Invited review

Dynamic earth system and ecological controls of rainfall-initiated landslides

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A B S T R A C T

Rainfall-initiated landslides continue to inflict damages and loss of life throughout the world. Processes and mechanisms revealed from hydrological, geomorphic, geotechnical, pedological, geological, hydrochemical, and biological investigations have advanced our understanding of these effects on slope stability; however, the interactions amongst these processes and attributes as they affect the initiation and propagation of landslides are not as well understood. Too often landslide studies are conducted from only one, or at most, two of these perspectives. Moreover, while precipitation and hydrology are recognized as dynamic influences, the earth system and ecological effects are often assumed to be static. We assess the interplay of these processes related to landslides triggered by positive pore water accretion and loss of soil suction. Each of these conditions arguably requires a different view on the processes that cause slope failure and predictive approaches.

This review starts from the perspective of dynamic, adapting earth and ecological systems and discusses how these attributes relate to landslide initiation, mode, location, and timing. Specifically, the role that large- and small-scale preferential flow plays in both contributing to and mitigating instability is elucidated, including effects of bedrock exfiltration. We also examine how and under what conditions these pathways manifest in different soils, lithology, and landforms. The multiple effects of rhizosphere processes on slope stability are discussed, including root reinforcement, evaporation from canopies and litter layers, transpiration, and the role of root structure affecting preferential flow paths.

Rainfall-initiated landslides involve highly dynamic hydrologic, earth surface, and ecological processes that persist over a range of spatial and temporal scales; however, guidance for overcoming these challenges has been elusive. A conceptual framework is presented to shed light on these dynamic and interactive processes that should lend insights into why and when certain slopes fail during storms, while other seemingly similar slopes do not fail. Such advances will benefit landslide hazard assessments and disaster responsiveness protocols.

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1. Introduction

Hydrology is redefining its role in earth and environmental sciences with a concurrent increase in hydrogeomorphic and ecohydrology research appearing in journals. The subsurface is no longer viewed as a static property through which water flows. Ehret et al. (2014) discuss pathways of new knowledge in catchment hydrology highlighting that previous engineering concepts of stationarity of various catchment boundary conditions do not hold for hydrological systems. Furthermore, they recognize that biotic, abiotic and anthropogenic factors all should be considered. These ideas are well aligned with the recent Pantra Rhei initiative launched by the International Association of Hydrological Sciences, which advocates broadening the focus of hydrological sciences (Montanari et al., 2014). Earth and environmental scientists have long recognized these dynamics and process feedbacks within regoliths (e.g., Selby, 1974; Swanson et al., 1988; Okunishi, 1991; Onda, 1992; Scatena and Lugo, 1995; Bogaard et al., 2000; Sidle et al., 2001; Chigira and Yokoyama, 2005; Binet et al., 2007), but the extent to which hydrologic dynamics have been captured and quantified in these investigations leaves something to be desired, partly due to scaling issues. This concept of dynamic hydro-eco-geomorphology is especially relevant for hydrological processes associated with rainfall-initiated landslides because landslides, by definition, are dynamic systems.

Mass movements are natural geomorphic processes that shape the landscape and provide both episodic and chronic inputs of sediments to streams and rivers: thus, they are an important part of the dynamic earth surface environment at various scales (Dunne, 1991; Benda and Dunne, 1997; Gomi et al., 2002; Korup, 2005; Imaiuzumi and Sidle, 2007; Kuo and Brierley, 2014). These movements scale from surficial processes to deep-seated landslides and occur throughout a wide range of temporal scales. Anthropogenic activities affect the occurrence of these mass wasting processes, and when property and lives are affected, these natural processes become socio-economic disasters. Estimates of landslide-related fatalities are fraught with difficulty because of inconsistent reporting amongst nations of differing socioeconomic status (Sidle and Ochiai, 2006). However, a recent global survey of non-seismic triggered landslides reported an average of 4617 deaths per year over a 7-yr period (Petley, 2012), much higher than a previous report of about 600 deaths per year for all types of landslides (Varnes, 1981).

Although slope failures can be initiated by earthquakes, volcanic activity, fluvial processes, and glacial retreat, the most common cause of landslides is hydrologic: rainfall and snowmelt inputs. The focus of most landslide investigations has typically been on either small-scale hydrologic processes and how these affect soil mechanical properties or on broader-scale, more descriptive studies that address geomorphic, geologic, and geophysical attributes of unstable terrain. The former typically includes theoretical, geotechnical, and soil hydrology laboratory and field investigations frequently coupled with modeling approaches (e.g., Collins and Znidaric, 2004; Mukhlisin et al., 2006; Perrone et al., 2008; Baum et al., 2010; Gerner and Braun, 2011; Mancarella et al., 2012; Terajima et al., 2014). On the other hand, broader-scale slope stability studies commonly use temporally explicit data from remote and terrestrial sensing, terrain mapping, and topographic analysis; these data are sometimes incorporated into empirical models (e.g., Carrara et al., 1991; Dhakal et al., 2000; Lee, 2005; Ghosh et al., 2011; Guzzetti et al., 2012). One of the challenges in translating laboratory-based investigations on geotechnical behavior of soils to field scales where landslides occur is the representation of large-scale hydrological processes and flow paths that occur in heterogeneous and anisotropic regoliths (Bogaard and Greco, 2015). These processes are not only affected by the spatial distribution and temporal evolution of regolith properties, but also by geomorphic attributes (e.g., Dunne, 1991; Terajima and Sakura, 1993; Noguchi et al., 1999; Bogaard et al., 2000; Sidle et al., 2000; Uchida et al., 2001; Gerscovich et al., 2006; Ghestem et al., 2011). As such, the emerging sciences of hydrogeomorphology (e.g., Dunne, 1994; Sidle and Onda, 2004) and hydropedology (e.g., Lin et al., 2006) are very germane to recent discussions on hydrology and dynamic earth systems, including how to quantify these effects and capture them in landslide models.

The goal of this paper is twofold. First we synthesize major developments in hydro-eco-geomorphic processes that affect rainfall-initiated landslides with the ultimate objective to describe niches where new research is needed that will advance understanding of the dynamics of both hillslope and earth system processes linked to these slope failures. Second, we present a conceptual framework of hydro-eco-geomorphic controls on these landslides that aims to elucidate the relative importance and interactions of these controls with the ultimate objective of guiding future landslide research.

2. Shallow and deep-seated rainfall-initiated landslides

Landslides are conveniently divided into shallow and deep-seated types with the former being ~2 m deep (Caine, 1980; van Asch et al., 1999; Sidle and Ochiai, 2006). The soil mantle or regolith provides both a buffer and a pathway for rainwater percolating to a potential failure plane. In the case of shallow, rapid landslides on hillslopes (Fig. 1a), the failure plane is usually located at a hydrologic discontinuity – e.g., the soil – bedrock interface or above a very low hydraulic conductivity C horizon (Harr, 1977; Sidle et al., 1985; Dhakal and Sidle, 2004a; Vieira and Fernandes, 2004). In these cases, a positive pore water pressure forms above this discontinuity either during rainfall or snowmelt, thus triggering the landslide (Sidle and Swanston, 1982; Harp et al., 1990; Kuriakose et al., 2008). The development of positive pore water pressure in the soil mantle is not an essential prerequisite of slope failure; landslides triggered by a loss of suction during the progressive wetting of the soil or regolith accompanied by an increase in overburden weight from the infiltrating rain water have been reported (Sasaki et al., 2000; Chigira and Yokoyama, 2005; Lacerda, 2007; Godt et al., 2009).

Deep-seated landslides, both rapid and slow-moving, are also controlled by water routing through the regolith (Bisci et al., 1996; van Asch et al., 1999; Bogaard et al., 2000; Bogaard and van Asch, 2002; Coe et al., 2003). Slow, deep-seated landslides (e.g., slumps and earthflows; Fig. 1c) typically require an extended period of water recharge to initiate movement (e.g., Iverson and Major, 1987; Malet et al., 2002), while rapid, deep-seated failures may initiate by either direct response to individual storms (e.g., Sidle and Chigira, 2004; Fig. 1b) or prolonged water inputs (e.g., Rogers et al., 1999; Zêvere et al., 2005). The location and timing of rainfall-initiated landslides, both shallow and deep-seated, within the landscape remains a complex and unresolved issue. As such, hydrologic response in the soil mantle together with soil physical, geotechnical, mineralogical, root strength and geomorphic properties, basically determine the depth as well as mode (i.e., slow to rapid) of failure (Wu and Sidle, 1995; Iverson, 2000; Lu et al., 2012; Milledge et al., 2014); these aspects are discussed in detail in the sections that follow.
3. Overview of dynamic earth system and ecological processes that affect landslides

Dynamic earth and ecosystem processes continually alter hillslopes and may either increase or decrease their stability. The rate of these changes depends on the dominance of particular processes and the geographic setting. The most important dynamic processes that affect landslide susceptibility include tectonics, weathering, geomorphic adjustments, vegetation, and, of course, hydrological influences. Several or all of these processes act together, but often at different space and time scales. Climate and meteorology affect or interact with all of these processes.

3.1. Tectonics

Tectonic compression and uplift and related faults have produced large areas of regolith deformation, particularly in the circum-Pacific region, as well as in the Himalaya, Tien Shan, Apennines, and European Alps. Neotectonic deformations destabilize slopes by fracturing, faulting, folding, and jointing (e.g., Ibetsberger, 1996; Pachauri et al., 1998; Carlini et al., 2016). The resultant weak rock provides opportunities for rapid weathering and regrading of slopes by mass movements (Pearce et al., 1981; Weidinger et al., 1996; Strecker et al., 2003; Carlini et al., 2016). In active tectonic regions, the relative importance of mountain uplifting, slope gradient, precipitation, regolith strength, and vegetation recovery on rates of landsliding has been strongly debated (e.g., Koons, 1989; Roering et al., 2001; Montgomery and Brandon, 2002; Blodgett and Isacks, 2007; Korup, 2008; Haberland et al., 2011); however, at least some of this research suggests that contemporary sculpting of landscapes is controlled by interactions amongst several of these processes. Bedrock fracture systems that develop in tectonic environments, including those induced by associated earthquakes, alter hydrologic pathways that affect pore pressure response, thus contributing to slope instability (e.g., Mikoš et al., 2004; Roessner et al., 2005).

3.2. Weathering processes

Enhanced weathering and soil formation in modified regoliths can also affect the reoccurrence of landslides (Sonoda and Okunishi, 1994; Chigira et al., 2002; Meisina, 2006). Both physical and chemical weathering of the regolith affects mineralogical composition, regolith strength, and hydrologic pathways (Chigira, 2001; Wakatsuki et al., 2005). Biological weathering contributes to physical and chemical processes through: (1) addition of organic materials (plant tissues and fauna) and their decomposition products; (2) interactions of vegetation roots with regoliths; and (3) other bioturbations (Bormann et al., 1998; Wilkinson and Humphreys, 2005; Phillips and Lorz, 2008; Pawlik et al., 2013). Typically weathering proceeds from the substrate surface inward, but chemical weathering may occur deep within the regolith via dissolution and preferential flow (Chigira, 2002; Wen et al., 2004; Wakatsuki et al., 2005). Weathering of metamorphic and metamorphosed sedimentary rocks is accelerated by shearing and fracturing, creating clay-rich regoliths that are susceptible to earthflows and soil creep (Swanson, 1978; Harden et al., 1981). Weathered, tectonically-altered sedimentary clay-shales, which experience widespread landsliding, exhibit complex patterns of microstructure, fissures, and strength properties that can rapidly change due to fast weathering processes (Picarelli et al., 2000; Bogaard et al., 2012). At smaller scales, the highly altered regolith affects hydrologic pathways, which can lead to pore pressure accretion either within the bedrock or overlying soil mantle (Fernandes et al., 2004, Debieche et al., 2012). Because of these internal alterations to mineralogical, hydrological, and mechanical attributes of regoliths, weathering profiles may determine the slip zone of landslides (e.g., Keefer and Johnson, 1983; Moore and Brunsden, 1996, Chigira, 2001; Wen et al., 2004; Andersson-Sköld et al., 2005; Yamao et al., 2016). Better understanding of the interaction of weathering processes with subsurface water movement and pore pressure generation should greatly benefit landslide assessments (e.g., Chigira, 2003; Di Maio et al., 2004; Sidle and Ochiai, 2006).

3.3. Geomorphic adjustments

Geomorphology, particularly slope shape and gradient, profoundly affects slope stability. Convergent topography concentrates subsurface flow and these geomorphic hollows in steep terrain (also called zero-order basins) have long been recognized as sites of recurrent shallow and moderate-depth landslides (Hack and Goodlett, 1960; Dietrich et al., 2016).
Fig. 2. (A) Geomorphic hollows are concave slope segments that concentrate shallow groundwater and are often sites of previous landslides in steep terrain; Coweeta, North Carolina USA. (B) Soil recovery in a geomorphic hollow following a landslide based on Eq. (1); $d_0 = 1$ m; $d_f = 0$ m; and $t_i = 40$ and 250 years, respectively, for the rapid and slow recovery scenarios. (C) Changes in $u_{\text{crit}}$ during soil accretion for the two recovery scenarios based on Eq. (3) for a mountain soil in Pacific Northwest USA; $C = 4$ kPa; $\gamma_f = 15$ kN m$^{-2}$; $d = 1$ m; $\alpha = 42^\circ$; and $\phi = 35^\circ$.

and Dunne, 1978; Sidle, 1984; Fernandes et al., 1994) (Fig. 2a). Once these sites fail, a series of interacting hydrologic, geomorphic, hydrogeological, and biological processes occur over both the short- and long-term to reestablish the soil mantle (Dietrich and Dunne, 1978; Okunishi and lida, 1981; Shimokawa, 1984; Heimsath et al., 1997; Sasaki et al., 2000; Imaizumi et al., 2013). This recovery can be quantified by a sigmoidal relationship (Sidle, 1987; Sidle and Ochiai, 2006), wherein soil accretion is rapid at first, dominated by surface wash, sloughing around the landslide scarp, dry ravel, inputs of wood debris, root wedging, and bioturbations, and becomes progressively slower with time as more chronic processes like soil creep, surface wash, and weathering dominate:

$$d_t = d_0 + ae^{bt}$$

where $d_t$ is the vertical soil depth (m) at time $t$ (yr) after landslide occurrence, $d_0$ is the soil depth (m) in the hollow just after the landslide, $a = d_a - d_q$ where $d_a$ represents the upper limit of soil accretion, and $b$ is $-2t_i$, where $t_i$ and $d_i$ are the $x$ and $y$ coordinates at the inflection point of the soil recovery curve. This relationship appears to be applicable for both drier environments, where soil accretion is relatively slow, and temperate and tropical climates, where infilling and weathering is rapid (Sidle and Ochiai, 2006).

An example of soil accretion after failure of a hollow is shown for hillslope soil conditions typical of coastal ranges in the Pacific Northwest USA (Fig. 2b). The rate of accretion of soil together with the occurrence of a large storm determines the timing of the subsequent landslide in the hollow – a process that can range from several decades to tens of thousands of years (Reneau et al., 1986; Shimokawa et al., 1989; DeRose, 1996; Heimsath et al., 2001; Imaizumi et al., 2015a). As a first assessment, we employ the simple infinite slope equation to analyze the dynamic stability of hollows, assuming that a planar landslide will initiate by accretion of a critical level of positive pore water pressure ($u_{\text{crit}}$) in the hollow and ignoring effects of unsaturated seepage forces:

$$F_S = \frac{C + (\gamma_f d \cos^2 \alpha - u) \tan \phi}{\gamma_f d \cos \alpha \tan \phi}$$

where $F_S = \text{factor of safety}$, $\gamma_f = \text{unit weight of soil at field moisture (kN m}^{-3}$), $d = \text{vertical soil depth (m)}$, $C = \text{soil cohesion (kPa)}$, $\alpha = \text{slope gradient (degrees)}$, $\phi = \text{internal angle of friction (degrees)}$, and $u = \text{pore water pressure (kPa)}$. Setting $F_S = 1$ (failure conditions) in Eq. 2 and solving for $u$, $u_{\text{crit}}$ is obtained:

$$u_{\text{crit}} = \frac{C_r f d \cos^2 \alpha - \gamma_f d \cos \alpha \sin \phi}{\tan \phi}$$

where $C_r$ represents combined soil and root cohesion (kPa). By substituting increasing values of $d$ for both rapid and slow infilling rates following failure (Fig. 2b), the critical pore pressure required to trigger a landslide is determined over this continuum (Fig. 2c). It is clear that hollows with more rapid infilling rates can fail again much sooner than those with slower infilling rates. The example presented in Fig. 2c illustrates that a storm which generates saturation in the lower 75% of the soil profile ($u = 4.06$ kPa) will trigger a landslide after only about 220 yr for the rapid rate of soil accretion, but will take 1390 yr for the slow rate. The value selected for $C' = 4$ kPa does not include contributions of root cohesion; introducing root strength dynamics would require a greater soil depth for slope failure to occur (thus a longer period of hollow infilling) associated with a specific pore pressure. The combined effects of seasonally high rainfall, easily weathered substrate, rapid infilling processes, and weak soils promote rapid reoccurrence of shallow landslides in hollows (Shimokawa, 1984; Sonoda and Okunishi, 1994; Sidle and Ochiai, 2006).
3.4. Vegetation influences

Vegetation influences landslide occurrence via multiple trajectories, including root strength, evaporation, transpiration, and root architecture associated with subsurface flow paths. Because most of these processes are linked to root distribution, they may strongly affect shallow landslides where the root systems are dense and penetrate the entire soil mantle. Moreover, for many cases in the rooted zone, reinforcement is a more important slope stabilizing agent than the effects of transpiration or creation of preferential flow paths (Phillips and Watson, 1994; Sidle and Ochiai, 2006).

Vegetation and climate play a large role in modifying soil moisture and subsurface hydrology through transpiration, evaporation from tree canopies and litter, redistribution of rainfall water, and development of preferential flow pathways via live and dead root systems (Keim and Skaugset, 2003; Scott et al., 2003; Gerrits et al., 2010; Ghestem et al., 2011). Transpiration may maintain stability of shallow soil mantles when rather deep-rooted woody species remove water near potential failure planes. However, in temperate regions where storms that trigger shallow landslides occur during fall and winter rainy seasons, soils are typically near field capacity and transpiration is minimal. The major effect in such environments would be to possibly expand the vulnerable period for landslides as affected by antecedent moisture conditions (Megahan, 1983; Sidle and Ochiai, 2006). Limited studies conducted in temperate forests have found little effect of vegetation on modifying pore pressure response during large winter storms that would typically initiate shallow landslides (Dhakal and Sidle, 2004a). The situation may differ in the tropics where vegetation modifies soil moisture year-round (Greenway, 1987; Sidle et al., 2006).

The role of forest canopy and litter layer interception on effective rainfall usually plays only a minor role on modifying shallow soil water and pore pressure propagation (Dhakal and Sullivan, 2014; Sidle and Ziegler, 2016), especially during prolonged wet periods. However, the forest litter layer has a rather constant storage capacity. Gerrits et al. (2010) quantified that evaporation from the litter layer of a beech forest in Luxembourg was 20% of throughfall even during winter, indicating that more research is needed on the interception evaporation from litter layers throughout the year and in different environments. In an application of the spatially-distributed STARWARS model (van Beek, 2002) to the slow moving, intensively monitored Super-Sauze catchment, higher (perched) groundwater, and possibly higher pore water pressures in olders stands; however, soil water will be extracted at different depths during the lifetime of a forest stand. A preliminary modeling study of this age-dependent transpiration effect indicates a significant increase in slope failure probability in such older stands (Meng et al., 2012). No studies appear to have been published combining the dynamic long-term effects of root reinforcement and transpiration at slope and forest-stand scales.

In contrast to root strength development due to forest aging or regeneration after harvesting, there is limited research describing the age-dependent water use of forest stands (Meng et al., 2014). Catchment-scale water resources assessments show that water use by forest stands is high in young forests, but declines significantly as stands age (e.g., Andréassian, 2004). Of course, the exact water use dynamics is species-specific (Fig. 4). For landslide assessment, this implies wetter catchments, higher (perched) groundwater, and possibly higher pore water pressures in olders stands; however, soil water will be extracted at different depths during the lifetime of a forest stand. A preliminary modeling study of this age-dependent transpiration effect indicates a significant increase in slope failure probability in such older stands (Meng et al., 2012). No studies appear to have been published combining the dynamic long-term effects of root reinforcement and transpiration at slope and forest-stand scales.

Roots of woody vegetation provide slope reinforcement by anchoring the lower portion of the soil mantle into more stable substrate, providing a membrane of strength within the soil, binding across planes of weakness, and providing local buttressing support proximate to the trunk and root mass (Gray and Megahan, 1981; Phillips and Watson, 1994; Schmidt et al., 2001; Roering et al., 2003; Sidle and Ochiai, 2006). Debate still persists about the relative roles of the two most important reinforcement mechanisms – anchoring and lateral root cohesion. Although dense root systems of grasses and forbs can contribute to soil strength at small scales and shallow depths, they generally cannot stabilize deeper soils and, as such, provide little or no protection against most landslides (Marden and Rowan, 1993; Bergin et al., 1995).

Slope reinforcement by roots has been extensively documented in field and modeling studies that demonstrate an increase in shallow landslide activity following clearance of woody vegetation (e.g., O’Loughlin and Pearce, 1976; Megahan et al., 1978; Sidle and Wu, 1999; Dhakal and Sidle, 2003; Imaizumi et al., 2008; Imaizumi and Sidle, 2012). Based on these and other investigations, there is a ‘window’ of approximately 3 to 15–20 years after forest clearing that coincides with an increase in landslide rate of about 2 to 10-fold compared to undisturbed forests. This ‘window’ of increased landslide susceptibility corresponds directly to the root strength minimum as modelled by decay of residual roots (after harvesting) followed by regrowth of regenerating vegetation (Sidle, 1991; Sidle et al., 2006) (Fig. 3). The primary landslide trigger mechanism, pore water pressure induced by rainfall, is still required, but the threshold for pore pressure to induce slope failure (Eq. (3)) is lowered during this period of reduced root strength (Sidle, 1992). Additionally, patterns of timber harvesting and natural structure of forest stands impart spatially variable root cohesion within hillslopes, which can influence local stability (Schmidt et al., 2001; Sakals and Sidle, 2004; Bischetti et al., 2009). Conversion of mountain forests to agriculture, pasture, or exotic plantations has much longer-term or even permanent consequences (compared to forest harvesting followed by regeneration) for landslide occurrence (Sidle et al., 2006).

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4. Hydrologic response in dynamic, unstable hillslopes

Hillslope hydrology is driven by temporal and spatial aspects of climate forcing, as well as being locally influenced by tectonics, lithology, geomorphology, weathering, soil development processes, vegetation, and bioturbations. While understanding of small-scale hydrologic mechanisms and patterns is important, it is essential to assess interactive hydro-eco-geomorphic processes at the hillslope and catchment scales because these are the land units in which landslides manifest (e.g., Sidle and Ochiai, 2006; Debieshe et al., 2012). Furthermore, the applicability of Darcy’s law and Richards’ equation to quantify saturated infiltration, leading to rapid and long runout debris flows (e.g., Anderson and Sitar, 1995; Iverson et al., 1997). However, exfiltration from fractured bedrock into the overlying soil mantle can also trigger both shallow and deeper landslides and promote liquefaction (e.g., Montgomery et al., 2002; Sidle and Chigira, 2004; Gerscovich et al., 2006). These two hydrological mechanisms that initiate landslides and promote liquefaction and runout are totally different, involving different hydrologic pathways and timing between the rain events and landslide occurrence. As such, these differences have strong implications for hazard assessment and risk management.

4.1. Positive pore water pressure accretion and effects of preferential flow

Shallow, rapid landslides (debris slides, debris avalanches, and debris flows) commonly initiate in hillslope soils during individual storms with durations of several hours to more than a day, which often exhibit a peak of intensity (Okuda et al., 1979; Sidle and Swanston, 1982; Terlien, 1997; Dhakal and Sidle, 2004b; Hawke and McConchie, 2011). Many of these slope failures are characterized by shallow, relatively low-cohesion soils; steep slopes (>25°); and a failure plane that is oriented approximately parallel to the ground surface (Fig. 1a). As noted previously, shallow landslides often occur in geomorphic hollows where subsurface water accumulates (Hack and Goodlett, 1960; Dietrich and Dunne, 1978; Sidle, 1984). Positive pore water pressure develops just above a hydrologic restrictive layer (e.g., bedrock, till) in rapid response to rainfall infiltration, causing soil shear strength to decline to the point where the slope fails (Harp et al., 1990; Haneberg, 1991; Collins and Znidaric, 2004; Matsuishi et al., 2006); between storms, this portion of the vadose zone is typically unsaturated. The extent of pore water accretion is also influenced by antecedent moisture, with wetter conditions promoting more rapid pore pressure response during storms compared to drier conditions (Haneberg, 1991; Tsuboyama et al., 2000; Kuriakose et al., 2008; Hawke and McConchie, 2011).

Rapid pore pressure accretion appears to be the most common and simplest triggering mechanism for landslides that occurs during an individual storm or prolonged rainfall period of several days; these conditions have been effectively modelled using an infinite slope factor of safety approach (e.g., Montgomery and Dietrich, 1994; Wu and Sidle, 1995). However, questions remain concerning how variability in soil properties, rainfall inputs, hydrologic pathways, and vegetation can effectively be incorporated into predictions (Burton et al., 1998; Dai and Lee, 2002; Haneberg, 2004; Sakals and Sidle, 2004; Schwarz et al., 2011; Zhao et al., 2013) and how to best include complex topographic effects. The highly variable lag times between rainfall occurrence and landslide initiation attest to the complexity of the hydrologic pathways and pore water pressure response.

While rapid, deep landslides and flows represent some of the most hazardous mass failures (Fig. 1b), hydrological processes within the regolith and bedrock that control their initiation, timing, and runout are poorly understood. For example, studies have shown that liquefaction can occur along the sliding plane in saturated cohesionless materials just after initial failure as the result of excess pore water pressure following rainwater infiltration, leading to rapid and long runout debris flows (e.g., Anderson and Sitar, 1995; Iverson et al., 1997). However, exfiltration from fractured bedrock into the overlying soil mantle can also trigger both shallow and deeper landslides and promote liquefaction (e.g., Montgomery et al., 2002; Sidle and Chigira, 2004; Gerscovich et al., 2006). These two hydrological mechanisms that initiate landslides and promote liquefaction and runout are totally different, involving different hydrologic pathways and timing between the rain events and landslide occurrence. As such, these differences have strong implications for hazard assessment and risk management.

Slower, deeper-seated landslides are normally initiated by pore water pressure accretion, but infiltrating precipitation or snow melt water is often buffered by thicker soil mantles, requiring cumulative rain and snow melt events to trigger a slope failure (Iverson and Major, 1987; Angeli et al., 1998; Bogaard and van Asch, 2002; Coe et al., 2003; Malet et al., 2005; Handweiler et al., 2013). These failures usually initiate in less steep terrain compared to shallow landslides and require a threshold of groundwater accretion prior to movement (Fig. 1c). Movement rates are generally slow (much less than 1 m day⁻¹) compared to shallow landslides, but secondary surges
have been reported during unusually wet conditions (e.g., Oyagi, 1977; Marden et al., 2008; van Asch and Malet, 2009; Lollino et al., 2014). Thus, understanding and quantifying groundwater recharge that contributes to pore pressure accretion in these unstable landforms is critical to predicting landslide activation (Bogaard and van Asch, 2002; Sidle and Ochiai, 2006).

For earthflows and other deep-seated landslides, the secondary porosity within the regolith and bedrock greatly controls water routing and thus may affect the observed highly variable timing of reactivation or initiation of such failures (Keefer and Johnson, 1983; Baum and Reid, 1995; Bogaard et al., 2000; Coe et al., 2003). Also, these deeper failures usually have clay-rich soil mantles that are subject to cracking during movement and wetting-drying cycles, which tends to govern the infiltration of water through the soil mantle.

An informative example of a heterogeneous deep-seated landslide with dynamic hydraulic characteristics is the Super-Sauze earthflow in France, which has been intensively monitored and modelled for two decades (Malet et al., 2003, 2005, de Montety et al., 2007; Bogaard et al., 2012; Debieche et al., 2012; Travelletti and Malet, 2012; Travelletti et al., 2012; Krzeminska et al., 2014). The hydromechanical response of this earthflow to rain and snowmelt inputs is strongly controlled by the spatial heterogeneity and temporal dynamics within the complex Super Sauze land mass (Travelletti and Malet, 2012; Travelletti et al., 2012); these conditions, in turn, control the spatially distributed hydrological processes (Malet et al., 2003; de Montety et al., 2007; Debieche et al., 2012; Krzeminska et al., 2014). Krzeminska et al. (2014) characterized infiltration and soil hydrological response in small plots on the landslide complex using sprinkling tests with tracers. Three types of hydrologic behavior were found: (1) areas where infiltration occurs through small desiccation cracks with both matrix and preferential flow facilitating percolation to limited depths and exfiltration occurring; (2) areas with large displacement fissures that support essentially unlimited infiltration capacity and subsequent lateral subsurface flow within the landslide mass; and (3) important areas with limited infiltration capacity (Fig. 5). In addition to the influence of preferential flow on infiltration, Debieche et al. (2012) showed that subsurface heterogeneity (e.g., underlying bedrock topography, unweathered inclusions of clay-shales) strongly affect the hydrological response and thus the stability.

In addition to rainwater recharging the groundwater system, deep concentrated bedrock flow can contribute to the pore water accretion, as reported for shallow landslides. Observing these water flows is difficult although hydrologic and hydrochemical information has been used to successfully detect and quantify these pathways in deep-seated landslides (e.g. Guglielmi et al., 2000; de Montety et al., 2007; Bogaard et al., 2007; Vallet et al., 2015). For example, Cervi et al. (2012) used hydrochemical evidence to show that deep groundwater feeding into the base of a large slump-earthflow through a fault line was the main cause of movement.

Deep-seated, slow moving and re-activated landslides, such as earthflows, are intrinsically unique, but share several hydrological characteristics. As mentioned previously, significant groundwater contributions often occur, and the hydrology in the area surrounding the landslide, the sliding mass, and depositional zone is complex creating nested groundwater systems. Secondary reactivation (e.g., debris flows) within these larger landslides can occur due to water convergence and local liquefaction, and small secondary rotational slides can take place due to undercutting of the slope by small channel incision within or along the landslide deposit. Interestingly, the changes in displacement rates of slow moving, deep-seated landslides are often controlled by relatively small differences in effective stress (Schulz et al., 2009). Furthermore, the conditions under which some deep-seated landslides develop into catastrophic, highly mobile mass movements, while others only modestly re-activate, are linked to small differences in initial conditions, such as antecedent moisture content (Herson et al., 2015). As shown in the intensively monitored and studied Super-Sauze earthflow, the hydrological complexity can be conceptualized, but can we measure these hydraulic effects at the slope scale? In situ hydraulic characteristics of earthflows can be derived using small-scale sprinkling experiments combined with hydrochemical tracers (Krzeminska et al., 2014), but those are laborious and require repeated measurements to capture spatial variability, not to mention their inherent scale limitations. Recent advances in geophysical monitoring, like Electric

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Fig. 5. Spatially distributed infiltration water pathways derived from 1 m² sprinkling experiments using hydrological and hydrochemical observations. The white dashed lines on the landslide map delimit the hydrogeomorphic units defined by Malet et al. (2005). Figure reprinted from Krzeminska et al. (2014).
Resistivity Tomography (Travelletti et al., 2012; Perrone et al., 2014) or Distributed Temperature Sensing using fiber optics methods (Krzeminska et al., 2012) combined with hydrological modeling can highlight and help quantify the spatial hydrological effects of preferential flow paths at the hillslope scale. Furthermore, to better understand the kinematics of landslides, further developments, applications and improvements in the following terrestrial, near-surface, and remote sensing methods will be helpful: (1) surface displacement monitoring using photogrammetry (e.g., Soeters and van Westen, 1996); (2) terrestrial Lidar (e.g., Aryal et al., 2015; Imaiuzumi et al., 2015b); (3) airborne Lidar (e.g., Corsini et al., 2013; Lin et al., 2013; Bossi et al., 2015); and (4) monitoring and three-dimensional localization of internal deformation using 2- and 3D micro- and nanoseisms (e.g., detection of slip-quakes) (Amiratino et al., 2007; Walter et al., 2013). Even though there are challenges with equifinality related to geophysical interpretations, especially in clay-rich materials, these geophysical techniques are promising for monitoring the hydromechanical evolution of slow-moving landslides.

Besides dynamic hydrometeorology, the landslide itself also behaves like an earth system that is continuously changing – e.g., intrinsic hydrologic properties at both the small (macropores) and broader-scales (mechanical fissures). Recent advances have been made in modeling the dynamics of hydrologic response in preferential flow networks in shallow, unstable slopes (Kosugi et al., 2004; Tsutsumi et al., 2005; Nieber and Sidle, 2010), but upscaling is required to capture larger-scale and complex preferential flow network effects on slope stability. For the larger-scale fissures, Krzeminska et al. (2013) modelled hydrologic and mechanical feedbacks in fissures in a deep-seated landslide mass and focused on the activation of preferential flow networks as wetness increases (e.g., Sidle et al., 2000). Based on this study, an empirical relationship between fissure volume and factor of safety was proposed (Krzeminska et al., 2013). Stumpf et al. (2013) showed how semi-automated methods could be used to map fissure patterns at the Super-Sauze landslide using remote sensing observations. Combining time-lapse observations of fissure networks within a landslide at the field scale with hydrological modeling that includes hydromechanical feedbacks, seems a promising way forward to better understand slope scale movement and behavior of slow, deep-seated landslides.

4.2. Loss of suction and increased weight

Another trigger mechanism for shallow landslides involves a decrease in soil strength associated with a reduction in soil matric suction during soil wetting (Fredlund and Rahardjo, 1993; Rahardjo et al., 1995; Ng and Shi, 1998; Tsai, 2011). Debate has persisted concerning the importance of this mechanism in the initiation of natural landslides. A considerable volume of field evidence suggests that although this mechanism is an important contributor to the initiation of many landslides, it is rarely the primary or sole contributing factor in well-aggregated (structured) or heterogeneous soils (Sidle and Swanston, 1982; Terlien, 1997; Vieira and Fernandes, 2004; Li et al., 2005; Biavati et al., 2006; Gerscovich et al., 2006; Lacerda, 2007; Perrone et al., 2008; Hencher and Malone, 2012). Nevertheless, other field studies have attributed the loss of cohesion due to rainwater infiltration as the primary triggering mechanism of landslides (Godt et al., 2009; Hawke and McConchie, 2011; Bittelli et al., 2012). Interestingly, results from studies at the same site in Washington, USA, have invoked both positive pore water pressure response (Biavati et al., 2006; Godt et al., 2008) and loss of cohesion (suction loss) (Lu and Godt, 2008; Godt et al., 2009) as the primary mechanisms for shallow landslide initiation. This is not uncommon, as it is intrinsically difficult to assess suction through large volumes of natural soils given heterogeneities and the small sample size of in situ suction measurements. This conundrum highlights the sensitivity of the system and processes under investigation. Most of the evidence supporting landslide initiation during unsaturated conditions (i.e., loss of suction as the primary trigger mechanism) is based on theoretical and experimental studies. Several advances have been made to extend Terzaghi’s (1936) effective stress principle to unsaturated soil conditions (e.g., Vanapalli and Fredlund, 2000; Lu and Likos, 2006; Nuth and Laloui, 2008; Simoni, 2009; Greco and Gargano, 2015) to deal with landslides that initiate during transient unsaturated conditions. This approach typically uses Richards’ equation to describe the saturated–unsaturated flow of water into and through the soil. This methodology relies on data derived from soil water retention curves which are quite variable (e.g., Capparelli and Versace, 2014), and based either on combined soil suction and soil moisture field measurements or on small core or repacked samples that poorly represent the larger-scale hydrologic matrix. Notwithstanding, in more homogeneous soils and artificially constructed ‘soils’ where vertical infiltration is characterized by the uniform progression of a wetting front, the Richards equation approach coupled with consummate losses in soil cohesion has proven to be a useful predictor of slope stability (Collins and Znidaric, 2004; Godt et al., 2009; Baum et al., 2010). However, while the Richards-based variably saturated zone approach is useful for predicting the timing, depth of failure, and acceleration of certain landslides, it is not able to capture the effects of preferential flow paths that are often pervasive in and around landslides (Uchida et al., 2001; Sidle and Chigira, 2004; Hencher, 2010; Bogaard and Greco, 2015). Consequently, it is quite difficult to calibrate such hydrological models using so-called effective parameterization, but even more difficult to appropriately test and verify them in the complex field conditions that exist at many landslide sites (Stephenson and Freeze, 1974; Bogaard and van Asch, 2002; Beven, 2006).

In addition to the loss of shear strength during progressive wetting, the concurrent increase in soil weight during a rain event, as well as any external loading (surcharge) promotes instability of steep slopes (Paul and Kumar, 1997; Chigira and Yokoyama, 2005; Sidle and Ochiai, 2006; Ray et al., 2010; Galeandro et al., 2013). The influence of increased surcharge due to rainfall is most effective in destabilizing very steep hillslopes with highly porous soils (Chigira and Yokoyama, 2005; Yamao et al., 2016). As such, the combined loss of suction and increase in soil weight may initiate landslides in homogeneous soils where preferential flow is minimal and in uniform, high porosity soils, such as volcanic ash and pyroclastic flow deposits (Kitamura et al., 2003; Eichenberger et al., 2013; Galeandro et al., 2013; Yamao et al., 2016).

As a first step in bridging the theoretical concepts and findings of soil suction dynamics to field situations, slope failure experiments in flumes have been conducted (Sharma and Nakagawa, 2010; Greco et al., 2010; Germer and Braun, 2011; Terajima et al., 2014). Some experimental studies have noted that deformation and cracking of homogeneous soils occurs during the application of artificial rainfall as matric suction decreases (Sasahara and Sakai, 2014; Wu et al., 2015). While such investigations inform some of the basic causal relationships, they do not capture the complexity of regolith heterogeneity that affects landslide initiation in the field (Bogaard et al., 2000; Sidle et al., 2001; Uchida et al., 2001; Hencher, 2010). In some cases, evidence exists that pockets of saturation within the soil mantle develop due to heterogeneous substrate and preferential flow paths, without the occurrence of a lower zone of saturation (Mulholland, 1993; Sidle et al., 1995; Terlien, 1997). Such phenomena could initiate small landslides via positive pore water pressure within a relatively ‘unsaturated’ soil matrix.

A special case where reduced matric tension can initiate landslides occurs when fine-grained soils overlie coarse-textured soils. Chigira and Yokoyama (2005) showed that unsaturated flow can accumulate above a weathering front in wet (s ≈ 6–9 kPa of suction), unwelded pyroclastic flow deposits, where fine-grained materials overlie coarser substrate. The resultant decrease in capillary tension down to near-saturation (s ≈ 1–2 kPa of suction) reduces soil shear strength to the point where a landslide could initiate. Similarly, in southern Italy, a series of catastrophic landslides and debris flows occurred several days after a period of continuous, but not intense, rainfall (Fiorillo and Wilson, 2004). Laboratory investigations noted that a capillary barrier
developed in fine-grained pyroclastic soil underlain by coarse-grained pumice may have contributed to a loss of soil strength sufficient to trigger these landslides in Italy (Mancarella et al., 2012). A similar phenomenon was observed in tropical soils in Malaysia where highly weathered laterite soils were underlain by coarse weathered rock (Lee et al., 2011; Kassim et al., 2012). While these investigations were typically initiated to explain why landslides occurred during conditions when direct rainfall and resultant positive pore water pressure accretion did not appear to be the trigger mechanisms, there remain questions as to whether such idealized boundary conditions exist over large enough scales to be a significant mechanism for landslide initiation. For example, regolith heterogeneities such as preferential flow pathways and fractures that link across the boundary where capillary barrier effects are presumed to reside may negate this influence (e.g., Sidle et al., 2001).

Despite the numerous theoretical and experimental investigations on unsaturated failure mechanics and the dynamic matric suction data that have been collected in unstable slopes (e.g., Terlien, 1997; Li et al., 2005; Biavati et al., 2006; Trandrafi et al., 2008; Bittelli et al., 2012; Damiano et al., 2012; Kassim et al., 2012), the significance of suction loss during periods of infiltrating rain water on failure of natural heterogeneous hillslopes remains elusive. A major challenge is to more explicitly characterize the processes of transient unsaturated conditions in the context of complex field settings.

4.3. Contrasting flow paths and hydrologic response in aggregated versus unstructured soils

In unstructured soils with few macropores, the hydraulic conductivity of the soil matrix can be used to quantify the subsurface flux of water both downslope and vertically. This involves a combination of unsaturated and saturated flow, with soil suction decreasing as the wetting front advances (Torres et al., 1998; Iverson, 2000; Tsai et al., 2008; Capparelli and Versace, 2014) (Fig. 6a). This approach works well in flume studies and embankments where soils (or soil layers) are relatively homogeneous (Okada and Ochiai, 2008; Chowdhury et al., 2010; Greco et al., 2010; Sharma and Nakagawa, 2010; Lee et al., 2011) and for recently deposited (largely unstructured) soils that have accumulated by chronic geomorphic processes (Godt et al., 2009; Shoaei and Sidle, 2009) (Fig. 6b). As noted previously, this reduction in soil suction during the progressive wetting of the soil accompanied by an increase in overburden weight from infiltrating rainwater can trigger landslides.

Nevertheless, most shallow and deep-seated landslides appear to be triggered by a buildup of positive pore water pressure at a hydrologic discontinuity within the regolith. For these failures, preferential flow may have a dominate influence on the flux of water to a potential failure surface and thus on effective pore water pressures and the timing of landslides (e.g., van Beek and van Asch, 1999; Malet et al., 2005; Wienhöfer et al., 2011; van der Spek et al., 2013). Most unstable landsforms have a rather complicated network of flow pathways, both at the micro- and meso-scales. These pathways have various orientations and thus affect both vertical (largely from the surface) and slope-parallel water flux (largely at depth) (Noguchi et al., 1999; Sidle et al., 2000; Uchida et al., 2001; Lin, 2006; Anderson et al., 2009; Debieche et al., 2012).

Small individual preferential flow paths form by biogenic, chemical, physical, and geomorphic processes as part of soil development (Fig. 7b). Biogenic features include worm holes, animal burrows, live and decayed roots, and buried organic debris (Edwards et al., 1988; Tsukamoto and Ohta, 1988; Sidle et al., 2001; Ghestem et al., 2011; van Schaik et al., 2014). Slope shape may affect the orientation of tree roots (both live and dead), which strongly influences preferential flow within hillslopes (Tsutsumi et al., 2004; Ghestem et al., 2011). Interaggregate spaces in well-structured subsoil also promote preferential flow (e.g., Bouma et al., 1977). Mesopores (also described as “invisible macropores” by Tsukamoto and Ohta, 1988) are zones of highly permeable soils or perimeters of larger macropores where fines have been flushed out, effectively enlarging macropores during wet conditions (Wilson and Luxmoore, 1988; Luxmoore and Ferrand, 1993; Noguchi et al., 1999; Sidle et al., 2000, 2001; Hardie et al., 2012) (Fig. 7b).

In clay-rich soils, desiccation cracks develop that promote primarily vertical transport of water (Grisak and Cherry, 1975; Simon et al., 2004); cracking can also be caused by freeze-thaw and glaciotectonic processes. Fissures, joints, or foliations in bedrock or other substrate can promote preferential flow into, through and out of the regolith (Montgomery et al., 1997; Noguchi et al., 1999; Gerscovich et al., 2006) (Fig. 7b). These preferential flow paths exchange and route subsurface water depending on the orientations of fractures with respect to the slope; where return flow occurs (exfiltration), substantial pore water pressures can generate at specific locations during storms. At a broader scale, tension cracks often exist within and around unstable sites due to differential movement prior to landslide initiation (Sidle et al., 1985; Chigira, 2001; Ocakoglu et al., 2002) (Fig. 7a). These features can override the effects of low permeability soil matrices and provide rapid conduits for rain water or snow melt to directly enter the failure plane or to infiltrate into fractured bedrock and be transported via fractures back into the soil mantle (Sidle and Chigira, 2004). Larger macropores, often called soil pipes, may initiate by subsurface erosion in the soil where saturated flow concentrates (Terajima and Sakura, 1993; Onda, 1994). While pipes in certain soils (e.g., peat, loess) may be continuous over long slope distances (Jones, 1981; Smart and Wilson, 1984; Midgley et al., 2013), in other cases it appears that

Fig. 6. (A) In unstructured soils, rainwater moves vertically and downslope in the unsaturated phase with a rather uniform wetting front; (B) examples of relatively unstructured soil profiles formed by the fluvial infilling of a geomorphic hollow; the site failed in during a long-duration storm in 2006, Nagano, Japan.
individual pipes and smaller macropores (e.g., bioturbations, cracks, decayed root channels, inter-aggregate pedds) do not extend more than a few meters (Noguchi et al., 1999; Carey and Woo, 2000; Sidle et al., 2001) (Fig. 7b).

Preferential flow has been cited both as a factor that may contribute to pore water pressure accretion (where flow paths converge and possibly truncate) and dissipation (where they act as efficient drains), thus having detrimental and beneficial effects, respectively, on slope stability (Uchida et al., 2001; Sidle and Ochiai, 2006; Bogaard and Greco, 2015) (Fig. 7c and d). In many cases, macropores or pipes have been observed along the headscarp of landslides and are believed to contribute to excess pore water pressures that initiate failures. Two conceptual models have been presented to explain how the connectivity of preferential flow systems collect and laterally transmit water through hillslopes: (1) a system where individual or networks of soil pipes are physically connected, intersect a rising water table, and basically act as subsurface drains (Jones, 1981; Tani, 1997); and (2) smaller, diverse preferential flow paths that self-organize as soil moisture increases via a system of connecting nodes (e.g., pockets of loose soil or organic matter) (Sidle et al., 2000, 2001; Nieber and Sidle, 2010; Krzeminska et al., 2012) (Fig. 7b).

Shao et al. (2015) modelled the effect of preferential flow in slopes on the initiation of landslides. Coupling a dual-permeability model with a factor of safety slope stability assessment, they showed that during low-intensity, long-duration rainfall, the preferential flow system has a positive (draining) effect on slope stability, whereas for high-intensity, short-duration storms the preferential flow system caused rapid pore pressure accretion and increased slope failure potential. As such, it was concluded that dual permeability could exert a significant influence on the timing and magnitude of a potential landslide.

5. Challenges for future research

5.1. Difficulties in predicting the timing and location of rainfall-initiated landslides

Subsurface hydrologic processes exert important controls on the timing, location, initiation mechanism, magnitude, and extent of landslides. It is also clear that both small- and large-scale earth system dynamics influence these processes. Given the spatial footprint of individual landslides, it is necessary to assess hydrological processes at appropriate scales to ascertain impacts on mass wasting phenomena. A major challenge is to include an appropriate level of detail of small-scale processes that affect water movement and concentration across hillslopes where landslides develop, transform, and move. Understanding flow pathways in regoliths that are susceptible to mass movement is critical for modeling and hazard assessments. Distinctions need to be drawn between conditions conducive to slow vertical recharge of water through relatively homogeneous soil mantles and ‘engineered soils’ and conditions where preferential flow dominates – either by rapid infiltration and lateral flow through interconnected preferential flow networks or via exfiltration through bedrock fractures, or both. While rainfall infiltration models based on saturated-unsaturated flow theory coupled with algorithms for suction loss may accurately predict slope failure conditions for certain events, such models will have significant difficulties predicting failure conditions under rainfall regimes with different intensities and durations due to the presence of preferential pathways (leading to non-linear hydraulic behavior) or where subsurface flow is dominated by bedrock exfiltration. Furthermore, models developed for specific applications need to recognize unique conditions that may dictate water pathways and failure mechanisms.

A better understanding of the complex interplay amongst meteorological forcing, subsurface hydrology, geotechnical properties of soils, geomorphology, and vegetation is needed to develop more realistic predictive and practical algorithms for landslides and real-time hazard assessments. Coupling spatially explicit patterns of rainfall into real-time landslide predictions or forecasts can contribute significantly to hazard assessments and warnings (Alfieri et al., 2012). Doppler radar systems can explain patterns of rainfall at spatial resolutions of 1 km and, when coupled with recording rain gages, can be effectively used in landslide forecasts or as inputs to models (Chiang and Chang, 2009). Closure is needed on whether interception from tree canopies and litter layers significantly affects antecedent wetness and pore pressure response during storms. Similarly, under what conditions and to what spatial (3-dimensional) extent does transpiration significantly influence pore pressure response at depth?
Advances in geotechnical behavior of soils at small-scales needs to be expanded and coupled with field-scale geomorphic and hydrologic studies. For example, better articulation is needed on how capillary barrier effects translate to field-scale landslide initiation, particularly on the spatial variability of this effect and how this influences hillslope-scale stability. This links to the importance of spatially variable pore pressure in general at the hillslope scale and the respective influence on slope-scale stability. Generalizations of uniform pore pressure (both positive and negative) across hillslopes can miss conditions that may trigger a landslide or may overestimate instability. One approach to address this problem is to link dynamic pore pressure phenomenon with hydrogeomorphic processes in the vadose zone coupled with distributed effects of vegetation (particularly root systems).

Routing mechanisms and timing of water movement into and through hillslopes have not been clearly elucidated, including why certain slope sections fail and others do not during the same storm. Opportunities exist for coupling spatially and temporally distributed estimates of landslide movement using LiDAR, aerial photographs, field observations, and vegetation indicators (Mackey and Roering, 2011; Corsini et al., 2013; Guerrero et al., 2013; Imaizumi et al., 2015b) with dynamic precipitation and selected groundwater data.

The manifestation of root systems at spatial scales equivalent to landslides needs to be investigated to better elucidate their effects on mechanical reinforcement and subsurface water routing associated with different biomes, vegetation management practices, and impending species adaptations due to climate change. Several modeling approaches have addressed the spatial characterization of root reinforcement in hillslopes (e.g., Sakals and Sidle, 2004; Schwarz et al., 2011), but more work is needed to quantify these effects in landslide probability estimates. Prior studies have pointed to the need to better understand the effects of root architecture and development on the dynamics of preferential flow as well as their interactions with slope shape (Tsutsumi et al., 2004; Ghemst et al., 2011). A complex, unresolved problem is the interaction of woody root systems with bedrock fractures and their combined effects on slope stability. While fractures appear to facilitate the penetration of anchoring roots into more stable substrate (Tsukamoto and Kusakabe, 1984), these fractures can either concentrate or dissipate pore water pressures in soils (Sidle and Ochiai, 2006; Ghemst et al., 2011). Lastly, the effect of aging vegetation (especially forest stands) on the water balance of hillslopes is usually not considered, but may have significant consequences for landslide hazard assessments in managed forested terrain. The fiber bundle model approach (Cohen et al., 2009) that estimates the progressive transition from very local failure conditions (weak zones) in the soil to the landslide-scale, linked to the concept of self-organized criticality, may provide insights into certain types of failure locations if coupled with acoustic emission signatures (Amiratano et al., 2007; Cohen et al., 2009; Michlmayr et al., 2012; Walter et al., 2013).

Long-term geomorphic and weathering effects on landslide occurrence are other major challenges. More progress is needed related to hydrologic response to rainfall in unstable landscape units – e.g., geomorphic hollows, deeply weathered and altered landforms, terraced and urbanized landscapes, and areas with complex subsurface topography – and how these units may evolve over the long-term. This involves a better understanding of feedbacks amongst temporally variable geomorphic infiltrating processes (including weathering), evacuation processes, and subsurface hydrologic dynamics during different rainfall conditions.

Many of the challenges articulated herein, require a combination of skills that include process understanding through field investigations, theoretical developments, experimental approaches, analytics, and modeling. What is important for scientific progress, and unfortunately often missing, is long-term monitoring with large spatial coverage and sufficient detail to identify key processes. Currently, much of our understanding is derived from relatively short-term mono-disciplinary monitoring at limited spatial scales. To promote meaningful progress in this field, teams of scientists that cover the range of these skills and approaches in multiple disciplines need to be working in tandem to ensure that we are incorporating the most relevant process-based knowledge into landslide analyses.

5.2. Structured framework for assessing coupled dynamic earth and rainfall-initiated landslide systems

To help elucidate how dynamic earth surface and ecological attributes and processes affect the occurrence and mode of rainfall-initiated landslides, we present a conceptual framework that offers insights into these interactive mechanisms and processes, as well as how they can appropriately be incorporated into models. Within this coupled system, four attributes are highlighted: (1) meteorological forcing (MF); (2) regolith/hillslope environment (RHE); (3) ecosystem dynamics (ED); and (4) tectonic/geomorphic dynamics (TGM) (Fig. 8). The interactions amongst climate, earth, and ecosystem dynamics are complex, but some general scenarios can be associated with specific types, triggering mechanisms, and the timing of these landslides (Fig. 9).

Rainfall characteristics (intensity, duration, and antecedent rainfall) are strongly linked to trigger mechanisms and timing of different types of landslides (see MF section of Figs. 8 and 9). The regolith and hillslope environment (RHE) includes landscape heterogeneities (e.g., tension cracks, fissures, fractures, macropores) that promote rapid infiltration either down to the failure plane or into fractured bedrock that cause water to exfiltrate back to the soil mantle, triggering landslides via rapid positive pore pressure accretion (see RHE section of Fig. 8). Regolith characteristics also influence the depth of the failure plane. Furthermore, landslides triggered (or at least primarily affected) by loss of suction and increase in weight during prolonged rainwater infiltration are affected by regolith, rainfall, and ecological characteristics that promote the slow progressive movement of a wetting front during infiltration – e.g., wet soils prior to rainfall, lower intensity rainfall, large cumulative rainfall, little influence of preferential flow, poorly structured soils, and slow evaporation and transpiration (see MF, RHE, and ED sections of Fig. 8 and “Shallow unsaturated” column of Fig. 9). The initiation or reactivation of slow, deep-seated landslides (e.g., earthflows, rotational slumps, or combinations thereof) is influenced by complex subsurface hydrologic interactions within a moving and changing landform. These typically large, clay-rich failures are activated and affected by spatially distributed rainfall over weeks to months (cumulative rainfall) with long lag times prior to movement, which create regions of augmented pore water pressure (Fig. 9). Evaporation and transpiration effects of evolving vegetation directly affect the movement of deep-seated landslides, but root reinforcement has only a minor influence (Fig. 9). Conversely, for shallow landslides, root reinforcement is a very important stabilizing agent while evaporation and transpiration play a minor role in landslide initiation. Removal of woody vegetation is widely recognized to increase the probability of slope failure following sufficient root decay, while dense and diverse forest cover promotes more stable landscapes (Fig. 8). Landslides in well-aggregated soils with abundant macropores and/or fissures generally occur with small lag times to rainfall inputs, whereas landslides in soils with poor structure and few macropores/fissures respond slowly with respect to rainfall inputs (see ED section of Fig. 8). Weathering and neotectonic processes tend to have a greater influence on deep landslides by altering the internal hydrology of these unstable landforms creating preferential flow paths (Fig. 9). However, surficial weathering and mountain uplift can also create instabilities in shallow soil mantles. Once a landslide occurs, infilling processes proceed rapidly at first and then more slowly with time as the regolith gradually weatherers (see TGD section of Fig. 8). These geomorphic processes may interact with neotectonic dynamics, particularly in the short-term.

The conceptual framework presented herein (Figs. 8 and 9) outlines the important dynamic processes and earth system attributes that need to be considered in landslide assessments and models. Selecting the
appropriate algorithms for water flow in these different unstable terrain features is paramount to the modeling success – both the timing and location of landslides. An important consideration is recognizing the interaction of hillslope hydrology in unstable terrain with the dynamic aspects of biota, geomorphology, tectonics, and weathering processes, all of which affect hydrologic pathways and response to rain events. These multidisciplinary questions should guide the next generation of landslide research.

Targeted field investigations are needed to better understand the relative importance of these interactive processes and to inform models of the appropriate processes that need to be quantified. Such targeted monitoring should be detailed and continuous over long timespans, and employ well-designed experiments that utilize multi-technological methods in cross-disciplinary collaborations (Bogaard et al., 2012). We emphasize that field experiments need not be expensive in-situ measurements of parameters, but rather incorporate research designs to unravel and quantify fundamental processes and their interactions, which should result in better process representation in predictive models.

These studies in unstable sites that, for example, examine coupled ecological dynamics (transpiration, evaporation, root system architecture, root strength distribution, and vegetation management) within the context of wider-scale landforms, rainfall regimes, soils, and hydrological processes will elucidate the significance of these sometimes overlooked interactive processes at the hillslope scale and suggest ways in which they can be incorporated in models. Better characterization of root architecture and spatial-temporal patterns of evaporation and transpiration within the landscape will improve predictions of subsurface hydrologic response, as will temporal influences of weathering and neotectonics. Such studies may elucidate why some hillslopes fail while others do not under seemingly similar conditions.

Given the importance of preferential flow and distributed pore pressure development in landslide initiation and runout, capturing good approximations of these subsurface features in models is required to improve landslide predictions. Advances in multi- and distributed sensor technology that could aid in articulating broad-scale flow paths and landslide predictions include: 3-dimensional geophysical...
monitoring such as electrical resistivity tomography, passive nano- and micro-seismic techniques, and distributed sensing using fiber optic cables (e.g., temperature, strain, acoustic signals, pore water pressure). These methods can be effectively combined with high-resolution surface monitoring derived from terrestrial Lidar, Structure from Motion photogrammetry, infrared photos, and other emerging techniques. Furthermore, hydrometric tests coupled with natural or applied tracers (including a new generation of SMART tracers) are also effective in elucidating preferential flow paths and behavior. Understanding the linkages and dynamics amongst important hydro-eco-geomorphic processes that affect various types of landslides (outlined in Fig. 8) together with the relative importance of these processes (Fig. 9) provides a framework for addressing these challenges.

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