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Natural Hazards and Earth System Sciences
Discussions

Invited perspectives: Landslide populations - can they be predicted?

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Landslides affects the slopes of all continents, and are serious menace to people, property and the environment. But landslides are different from other natural hazards. Unlike volcanos, landslides do not threaten human civilization (Papale and Marzocchi, 2019). Unlike tsunamis, they do not affect simultaneously thousands of kilometres of coastlines – although a submarine landslide in Norway has caused a tsunami that affected Scotland (Dawson et al., 1988). Unlike floods and earthquakes, they do not cause hundreds of thousands of casualties in a single event – although a landslide has killed thousands in Peru (Evans et al., 2009), and a few debris flows tens of thousands in Colombia (Wieczorek et al., 2001). Compared to other geological and hydrological hazards, landslides are subtle, they frequently go unnoticed, and their consequences are underestimated. This hampers the design and implementation of effective risk reduction strategies.

Like for other hazards, the design and implementation of effective risk reduction strategies depend on the capability to predict (i.e., forecast, anticipate, project) landslides and their consequences. I have argued that "*our ability to predict landslides and their consequences measures our ability to understand the underlying physical […] processes that control or condition landslides, as well as their spatial and temporal occurrence*" (Guzzetti, 2021). This assumes that landslide prediction is possible; something that has not been proved (or negated), theoretically. Still, there is nothing in the literature that prevents landslide prediction; provided that one clarifies the meaning of "landslide prediction" (Guzzetti, 2021), and the prediction is scientifically based (Guzzetti, 2015).

Given the assumption, I outline what I consider main themes to pursue to advance our collective ability to predict landslide hazards and risk, at all geographical and temporal scales (Figure 1). The field is vast, and I limit my perspective to the hazards and risk posed by populations of landslides – i.e., many landslides caused by a triggering event, or by multiple events in a period. In this context, predicting landslide hazard means predicting *where*, *when*, *how frequently*, *how many*, and *how large* landslide populations are expected, and predicting landslide risk consists in anticipating the consequences of landslide populations to different elements at risk (Alexander, 2005; Glade et al., 2005; Galli and Guzzetti, 2007; Salvati et al., 2018).

Predicting *where* landslides will occur is achieved through susceptibility modelling. A review of data-driven landslide susceptibility studies has shown that there is no shortage of methods for landslide spatial prediction. Rather, there is a clear lack of accurate environmental and landslide data, and of standards for the construction, validation, and ranking of the susceptibility models (Reichenbach et al., 2018). An earlier evaluation and review of landslide mapping methods (Guzzetti et al., 2012) further revealed the absence of standards for the preparation and the evaluation of landslide maps. I argue that the absence of standards reduces the credibility and usefulness of the landslide maps and the prediction modes (Guzzetti, 2021). The increasing availability of remote-sensing imagery, some of which repeated in time and free of charge, opens to unprecedented possibilities to prepare landslide maps for very large areas, including event and multi-temporal inventories, which are essential for the construction of space-time prediction models (Lombardo et al., 2020), to investigate the heritage of old landslides on new landslides (Samia et al., 2017), and to obtain accurate environmental data for susceptibility modelling.

Predicting *when* or *how frequently* landslides will occur is done for short and for long periods. For short periods – hours to weeks – the prediction is obtained through process-based models, rainfall thresholds, or their combination. Process-based models rely upon the understanding of the physical laws controlling the slope instability conditions of a landscape forced by a transient trigger e.g., a rainfall, snow melt, seismic, or volcanic event. Thresholds are empirical or statistical models linking physical quantities (e.g., cumulated rainfall, rainfall duration) to the occurrence – or lack of occurrence – of known landslides. Reviews of the literature (Guzzetti et al., 2008; Segoni et al.; 2018) have revealed conceptual problems and limitations with the definition and use of rainfall threshold models for operational landslide forecasting and early warning (Piciullo et al., 2018; Guzzetti et al., 2020) including e.g., the lack of standards for the definition of the thresholds and their associated uncertainty (Melillo et al., 2018), and the validation of the threshold models and of the early warning systems (Piciullo et al., 2017). The projection of the landslide frequency for

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long periods – decades to millennia – is far more difficult and uncertain, as it depends on climatic and environmental characteristics that are poorly known, and difficult to measure and model (Gariano and Guzzetti, 2016). The literature on the analysis of historical landslide records remains meagre (Rossi et al., 2010), but the number of studies projecting the future occurrence of landslides is increasing.

Predicting *how many*, and *how large* landslides are expected means anticipating the size (e.g., area, volume, length, width, depth) and number of landslides in an area – with size and number related in a landslide population. The information, essential to evaluate landslide hazard (Guzzetti et al., 2005), is obtained constructing and modelling frequency and probability distributions of landslide sizes using data obtained from event landslide inventory maps (Malamud et al., 2004). The literature on the topic is limited, and with differences in the way the statistics are calculated. This hampers the possibility to compare statistics from different areas. Albeit models have been proposed to explain the probability size distributions (Katz and Aharanov, 2006; Stark and Guzzetti, 2009; Klar et al., 2011), further efforts are needed to explain the empirical distributions of landslide sizes observed in nature, and to evaluate their variability.

By combining probabilistic information on *where*, *when* or *how frequently*, and *how many* or *how large* landslides are, one can evaluate landslide hazards (Guzzetti et al., 2005), for different landslide types. Assessing landslide hazard is important but, for social applications, what is needed is the estimation of the landslide consequences, which means assessing the vulnerability to landslides of various elements at risk (Alexander 1999; Galli and Guzzetti 2007), and evaluating landslide risk (Cruden and Fell, 1997; Glade et al., 2005; Porter and Morgenstern, 2013), including risk to the population (Petley, 2012; Froude and Petley, 2018; Salvati et al., 2018; Rossi et al., 2019). Here, the limitation lays in the difficulty in obtaining data on landslide vulnerability, and reliable records of landslide events and their consequences (Petley, 2012; Froude and Petley, 2018; Salvati et al. 2018). Where the information is available, comprehensive landslide risk models can be constructed, and validated (Rossi et al., 2019).

Ultimately, I note that in medicine – a field of science which I consider conceptually close to the field of landslide hazards and risk (Guzzetti, 2015) – the paradigm of "convergence research" is emerging (Sharp and Hockfield, 2017), where *"convergence comes as a result of the sharing of methods and ideas … It is the integration of insights and approaches from historically distinct* *scientific and technological disciplines”* (Sharp et al., 2016). I maintain that to advance significantly the ability to predict landslide hazards and their consequences, the scientific community should embrace the “converge research” paradigm.

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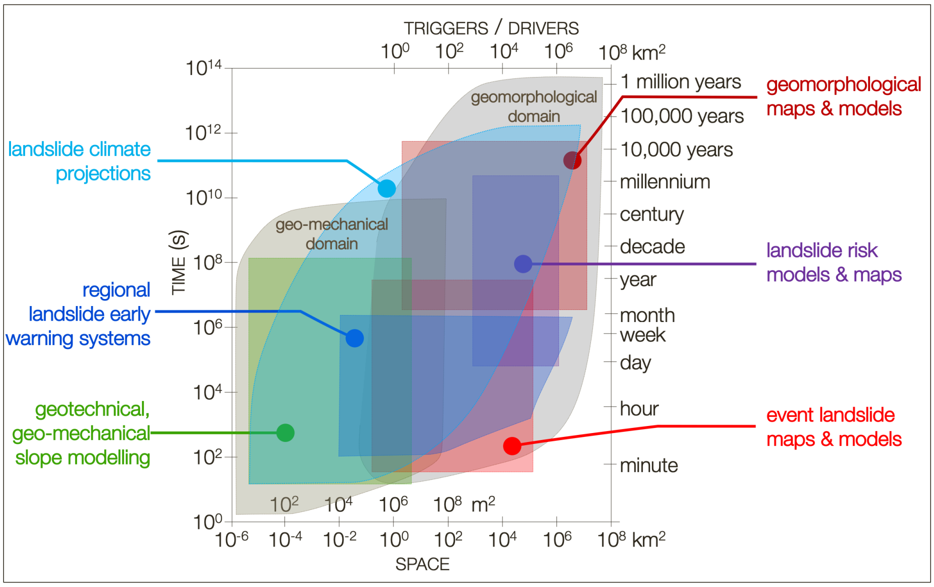

Figure 1. Space (lower x-axis) – time (y-axes) chart showing main geomorphological and geo-mechanical landslide domains, and typical length-scale of main meteorological and geophysical triggers and drivers of populations of landslides. Coloured polygons show approximate sub-domains for typical landslide hazards and risk mapping and modelling efforts. Modified after Guzzetti (2021).