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The future of landslides' past—a framework for assessing consecutive landsliding systems

Abstract Landslides often happen where they have already occurred in the past. The potential of landslides to reduce or enhance conditions for further landsliding has long been recognized and has often been reported, but the mechanisms and spatial and temporal scales of these processes have previously received little specific attention. Despite a preponderance of qualitative and anecdotal evidence, analysis has been limited. As a result, there is little consensus on the meaning of terms such as landslide repetition, recurrence, and reactivation. This source of confusion is evident when such terms are also used to describe systems where landsliding is prevalent but unrelated to landslide history. Recent findings, partly based on a rare multi-temporal landslide inventory for an area in Italy, show that the impacts of earlier landslides affect a substantial fraction of landslides, that landslides following earlier landslides differ from those that do not, and that accounting for the effect of previous landslides can improve susceptibility assessments. These findings await confirmation in other landslide-prone landscapes but show that consecutive landsliding deserves more attention, which requires consistent terminology. No such terminology is presently available, and we therefore propose it in this manuscript. We use the term "uncorrelated landsliding" to describe situations where landslides are common, but where a correlation with environmental variables such as terrain steepness is not implied. We propose "correlated landsliding" to describe situations where landslides are common and correlations with environmental variables exist, and "path-dependent landsliding" to describe situations where causal relations exist between consecutive landslides, for instance, when landslides occur at the scarp of previous landslides. These are situations where past landslides impact future landslides. Within the path-dependent category, we distinguish three subcategories based on the spatial distance between earlier and later landslides: "reactivation" or "continuation" if essentially the same material recommences or continues to slide, "local activation" if an earlier slide causes changes in a local hillslope that cause a later slide, and "remote activation" if an earlier slide causes changes elsewhere in the landscape that cause a later landslide. We use this proposed set of terms to outline some prominent knowledge gaps and potential research questions.

Introduction: consecutive landslides

One of the largest recorded historic landslides, involving about 36 million m³ of rock, was on September 2, 1806, in the Swiss canton of Schwyz. The slide occurred after a wet August and destroyed the village of Goldau, where 437 people died (Meyer 1806). Subsequent investigations of the hillslope overlying Goldau revealed at least two earlier slides of a similar magnitude. In each case, the mobilized material was dominated by conglomerate which appeared to

have failed along a contact with underlying marl (Thuro et al. 2006). Smaller landslides (rockfalls sensu Varnes (1978), and Hungr et al. (2014)) from the same slopes have been observed in that area since 1806, for instance, in 1970, 2002, and 2005, and a potential for several more such events, particularly along the 1806 scarp, has been recognized (Thuro et al. 2006). The triggering of the older massive rock slope failures (MRSFs) cannot be reliably established, and it is therefore not certain that earlier MRSFs created or maintained conditions for occurrence of later MRSFs. However, the smaller events after the 1806 MSRF are described as part of event cascades, "directly triggered" by the older failures (Keller 2017, p. 1646). The implied causality is one of many examples of the impact of landslides on later landsliding in the literature.

Repeated unique landslides from the same source area into the same depositional area have also been discussed among others by Moore and Mathews (1978), who describe the likelihood of "correlated" landsliding in Rubble Creek in British Columbia, Canada, and by Crandell and Fahnestock (1965), who describe multiple rock avalanches originating as rockfall events from Little Tahoma Peak in Washington State in the USA. These two studies do not describe a causal relation between consecutive landslides and rockfalls, although triggering conditions seem to mirror those found in Schwyz in Switzerland, with earlier failures maintaining or creating a scarp from which later landslides originate.

On the slower end of the landsliding velocity spectrum (Hungr et al. 2014), the Slumgullion landslide on Mesa Seco in Colorado in the USA has been described as a reactivation of part of an older flow of which the remaining part is currently stable. Reactivation was caused by mass failure on top of the landslide deposit (loading) when the old scarp on Mesa Seco failed (Fleming and Baum 1999). The current Slumgullion landslide is a good example of long-lasting activity of the same slow-moving deposit over centennial timescales: it has been moving for at least 300 years, and has been quantified since 1939, with speeds on the order of 5 m per year (Crandell and Varnes 1961). Reactivation of landslides, such as experienced at Mesa Seco, is common. In the Flemish Ardennes in Belgium, for instance, about 30% of mapped deep-seated landslides have experienced one or more reactivations over the last few decades (Van Den Eeckhaut et al. 2007). The region's best studied representative landslide, in a site called Hekkebrugstraat, has reactivated and moved at least six times since 1955. Causal factors for reactivation were heavy rainfall and/or human activity such as the creation of ponds that led to overloading (Van Den Eeckhaut et al. 2007). The fatal 2014, State Road 530 landslide in Washington State in the USA, also known as the Oso landslide, followed a 2006 landslide in the same location (the "Hazel" landslide) and likely reactivated some of its material. Here too, unusually high long-term rainfall totals contributed to the recurrence (Iverson et al. 2015).

Landslides can be causally related over substantial distances, for instance, where lakes dammed by a first landslide saturate slopes, leading to weakening of sediments and increased buoyancy and hence follow-up landsliding. This effect has been quantified mainly in the context of engineered dams, for instance, for the Grand Coulee Dam in Washington (Jones et al. 1961) and the Yellowtail Dam in Montana (Dupree et al. 1979), both in the USA, but the basic mechanism should be equally valid in the case of landslide-dammed lakes, which can be as deep as engineered reservoirs (Schuster and Costa 1986), and which can affect landscapes in many places simultaneously after catastrophic seismic or meteorological events (Korup and Wang 2015). In the Washington and Montana cases, substantial landsliding was observed during the initial impounding of the reservoirs. In Roosevelt Lake, the reservoir behind the Grand Coulee Dam, additional landsliding happened during lowering phases of the reservoir surface (Jones et al. 1961). These lowering phases left behind saturated slopes that were no longer supported by the mass of the water and failed (Schuster 2006). Landslides can also be caused when landslide dams fail catastrophically and downstream flooding scours downstream valleys and undermines hillslopes (Jansen 1988).

Although not the focus of this contribution, causal relations between geomorphic events through transient effects appear to also play a role in other systems. Among these are volcanic eruptions, earthquakes, and sinkholes (Galve et al. 2009, 2011).

Despite these examples from a range of different settings, landslide-on-landslide effects have only recently received specific attention. A systematic attempt to characterize and quantify local landslide-on-landslide effects at the scale of a landslide inventory of over 3000 slides was made by Samia et al. (2017a, b), using data from the 79 km² Collazzone region in the Italian Apennines (Galli et al. 2008; Guzzetti et al. 2006). Results highlighted a local and transient effect of shallow landslides on the likelihood of later landslides within a few dozen meters and about 20 years (Samia et al. 2017a, b). This impact at the landscape scale is easily quantified and has been shown to improve the performance of landslide susceptibility models (Samia et al. 2020)—even though the mechanism by which landslides in this region temporarily affect the likelihood of later landslides remains unknown.

Natural experiments are being used to explore the mechanisms behind such landslide-on-landslide effects. In work by Mirus et al. (2017), a landslide-disturbed hillslope was compared with an otherwise similar undisturbed hillslope nearby. The disturbed slope had less vegetation, weaker soil structure, lower matrix porosity, and hydraulic conductivity than the undisturbed slope. These physical changes caused by the initial landslide also resulted in hydrological differences where the landslide-disturbed hillslope began seasonal wetting earlier in the year, maintained elevated antecedent pore-water pressures between rainfall events, and maintained saturated conditions many months after the undisturbed hillslope dried out. These differences in susceptibility throughout the winter landslide season contributed to repeated complex failures at the landslide-disturbed hillslope and thus allow inference about landslide-on-landslide mechanisms.

Authors of landslide classifications were aware that landsliding can affect later landsliding. Summarizing decades of work in a Swiss alpine background, Heim (1932) distinguished 20 types of landslides, including "periodically recurring debris slides" (type III), "debris slides that are continuously at work" (type IV), "continuing rockfall" (type XVI),

"composite landslides" (type XVII), "unfinished or interrupted landslides" (type XVIII), and "subsequent landslides" (type XIX). These classes clearly indicate an appreciation of the diachronous character of landslide activity, even though not all classes were formally defined and the type of landslide was conflated with landslide behavior over time. Sharpe's classification (Sharpe and Charles 1938) includes "natural agencies" among causes for landslides. The gravitational or seismic impacts of earlier landslides were mentioned as possible natural agencies. Landslide relations, but not their causes, were also captured in landslide "style," as first defined by Cruden and Varnes (1996). "Style" can capture how a landslide is part of a sequence of slides (Fig. 1). Values for "style" that may indicate landslide-on-landslide effects are "complex," where one landsliding event sets the scene for a second event of a different type, partly in the same material; "multiple," where landslides of the same type move repeatedly, often with later landslides enlarging the area of the earlier landslides; and "successive," where landslides of the same type move repeatedly but are not in contact with each other. Other styles are "single," indicating a landslide unrelated to others and "composite," indicating a landslide that changes its character according to topographic position. The style "composite" matches closely with Heim's type XVII (1932, see above). More recently, the classification of Hungr et al. (2014, p. 167) confirms that "many landslides exhibit a number of movement episodes, separated by long or short periods of relative quiescence," but does not detail relations between different landslides.

Regrettably, because of their focus on individual landslides, existing classifications are not equipped to describe and distinguish aggregate landslide-on-landslide effects at the landscape scale. In addition, they do not clearly specify the kind of relation between landslides. For instance, even a "single" landslide (sensu Cruden and Varnes (1996)) can be causally related to a landslide dam breach upstream and a "successive" failure may or may not be caused by disruptions to hillslope hydrology caused by the earlier landslide, for instance.

We thus conclude that (1) landslide-on-landslide effects are a common occurrence and have been described in a range of landscapes for a range of landslide types, and (2) no consistent terminology describes various types of such landslide-on-landslide effects at the scale of the landscape, i.e., the geomorphic system. The lack of consistent terminology complicates communication and literature searches, as we experienced when researching this topic. A formalized and consistent framework will help communication and allows us to better take stock of what we know and what we do not know about how landslides in the future depend on landslides' past. Our aim here is therefore to propose a framework for terminology and identify some pertinent knowledge gaps and open research questions.

Terms for spatiotemporal relations among landslides

Our proposed terminology describes different levels of relations between landslides in space and time. We propose to use the term "uncorrelated landsliding" for all cases where multiple sliding events are discussed, but where relations between subsequent landslides, or relations between landslides and landscape position, are not apparent (Fig. 2). An example is the Sarkar (1999) study of historical landslides in the Indian Himalaya that focused on temporal changes in overall landslide rates between 1849 and 1999, yet did not find clear relations between slides and landscape position, or between successive nearby landslides: "The study reveals that
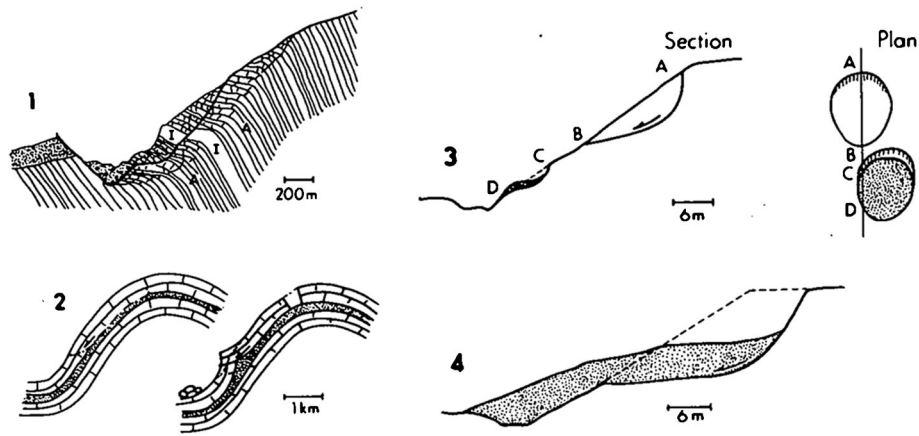
Fig. 1 Landslide style illustrations, adapted from Cruden and Varnes (1996, p.48). Type 1 is "complex," with topples followed by a slide in the toppled material. Type 2 is "composite," where a slide causes toppling at its toe. Type 3 indicates "successive" style, where two slides of the same type occur at different times and in a different place, but close enough to be considered jointly. Type 4 indicates "single" style, with just one landslide. "Multiple" style (not indicated) denotes a landslide that occurs in the same place as a previous slide, and shares some of its material

each slide has its own peculiarities and its initiation is not due to any single factor" (p. 299). It is expected that "uncorrelated landsliding" as a term will be mainly useful to indicate that landslide-landslide effects or landslide-landscape effects were not readily apparent (e.g., Salinas-Jasso et al. (2017); Xinbin et al. (2010))—rather than to deny that such effects exist.

The stricter term "correlated landsliding" is proposed to denote situations where consecutive landslides are correlated with landscape variables such as slope steepness or slope position. "Correlated" is used here to denote recurrence of landslides in similar settings, and may be observed from

landslides that happen simultaneously in several locations, successively in several locations, or successively in the same location—as long as later landslides are related to location properties rather than to earlier landslides. The vast majority of empirical, quantitative landslide susceptibility studies, as reviewed by Reichenbach et al. (2018), assume correlated landsliding and quantify the correlations with landscape variables to produce static susceptibility maps. The landslides discussed above by Crandell and Fahnestock (1965) and Moore and Mathews (1978) fit this category because these authors describe multiple landslides that happen
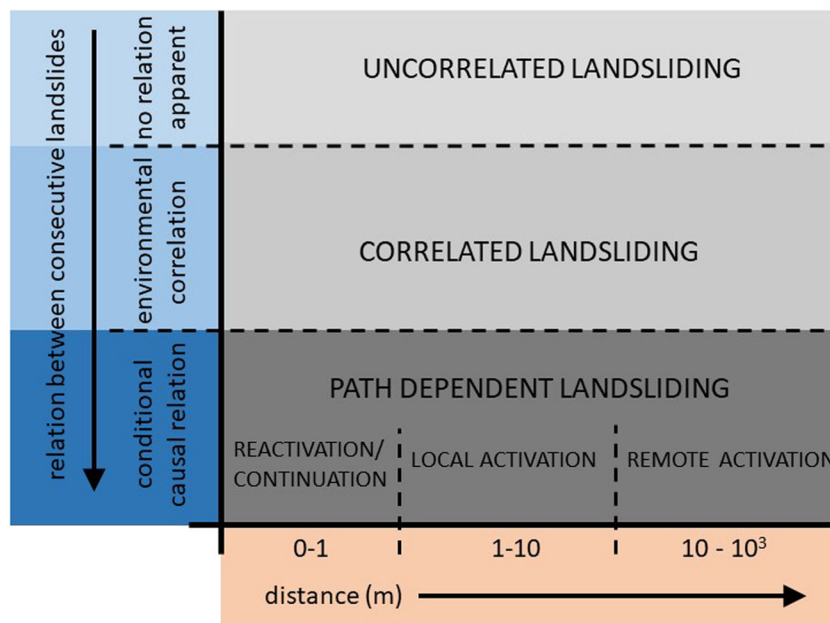

Fig. 2 Proposed terminology to distinguish different relations between consecutive landslides. Relations range from conditional causal relations, through correlation, to an absence of relations. Within the conditional causal category, distinction is made between reactivations; where deposits of a previous landslide continue or resume their move downslope, local activation; where previous landslides create conditions that favor later landslides nearby within the same hillslope, and remote activation; where previous landslides create conditions that favor later landslides farther away

in the same location for the same reasons, but not the possibility of a causal relation between them.

The strictest term, "path-dependent landsliding," is proposed for situations where earlier landslides additionally have an observed or inferred causal relation with later landslides. The term "path dependence" in general refers to situations where not only the present state of a system (in our case a landscape with its lithology, morphology, soil patterns, and land cover), but also its past activity (in our case, its recent landslides) must be known to predict its future (Phillips 2009). Path dependence thus does not reference a physical "path" but a system's history.

In most landscapes, the causal relationship implied in path dependence will be conditional, which means that earlier landslides are a necessary but not sufficient condition for new landslides. Slow-moving, deep-seated earthflows such as the Slumgullion earthflow or the Montaguto earthflow in Italy (Guerriero et al. 2013) are good examples of path-dependent landsliding because they create the conditions for their own repeated reactivation or continuation. Such earthflows are also a good illustration of conditional causality: wetness is additionally required to drive movement (Bennett et al. 2016). Other examples of path-dependent landsliding are the rockfalls originating from the scarp of the large slope failures in Schwyz in Switzerland, where the rockfalls were "directly triggered" by the prior failure (Keller 2017, p. 1646).

Unconditional causality in landsliding, where an earlier landslide is necessary and sufficient to cause a later landslide, can probably only be established for landslides that immediately follow and touch or overlap precursor landslides, i.e., those with Cruden and Varnes' (1996) "complex" or "composite" styles. Hutchinson and Bhandari (1971) described a mechanism for such unconditional causality, undrained loading, where upper parts of a landslide add pressure to lower undrained slope material that would not otherwise fail, to the point of failure. Basal liquefaction, which contributes to enhance landslide mobility such as observed in the Oso landslide in 2014, may be another mechanism (Collins and Reid 2019).

Within the path-dependent landsliding category, we propose three subcategories that describe different spatial relations between earlier landslides and later landslides that are caused or conditioned by them. The first subcategory is used to describe "reactivation" or "continuation" of the same landslide deposit—such as in earthflows. In this case, geographical distance between the first and subsequent landslides is minimal. As far as we know, one main mechanism has been proposed for this causal relationship between landslides: the "bathtub" mechanism, where smearing of clay on the contact between the slide and underlying rock or deposits leads to almost permanent weak permeability and low shear stress (Bennett et al. 2016; Van Den Eeckhaut et al. 2007). Infiltration into the landslide body then leads to gradual filling and saturation of the landslide deposit from below, similar to a bathtub filling with water (Baum and Reid 2000). Subsequent failures ("reactivations" in the case of clear stability in between events or "continuations" in the case of continued movement) would occur along this same contact.

The second subcategory is "local activation". This describes landsliding that is conditionally caused by nearby landslides that happened in the same hillslope unit, such as observed in shallow landsliding in the Collazzone multi-temporal inventory by Samia et al. (2017a, b). The term "activation" reflects that a new landslide is formed, along a new failure surface.

Multiple candidate mechanisms have been proposed to explain local activation, which we discuss below.

The third subcategory is "remote activation," and describes landslides remotely caused by geomorphic activity triggered by previous landslides. Good examples are landslides caused by landslide damming, through either upstream flooding while a dam persists or downstream flooding when a dam fails (Jansen 1988; Schuster 2006). Situations where landslides cause rerouting of streams that subsequently undercut slopes on the opposite side of the valley are also described by this term (Korup and Crozier 2002).

Extending the temporal aspect of the distinction between "continuation" (immediately continuing sliding) and "reactivation" (stability in between sliding episodes) to local and remote activation is attractive. We propose "immediate" and "delayed" as terms for this distinction, with the persistence of the trigger or event that causes the earlier landslide as the distinguishing timescale. Thus, "immediate local activation" describes local activation of a later landslide by an earlier landslide while the original trigger (e.g., the original rainfall event that caused the earlier landslide) persists, while "delayed remote activation" describes remote activation of a later landslide by an earlier landslide after the original trigger of the earlier landslide has passed. When useful, delayed activation can be specified further, for instance, using classes delimited by order of magnitude differences in delay time (i.e., class limits of 10^4 s, 10^5 s, and 10^6 s).

Although we are convinced that the conceptual distinction is clear, it can in practice be impossible to distinguish between "correlated" and "path-dependent" landsliding when successive landslides happen in the same geographic location, and no information on the presence or permanence of transient effects of earlier landslides is available. Clearly, with increasing time between earlier and later landslides, it becomes less likely that a positive effect of the earlier landslide continued to contribute to the occurrence of the later landslide. It may also be reasonable to assume that effects of large, deep landslides remain present longer than effects of small, shallow landslides. However, without direct field observations of triggering conditions (such as in Mirus et al. (2017)), large numbers of landslides, captured in multi-temporal inventories, may be needed to confidently draw this conclusion. We believe that more widely available remotely sensed imagery will alleviate this problem (see below).

The framework in Fig. 2 deliberately does not specify properties of landslides, and only focuses on relations between landslides. Our choice of examples above betrays our expectation that it can be useful for both shallow and deep-seated landslides. However, we fully expect that different landslide types may exhibit different relations between landslides. For instance, deep-seated landslides may be much more likely than shallow landslides to cause remote activation of follow-up landslides. However, we are convinced that both types of sliding (and the boundary cases between them in lithologies with gradual weathering fronts, cf. Phillips et al. (2019)) can in principle exhibit all options.

Path-dependent landsliding: recent findings

Recent work leveraging a 17-time slice, multi-temporal inventory for the Collazzone area, Umbria, in the Italian Central Apennines has resulted in landscape-level characterizations and quantifications of path-dependent landsliding. A brief review of these

findings will contextualize some of the main open questions regarding path-dependent landsliding.

The multi-temporal inventory of landslides for the Collazzone region contains ~ 3000 mapped landslides that are dominantly shallow and were inventoried between 1939 and 2014 (Galli et al. 2008; Guzzetti et al. 2006). Initial analysis of the inventory revealed substantial overlap between landslides, with about 30% of landslides overlapping or touching earlier landslides. Overlapping and touching landslides were substantially and significantly larger and rounder than other landslides and had significantly different parameters for the inverse gamma distribution of landslide sizes (Samia et al. 2017b). Interestingly, the degree of overlap between landslides from consecutive time slices in the Collazzone dataset appeared to be a negative function of the time passed between the time slices, leading to the hypothesis that landslides temporarily changed local conditions for subsequent landslides. Transience of the landslide effect was confirmed in a follow-up study (Samia et al. 2017a), where the degree of overlap between landslides from different time slices was estimated about 15 times higher immediately after the first time slice than after several decades (Fig. 3a). The characteristic timescale of the exponential decrease was about 7 years.

Two further studies explored the possible use of this path-dept-dependent effect in landslide susceptibility assessments. The first assessed susceptibility at the scale of hill slope units (HSUs) (Samia et al. 2018). HSU areas are one or two orders of magnitude larger than landslide areas (Alvioli et al. 2016). A conventional landslide assessment, using geomorphic and geologic conditioning factors, was compared with a landslide assessment that included the time since the last local landslide in addition to the other conditioning factors. Model performance was not significantly different between both assessments, possibly because the local impact of individual landslides did not substantially affect susceptibility at the larger HSU scale (Samia et al. 2018).

The second study again compared a traditional model with a model that additionally accounted for path dependency, but now at much finer resolution: 10 m pixels. A variable that reflected the local, transient impact on the landscape of all pixels that were affected by previous landslides was calculated using Ripley's K (Ripley 1976). Ripley's K has been used mainly in ecology to quantify deviations from randomness in spatial patterns (e.g., Haase (1995); Lynch and Moorcroft (2008)). Applied to landslides, Samia et al. (2020) used Ripley's K to quantify how often pixels experienced landsliding as a function of the distance in space and time from the center of earlier landslides (Fig. 3b). The observations confirmed the earlier findings: landslides occurred substantially and significantly more often than expected when spatially or temporally close to the center of a previous landslide. An exponentially decreasing susceptibility was found characteristic spatial scale of 60 m and temporal scale of 17 years. Using the exponentially decaying increase in landslide occurrence as an additional variable in susceptibility modeling substantially increased model performance.

Open research questions

Extracting aggregate path-dependency metrics from multi-temporal inventories and using these metrics to improve the performance of landslide susceptibility models, for instance, as performed by Samia et al. (2017a, 2018, 2020) is a promising perspective. However, more work is needed to better understand path-dependency mechanisms, improve their quantification, and optimally leverage them. This section lists our assessment of the most pressing of those questions.

Assembling multi-temporal landslide inventories

Large (i.e., substantially complete, Malamud et al. (2004)) multi-temporal landslide inventories are necessary for the identification and analysis of consecutive landsliding systems. Additionally, inventories need high spatial accuracy to confidently distinguish between individual landslides that have moved in between time slices on the one hand, and new nearby landslides that partially overlap and were triggered by earlier landslides on the other hand. Regrettably, such inventories are rare. The retrospective production of inventories is temporally limited by the availability of remotely sensed data with sufficient resolution. The Landsat series of satellites (from 1973) provides an initial spatial resolution of
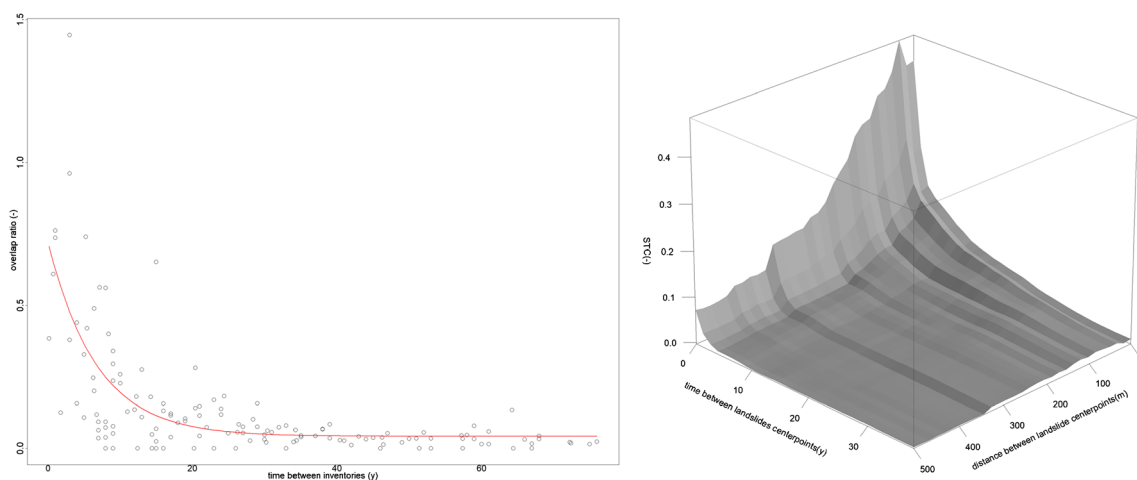

Fig. 3 Two indications of temporary increase in landslide susceptibility after earlier landslides. Left: a measure of overlap between consecutive time slices corrected for the size of time slices which displays a decrease with time between time slices, adapted based on Samia et al. (2017a). Right: STC (space-time clustering) values over zero reflect a higher susceptibility to landsliding in spatial and temporal proximity of previous landslides adapted based on Samia et al. (2020)

60 m—improved to 30 m in most bands after 1982. The SPOT series of satellites, from 1986, provides 10-m resolution over most of the globe. These spatial resolutions are insufficient to accurately inventory most shallow landslides. Spatial resolutions of less than 5 m have only become available after 2000, for instance through the EROS and QuickBird satellites.

With satellite-based imagery thus typically unavailable or insufficiently detailed for the assembly of multi-decadal retrospective inventories, traditional aerial photography will probably be the data source of choice for this task for the foreseeable future. In many countries, aerial surveys date back to the first half of the twentieth century, often at resolutions near 1 m. The limiting factor for aerial photography will more likely be the temporal frequency of imagery, with early surveys often spaced decades apart, the continued availability of trained aerial photo interpreters, and financial constraints related to the manual aspect of the work (Galli et al. 2008). If characteristic timescales of landslide path dependence are in the same range as that observed in Collazzone (~ 17 years), the temporal frequency of aerial photographs will probably limit analyses in the earlier time slices of multitemporal inventories.

Aggregate quantification of path dependency

Correct and informative quantification of path dependency between landslides in a landscape requires further development of analytical methods. Several aspects of current methods are unsatisfactory.

First, Samia et al.'s (2019) calculation of characteristic space and time scales using Ripley's K, although useful, ignores the landscape position of landslides. This is problematic because unrelated landslides that occur, for instance, near each other on different sides of a drainage divide will be counted as evidence of clustering. This problem should be solved, for instance, for local activation by assigning landslides to hill slope units (e.g., Alvioli et al. (2016)) and considering only pairs of slides that share HSUs in the calculation of Ripley's K.

Second, using simple geometric distances between landslides to calculate spatial clustering ignores landscape context. A better approach, based on geomorphometry (e.g., Hengl and Reuter (2009)), would be to calculate Ripley's K in one temporal and two spatial dimensions, where the spatial dimensions are, for instance, for local activation, the along-slope and slope-parallel distance between geometric centers of landslides (Fig. 4). This would allow for distinction of situations where landslide-on-landslide mechanism acts along slopes versus parallel to slopes. For remote activation, an appropriate spatial dimension could, for

instance, be landscape position upstream and downstream of locations where previous landslides dam valleys.

Third, the use of geometric centers of landslides in clustering measures does not consider the fact that landslides differ in size and shape (e.g., Taylor et al. (2018)). Methods are needed to assess whether larger landslides affect the susceptibility for later landsliding differently than smaller landslides—possibly by calculating the spatial distance between landslides from the edges rather than the centers of landslide polygons.

Finally, simultaneous estimation of the impact of earlier landslides and environmental factors on later landslides is preferable over the estimation of the impact of earlier landslides before or after the estimation of environmental factors. Ripley's K is not suited for such simultaneous estimation, but frameworks such as generalized additive models (GAMs) that fit linear models in addition to smoothing are potentially appropriate. Open-source frameworks that may be useful for this purpose include the mgcv package in R (Wood et al. 2016).

A consistent framework for quantifying relations between path-dependent landslide bodies would allow direct comparisons of the importance of this phenomenon between different regions and geomorphic regimes. This would allow a test of the crucial hypothesis that main path-dependency characteristics such as the Ripley-based space-time clustering (STC) measure (Samia et al. 2020) are similar when geomorphic regime and climatic or seismic setting are the same. This would link clustering measures to geomorphic processes, and it would allow the use of STC values obtained in places with a rich multi-temporal inventory in similar places without such inventory.

Geomorphic inference

Confirming this hypothesis would also allow the creation of a library of characteristic space and time scales of path dependency as a function of regional environmental properties such as average slope, total relief, geology, and climate. Such a library would serve dual purposes. First, it would be of value as a source of STC values for areas where no multi-temporal inventories are available, as discussed above. More importantly, a library of these path-dependency parameters describing the characteristic space and time scale of path dependency would allow process inference, comparable with the environmental seismology catalog which allows interpretation of the geomorphic source of seismic signals (Dietze 2018).

Basic forms of the characteristic space and time scales of STC can be hypothesized from literature reviewed above and geomorphic intuition (Fig. 5). Previous findings (Samia et al. 2017a, b) suggested that the creation of a lower permeable layer in the
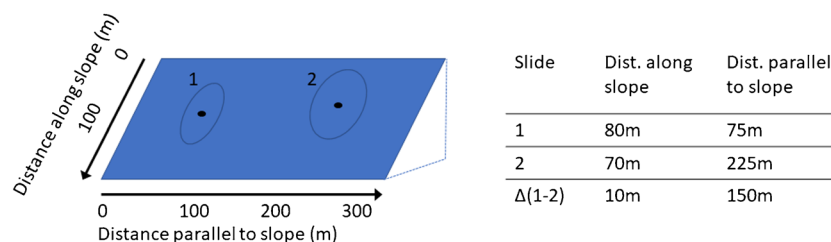

Slide	Dist. along slope	Dist. parallel to slope
1	80m	75m
2	70m	225m
Δ(1-2)	10m	150m

Fig. 4 Illustration of the use of distance along slope and distance parallel to slope to characterize landscape position, and difference in landscape position between landslides. Two example landslides are shown with their geometric centers

subsoil was responsible for path dependence at the characteristic spatial scale of about 60 m, and a characteristic timescale of about 17 years, observed in the Collazzone area. They hypothesized that vegetation growth (from arable crops rooting between 50 and 100 cm) was responsible for the deterioration and ultimate removal of the impermeable layer over the 17-year timescale. Bioturbation by soil fauna and other pedogenetic processes of soil structural development may aid this process (Mirus et al. 2017) and should be studied in a chronosequence setting.

Ultimately, the temporal extent of the impact of individual landslides and the landslide recurrence timescale determine whether a landscape experiences "correlated" landsliding or "path-dependent" landsliding (Fig. 2). A landscape experiences "path-dependent" landsliding if landslides influence the susceptibility for later landslides and landslides typically reoccur while the transient effect lasts. If landslides reoccur after the transient effect has decayed, landsliding is "correlated," or potentially "uncorrelated" if relation to controlling landscape factors is not apparent. If landslides do not influence the susceptibility for later landslides at all, a landscape also experiences "correlated" or potentially "uncorrelated" landsliding.

Slow, long-lived earthflows create the conditions for their own local continuation for hundreds or thousands of years (the "bathtub" mechanism of path dependence, Crandell and Varnes 1961; Fleming and Baum 1999). Shallow landslides that occur on steep slopes with thin soils need local weathering and sediment accumulation to develop regolith for a subsequent failure (the "exhaustion" mechanism sensu Phillips (2003), leading to negative clustering over short distances and long times). Earthquakes cause an increase in landslide susceptibility over a large area for a few years after the earthquake, translate into a third mechanism where later landslides are not affected by previous landslides but by temporary reduction in ground strength (the "earthquake" mechanism, e.g., Marc et al. (2015)).

Two elements are necessary to test predictions of the characteristic spatial and temporal scale of different mechanisms. First, detailed multi-temporal landslide inventories need to be more widely available, as discussed above. Second, confirmation is required of the impacts of earlier landslides on the landscape that may affect susceptibility for later landslides. In some cases, these impacts can be remotely sensed, for instance, when landslides cause substantial changes to surface topography or vegetation density that affect the susceptibility for later landsliding. In other cases, field investigations will be needed to determine changes made by earlier landslides, for instance, in the case of thin, buried clay layers of low permeability. These investigations should seek to detail the possible impact of previous landslides on hillslope hydrology, soil and hillslope mechanical properties, and vegetation status.

Separately, landslide path dependency has implications for the validity of the concept of topographic equilibrium. Topographic equilibrium is the situation where landscapes experience equal rates of uplift and erosion, leading to no net change in altitude or morphology (Thorn and Welford 1994). The concept has been criticized on the grounds that driving factors such as climate and uplift rate can rarely be assumed stable over the timescales needed to achieve equilibrium (Phillips 2010). Path dependence adds to that criticism because of its implication that a series of landslides, causally related to each other, can accelerate mass transport and denudation from one hillslope above uplift rates, whereas similar nearby slopes remain relatively stable, perhaps below uplift rates, because they did not experience the initial landslide. In this case, it is not the temporal stability of the driving factors that limits the applicability of the equilibrium concept, but the long-lived landscape response to small spatial variations in them that kick-start series of landslides.

Soil-landscape modeling

In the case of reactivation, continuation, and local activation, landslide path dependency involves coupled feedbacks between localized geomorphic processes (e.g., landsliding) and soil-forming processes (e.g., formation of a clay-rich subsoil that hampers drainage or the slow disruption of thin smeared clay layers by plant roots). A proper test of our understanding of these feedbacks requires that we predict their implications and contrast these with observations. Specifically, it would be necessary to predict path-dependence parameters for different geomorphic, climatic, and lithologic settings, and contrast these with empirical values of the parameters observed from multi-temporal inventories. Soil-landscape evolution models (SLEMs, Minasny et al. 2015) are currently able to simulate the range of relevant geomorphic and pedologic processes and record possible emergent landslide path dependence. However, such models may need to improve their representation of hillslope and soil hydrology relative to current capabilities given the crucial role of hydrology in landslide triggering processes (van der Meij et al. 2018).

Optimal use of dynamic susceptibility maps

Susceptibility maps that explicitly account for path dependency are dynamic: susceptibility values near previous landslides change as a function of time following the occurrence of nearby previous landslides (Samia et al. 2018), although permanent location characteristics such as aspect or slope curvature also play a role. This raises the question of how to optimally communicate landslide susceptibility. Several options exist. The first is communicating only the static portion of a dynamic susceptibility map, i.e., the susceptibility map that shows only the effect of static explanatory factors after the effects of previous landslides have practically disappeared. The second is communicating the complete dynamic susceptibility map, and the third is communicating only the dynamic portion of the map.

The optimal mapping product for communication likely depends on the target audience. Engineers, landscape architects, and others who make decisions about infrastructure and buildings for the long term may be best helped by the static portion of a dynamic susceptibility map, whereas farmers and agroforesters may be more interested in the complete dynamic susceptibility map, or even only the dynamic portion of the map that shows regions likely to be affected in the next growing seasons or years. Operational landslide forecasters would be interested in both the static and the dynamic portions of susceptibility maps. The choice for optimal mapping products should be the topic of further study, particularly study involving stakeholders such as railroad and utility companies, farmer cooperatives, and insurance agencies (Fuchs et al. 2017).

These implications for susceptibility maps and models extend to maps and models using the newly introduced concept of landslide intensity. Landslide intensity and models that estimate it (Lombardo et al. 2019) deal with landslides as a scalar (number of slides in a mapping unit) as opposed to a binary variable
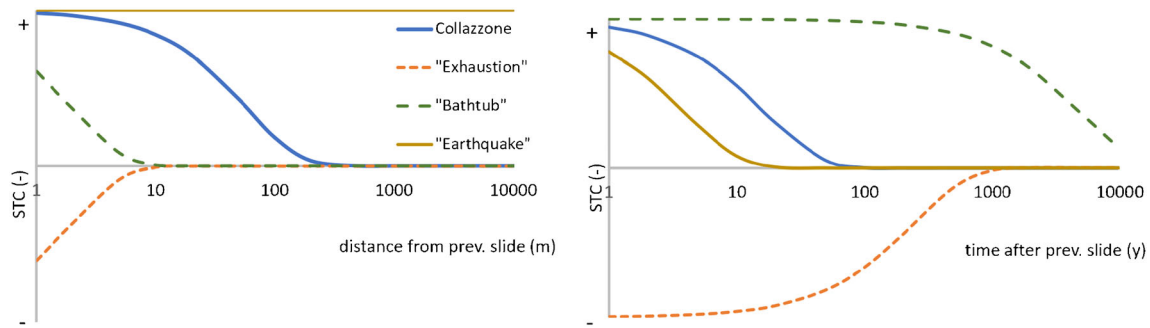
Fig. 5 Example STC dependence on distance in space (left) and time (right) for two geomorphic processes and the Collazzone dataset. "Exhaustion" fits with sediment-limited landsliding, where weathering of bedrock limits the susceptibility for later landslides over short spatial and long temporal scales; "bathtub" follows from work on slow earthflows that increase susceptibility for their own continuation or reactivation over short spatial and long temporal scales; "earthquake" denotes the temporary increase in landslide susceptibility over areas > 100 km^2 after an earthquake

(presence or absence of slides in a mapping unit). This potentially allows for a better distinction between different susceptibility levels, especially for larger mapping units that can contain multiple slides. Landslide path-dependent systems, where earlier landslides conditionally cause later landslides, could be distinguished within this system from correlated systems within an adapted intensity concept that takes time into account (for instance, with a variable expressed in number of slides in a mapping unit per unit time). Intensity, with that unit, would be constant over time for correlated landsliding, but not for path-dependent landsliding.

Conclusions

For more than a century, in a wide range of study sites and for different landslide types, researchers have observed that initial landslides can influence subsequent landsliding. Landslide-on-landslide effects are apparently prevalent across geomorphic settings. We introduce here a new framework and terminology intended to facilitate the assessment of landslide influences on subsequent landsliding and the communication of findings of such assessments. The framework focuses on landsliding systems rather than individual landslides and is thus largely complementary to existing frameworks for landslide classification.

The expected increased availability of large multi-temporal landslide inventories fueled by more frequent availability of high-quality remotely sensed imagery in the near future will likely facilitate further analysis of landslide-on-landslide systems. In our opinion, such further analysis should focus on the identification of landscapes that experience landslide-on-landslide effects (i.e., path dependency), the quantification of the main parameters of such effects (i.e., the characteristic space and time scales of the decaying impact of earlier landslides on later landslides), and the explanation and exploitation of differences in landslide-on-landslide effects between regions.

Accounting for landslide path dependency will result in dynamic landslide susceptibility assessments, where the susceptibility of a given location to landsliding will change over timescales of human interest. Design of optimal use of the static and dynamic portions of such assessments should involve discussions with stakeholders ranging from landscape planners to operational landslide forecasters, so that the future of landslides' past can improve a range of professional practices.

References

Alvioli M, Marchesini I, Reichenbach P, Rossi M, Ardizzone F, Fiorucci F, Guzzetti F (2016) Automatic delineation of geomorphological slope units with <tt>r.slopeunits v1.0</tt> and their optimization for landslide susceptibility modeling. Geosci Model Dev 9:3975–3991. https://doi.org/10.5194/gmd-9-3975-2016

Baum RL, Reid ME (2000) Groundwater isolation by low-permeability clays in landslide shear zones. In: Bromhead E, Dixon N, Ibsen M (eds) Landslides in Research, Theory and Practice. Proceedings of the 8th International Symposium on Landslide. Thomas Telford, London, p 139–144

Bennett GL, Roering JJ, Mackey BH, Handwerger AL, Schmidt DA, Guillod BP (2016) Historic drought puts the brakes on earthflows in Northern California. Geophys Res Lett 43:5725–5731. https://doi.org/10.1002/2016GL068378

Collins BD, Reid ME (2019) Enhanced landslide mobility by basal liquefaction: the 2014 State Route 530 (Oso), Washington, landslide. GSA Bull. https://doi.org/10.1130/B35146.1

Crandell, D.R., Fahnestock, R.K., 1965. Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington, Bulletin https://doi.org/10.3133/b1221A

Crandell DR, Varnes DJ (1961) Movement of the slumgullion earthflow near Lake City, Colorado. In: Short Papers in the Geologic and Hydrologic Sciences, pp B136–B139

Cruden DM, Varnes DJ (1996) Chapter 3: landslide types and processes. In: Turner A, Schuster R (eds) landslide: investigation and mitigation. National Academy Press, pp 36–75

Dietze M (2018) The R package "eseis"–a software toolbox for environmental seismology. Earth Surf Dyn 6:669–686. https://doi.org/10.5194/esurf-6-669-2018

Dupree HK, Taucher GJ, Voight B (1979) Bighorn Reservoir Slides, Montana, U.S.A. Dev Geotech Eng 14:247–267. https://doi.org/10.1016/B978-0-444-41508-0.50014-4

Fleming, R.L., Baum, R.L., 1999. Map and description of the active part of the Slumgullion landslide, Hinsdale County, Colorado

Fuchs S, Röthlisberger V, Thaler T, Zischg A, Keiler M (2017) Natural hazard management from a coevolutionary perspective: exposure and policy response in the European Alps. Ann Am Assoc Geogr 107:382–392. https://doi.org/10.1080/24694452.2016.1235494

Galli M, Ardizzone F, Cardinali M, Guzzetti F, Reichenbach P (2008) Comparing landslide inventory maps. Geomorphology 94:268–289. https://doi.org/10.1016/j.geomorph.2006.09.023

Galve JP, Gutiérrez F, Cendrero A, Remondo J, Bonachea J, Guerrero J, Lucha P (2009) Predicting sinkholes by means of probabilistic models. Q J Eng Geol Hydrogeol 42:139–144. https://doi.org/10.1144/1470-9236/08-039

Galve JP, Remondo J, Gutiérrez F (2011) Improving sinkhole hazard models incorporating magnitude-frequency relationships and nearest neighbor analysis. Geomorphology 134:157–170. https://doi.org/10.1016/j.geomorph.2011.05.020

Guerriero L, Revellino P, Coe JA, Focareta M, Grelle G, Albanese V, Corazza A, Guadagno FM (2013) Multi-temporal maps of the Montaguto earth flow in Southern Italy from 1954 to 2010. J Maps 9:135–145. https://doi.org/10.1080/17445647.2013.765812

Guzzetti F, Galli M, Reichenbach P, Ardizzone F, Cardinali M (2006) Landslide hazard assessment in the Collazzone area, Umbria, central Italy. Nat Hazards Earth Syst Sci 6:115–131. https://doi.org/10.5194/nhess-6-115-2006

Haase P (1995) Spatial pattern analysis in ecology based on Ripley's K-function: introduction and methods of edge correction. J Veg Sci 6:575–582. https://doi.org/10.2307/3236356

Heim A (1932) Bergsturz und Menschenleben. Fretz & Wasmuth, Zurich

Hengl T, Reuter HI (2009) Geomorphometry: concepts, software, applications. Dev Soil Sci 33:772

Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. Landslides 11:167–194. https://doi.org/10.1007/s10346-013-0436-y

Hutchinson JN, Bhandari RK (1971) Undrained loading, a fundamental mechanism of mudflows and other mass movements. Géotechnique 21:353–358. https://doi.org/10.1680/geot.1971.21.4.353

Iverson RM, George DL, Allstadt K, Reid ME, Collins BD, Vallance JW, Schilling SP, Godt JW, Cannon CM, Magirl CS, Baum RL, Coe JA, Schulz WH, Bower JB (2015) Landslide mobility and hazards: implications of the 2014 Oso disaster. Earth Planet Sci Lett 412:197–208. https://doi.org/10.1016/J.EPSL.2014.12.020

Jansen RB (1988) Advanced dam engineering for design, construction, and rehabilitation. Van Nostrand Reinhold. https://doi.org/10.1007/978-1-4613-0857-7

Jones FO, Embody DR, Peterson WL, Hazlewood RM (1961) Landslides along the Columbia River valley, northeastern Washington, with a section on seismic surveys. Professional Paper. https://doi.org/10.3133/PP367

Keller B (2017) Massive rock slope failure in Central Switzerland: history, geologic–geomorphological predisposition, types and triggers, and resulting risks. Landslides 14:1633–1653. https://doi.org/10.1007/s10346-017-0803-1

Korup O, Crozier M (2002) Landslide types and geomorphic impact on river channels, Southern Alps, New Zealand. In: Rybar J, Stemberk J, Wagner P (eds) Landslides. Swets & Zeitlinger, Lisse, pp 233–238

Korup O, Wang G (2015) Multiple landslide-damming episodes. Landslide Hazards, Risks and Disasters:241–261. https://doi.org/10.1016/B978-0-12-396452-6.00008-2

Lombardo L, Bakka H, Tanyas H, Westen C, Mai PM, Huser R (2019) Geostatistical modeling to capture seismic-shaking patterns from earthquake-induced landslides. J Geophys Res Earth Surf 124:1958–1980. https://doi.org/10.1029/2019JF005056

Lynch HJ, Moorcroft PR (2008) A spatiotemporal Ripley's K-function to analyze interactions between spruce budworm and fire in British Columbia, Canada. Can J For Res 38:3112–3119. https://doi.org/10.1139/X08-143

Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P (2004) Landslide inventories and their statistical properties. Earth Surf. Process. Landforms 29:687–711. https://doi.org/10.1002/esp.1064

Marc O, Hovius N, Meunier P, Uchida T, Hayashi S (2015) Transient changes of landslide rates after earthquakes. Geology 43:883–886. https://doi.org/10.1130/G36961.1

Meyer JH (1806) Der Bergfall Bey Goldau Im Canton Schwyz, Am Abend Des Zweyten Herbstmonats 1806. Orell, Fussli and company, Zurich

Minasny B, Finke P, Stockmann U, Vanwalleghem T, McBratney AB (2015) Resolving the integral connection between pedogenesis and landscape evolution. Earth-Science Rev. 150:102–120. https://doi.org/10.1016/j.earscirev.2015.07.004

Mirus BB, Smith JB, Baum RL (2017) Hydrologic impacts of landslide disturbances: implications for remobilization and hazard persistence. Water Resour Res 53:8250–8265. https://doi.org/10.1002/2017WR020842

Moore DP, Mathews WH (1978) The Rubble Creek landslide, southwestern British Columbia. Can J Earth Sci 15:1039–1052. https://doi.org/10.1139/e78-112

Phillips JD (2003) Sources of nonlinearity and complexity in geomorphic systems. Prog Phys Geogr 27:1–23

Phillips J (2009) Changes, perturbations, and responses in geomorphic systems. Prog Phys Geogr 33:17–30. https://doi.org/10.1177/0309133309103889

Phillips JD (2010) The convenient fiction of steady-state soil thickness. Geoderma 156:389–398

Phillips JD, Pawlik Ł, Šamonil P (2019) Weathering fronts. Earth-Science Rev. 198. https://doi.org/10.1016/j.earscirev.2019.102925

Reichenbach P, Rossi M, Malamud BD, Mihir M, Guzzetti F (2018) A review of statistically-based landslide susceptibility models. Earth-Science Rev 180:60–91. https://doi.org/10.1016/J.EARSCIREV.2018.03.001

Ripley BD (1976) The second-order analysis of stationary point processes. J Appl Probab 13:255–266. https://doi.org/10.2307/3212829

Salinas-Jasso JA, Salinas-Jasso RA, Montalvo-Arrieta JC, Alva-Niño E (2017) Inventario de movimientos en masa en el sector sur de la Saliente de Monterrey. Caso de estudio: cañón Santa Rosa, Nuevo León, noreste de México. Rev. Mex. Ciencias Geológicas 34:182. https://doi.org/10.22201/cgeo.20072902e.2017.3.459

Samia J, Temme A, Bregt A, Wallinga J, Guzzetti F, Ardizzone F, Rossi M (2017a) Characterization and quantification of path dependency in landslide susceptibility. Geomorphology 292:16–24. https://doi.org/10.1016/j.geomorph.2017.04.039

Samia J, Temme A, Bregt A, Wallinga J, Guzzetti F, Ardizzone F, Rossi M (2017b) Do landslides follow landslides? Insights in path dependency from a multi-temporal landslide inventory. Landslides 14. https://doi.org/10.1007/s10346-016-0739-x

Samia J, Temme A, Bregt A, Wallinga J, Stuiver J, Guzzetti F, Ardizzone F, Rossi M (2018) Implementing landslide path dependency in landslide susceptibility modelling. Landslides 15:2129–2144. https://doi.org/10.1007/s10346-018-1024-y

Samia J, Temme A, Bregt A, Wallinga J, Guzzetti F, Ardizzone F (2020) Dynamic path dependent landslide susceptibility modelling. Nat Hazards Earth Syst Sci 20:271–2020. https://doi.org/10.5194/nhess-20-271-2020

Sarkar S (1999) Landslides in Darjeeling Himalayas, India. Chikei 20:299–315

Schuster RL (2006) Impacts of landslide dams on mountain valley morphology. In: landslides from massive rock slope failure. Springer Netherlands, Dordrecht, pp 591–616. https://doi.org/10.1007/978-1-4020-4037-5_31

Schuster RL, Costa JE (1986) Landslide dams: processes, risk and mitigation: proceedings of a session. In: Landslide dams: processes, risk, and mitigation. Proceedings of a Session in Conjunction with the ASCE Convention. ASCE, p. 164

Sharpe CFS, Charles FS (1938) Landslides and related phenomena, 1st edn. Columbia university press, New York

Taylor FE, Malamud BD, Witt A, Guzzetti F (2018) Landslide shape, ellipticity and length-to-width ratios. Earth Surf Process Landforms 43:3164–3189. https://doi.org/10.1002/esp.4479

Thorn CE, Welford MR (1994) The equilibrium concept in geomorphology. Ann Assoc Am Geogr 84:666–696. https://doi.org/10.1111/j.1467-8306.1994.tb01882.x

Thuro K, Berner C, Eberhardt E (2006) The 1806 landslide of Goldau-200 years after the event [Der Bergsturz von Goldau 1806–200 Jahre nach dem Ereignis]. Felsbau 24:59–66

Van Den Eeckhaut M, Poesen J, Dewitte O, Demoulin A, De Bo H, Vanmaercke-Gottigny MC (2007) Reactivation of old landslides: lessons learned from a case-study in the Flemish Ardennes (Belgium). Soil Use Manag 23:200–211. https://doi.org/10.1111/j.1475-2743.2006.00079.x

van der Meij WM, Temme AJAM, Lin HS, Gerke HH, Sommer M (2018) On the role of hydrologic processes in soil and landscape evolution modeling: concepts, complications and partial solutions. Earth-Science Rev. 185:1088–1106. https://doi.org/10.1016/j.earscirev.2018.09.001

Varnes DJ (1978) Slope movement types and processes. Transp Res Board Spec Rep 176:11–33

Wood SN, Pya N, Saefken B (2016) Smoothing parameter and model selection for general smooth models (with discussion). J Am Stat Assoc 111:1548–1575

Xinbin T, Fuchu D, Kwong AKL, Tham LG, Ling X (2010) Causes of recurring landslides in loess Plateau, Shaanxi Province, China. HKIE Trans 17:36–44. https://doi.org/10.1080/1023697X.2010.10668186

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