieczorek, 1995; Crozier, 1999; Glade, 2000; Chirico et al. 2000; Gabet et al, 2004; Godt et al, 2006; Ponziani et al, 2012). Interestingly, by including a water balance of the potentially unstable soil, a statistical ID threshold evolves conceptually from a plot with one prevalent driver and data source (precipitation) into a plot containing two predominant drivers with two distinct time-scales: the antecedent hydrological 'cause' and the precipitation 'trigger'. Besides soil water balance calculations, different sources of hydrological information can be used to quantify the hydrological 'cause' of landslides. This is largely unexplored ground, partly as data availability can be cumbersome and partly because physically-based, (semi-) distributed modelling was preferred.

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

As mentioned before, there are – besides the soil moisture storage calculations previously described - various examples of hydrological information added to landslide thresholds. Hashino and Murota (1971) published an analysis of landslide triggers in a catchment related to debris production using measured river discharge data to link the landslide triggers to the water balance of the catchment. They identified that the landslides in their study area occurred during above average antecedent conditions. This is one of the earliest reported studies we know of explicitly looking at catchment water balance as an important source of information on the antecedent hydrological condition of an area in relation to landslide occurrence. Reichenbach et al (1998) made a combined flood and landslide hazard analysis of the Tiber river catchment using 72 years of historical daily discharge data from different gauging stations where hydrological parameters were calculated, such as maximum mean daily discharge, specific discharge and flood volume and duration. Probability of occurrence of landslides and floods was based on the ranking of the events. Combining maximum mean daily discharge and discharge intensity, regional hydrological thresholds for landslide and flood hazard (individually or combined) could be drawn. Chitu et al (2016) followed a somewhat similar approach, analyzing the river discharge in several catchments in the Ialomita Subcarpathians in Romania for landslide events in 2014. The catchments could be characterized as having low/high relative storage. Additionally, a calibrated regional rainfall-runoff model was used for hydrological analysis of landslides in specific catchments. Detailed analysis of the (modelled) hydrological response indicated that in two catchments with low infiltration capacity the direct runoff was strongly related to landslide occurrence, whereas it could be linked to modeled soil infiltration flux in another catchment. Extending the above to deep-seated landslides, the connected regional groundwater level could be informative. Bogaard et al (2013) studied the hydro-meteorological triggering threshold of the re-activating coastal Villerville–Cricqueboeuf landslide, Normandy, France. In this situation the hinterland of the coastal cliff consists of a well-defined regional groundwater level. Landslide reactivation was seen to take place only when water level was in the upper, more permeable top layer. The triggering rain event together with surpassing a certain regional groundwater threshold could explain 3 of the 4 re-activations. Note that these groundwater levels were not taken in the active landslide area but several kilometers inland.

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

These examples indicate that considering hydrological causes could be useful for a better identification of landslide initiation, but, at the same time, they show that the correct identification of the hydrological processes involved in the establishment of the predisposing conditions for landslides is mandatory for choosing the most informative hydrological variable to be plotted along the x-‘cause’-axis.

## 4 CONCLUDING REMARKS AND OUTLOOK

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

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

We propose to use the cause-trigger concept for defining regional landslide initiation thresholds. This, we agree, is challenging, but, in our opinion, not impossible. First of all, it is needed to define the characteristic time-scale separating the (dynamic) long-term predisposing hydrological cause from the short ‘final’ landslide hazard triggering. This obviously depends on the landslide type and physiographic characteristics. Looking at the discussed examples, it becomes clear that the choice of the most informative hydrological variable to be used as a proxy for landslide predisposing conditions strictly depends on site-specific geomorphological characteristics, and that accurate analysis of the boundaries through which the potentially unstable area exchanges water with the surrounding hydrological systems is mandatory. In other words, for the assessment of landslide predisposing conditions, the water balance of the slope should be assessed, but getting the information about the inherent hydrological processes (e.g. evaporation, runoff, groundwater recharge) at the required spatial-temporal resolution is often a challenge and could require some kind of calculations or modelling. However, rapidly more and higher resolution hydrological data become available which can be used in assessing the hydrological predisposing condition.

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