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Conceptual framework for assessing disturbance impacts on debris-flow initiation thresholds across hydroclimatic settings

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Abstract

The destructive and deadly nature of debris flows has motivated research into empirical rainfall thresholds to provide situational awareness, inform early warning systems, and reduce loss of life and property. Disturbances such as wildfire and land-cover change can influence the hydrological processes of infiltration and runoff generation; in steep terrain this typically lowers empirical thresholds for debris-flow initiation. However, disturbance impacts, and the post-disturbance recovery may differ, depending on the severity, nature, extent, and duration of the disturbance, as well as on the prevailing hydroclimatic conditions. Thus, it can be difficult to predict impacts on debris-flows hazards in regions where historically such disturbances have been less frequent or severe. Given the increasing magnitude and incidence of wildfires, among other disturbances, we seek to develop a conceptual framework for assessing their impacts on debris-flow hazards across geographic regions. We characterize the severity of disturbances in terms of changes from undisturbed hydrologic functioning, including hillslope drainage and available unsaturated storage capacity, which can have contrasting influences on debris-flow initiation mechanisms in different hydroclimatic settings. We compare the timescale of disturbance-recovery cycles relative to the return period of threshold exceeding storms to describe vulnerability to post-disturbance debris flows. Similarly, we quantify resilience by comparing the timescales of disturbance-recovery cycles with those of disturbance-recurrence intervals. We illustrate the utility of these concepts using information from U.S. Geological Survey landslide monitoring sites in burned and unburned areas across the United States. Increasing severity of disturbance may influence both recovery timescales and lower the return period for debris-flow inducing storms, thus increasing the vulnerability to disturbance-related hazards while also decreasing system resilience. The proposed conceptual framework can inform future data acquisition and model development to improve debris-flow initiation thresholds in areas experiencing increasingly frequent, severe, and even overlapping landscape disturbances.

Keywords: disturbance; hydrologic thresholds; rainfall threshold; debris flows; wildfire; resilience; vulnerability

1. Introduction

Debris flows are a particularly damaging and deadly category of landslides, which move rapidly down steep slopes and channel networks (Iverson, 1997; Coe et al., 2008). Investigations of hydrologically triggered debris flows often focus on the historical rainfall conditions measured during widespread landsliding events, which has facilitated the development of critical rainfall intensity-duration (ID) thresholds for situational awareness (Caine, 1980; Keefer et al., 1987; Kean et al., 2011; Jakob et al., 2012). These ID thresholds are a simple empirical proxy for the complex hydrological processes of infiltration, drainage, and runoff, which influence the force imbalance that triggers failures (Lu and Godt, 2013; Sidle and Ochiai, 2013). Despite recent efforts to develop hydro-meteorological thresholds that incorporate these processes (Mirus et al., 2018; Bogaard and Greco, 2018), empirical ID thresholds are constrained to a specific geographic area and, within this area, limited to hillslopes with similar hydrologic conditions (Guzzetti et al., 2008; Baum and Godt, 2010). As a consequence, such thresholds are stationary and non-transferrable to different regions, as they do not account for the dynamic influence of climate and land-use changes or other disturbances.

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In zero-order basins that are typical of debris-flow source areas, the balance between rainfall input via infiltration, unsaturated soil storage, drainage, and runoff is controlled by soil-hydraulic properties, climate, topography, and land cover (Mirus and Loague, 2013; Sidle et al., 2018). Landscape disturbances can influence this hillslope water balance by abruptly changing these properties and process thresholds, which impacts hydrologic functioning (Ebel and Mirus, 2014; Mirus et al., 2017a). One important hydrologic function in soil-mantled hillslope environments is balancing drainage and storage to maintain slope stability (Mirus et al., 2017b). Efficient subsurface drainage during large storm events can limit slope failures, but slopes must also store some water between storms to support transpiration by vegetation, whose root strength reinforces slopes.

A wide variety of land-cover disturbances can influence the hillslope water balance across various landscapes and hydroclimatic settings in different ways. Wildfires reduce infiltration capacity, thereby increasing the likelihood of runoff-generated debris flows during relatively moderate rainfall events (Cannon, 2001; Staley et al., 2013). Following the recovery of soils impacted by wildfire, the lack of vegetation can increase the potential for landslides due to reduced root reinforcement or decreased interception and transpiration. Deforestation and road construction also limit root reinforcement and impact subsurface drainage, which can increase landslide susceptibility during prolonged storms (Swanson et al., 1975; Mirus et al., 2007). Previous landslides are another type of disturbance that influence the potential for further slope failures. Debris flows that evacuate mobile material can decrease the potential for a subsequent landslide until the source material is replenished (Imaizumi et al., 2015). However, when failed earth materials are not completely evacuated a positive feedback cycle of repeated landsliding or catastrophic debris flows may result (Iverson et al., 2015; Mirus et al., 2017b; Samia et al., 2017; Morino et al., 2018).

The area of the Earth's surface affected by wildfire and vegetation clearing is likely to continue rising (Cannon and DeGraaf, 2009; Mirus et al., 2017a), as is the frequency of extreme storm events. In this context, we propose a generalized conceptual framework for understanding disturbance impacts on associated debris-flow hazards. Our approach relates the transient changes caused by disturbances to the underlying hydrologic processes that trigger debris flows by relating the hillslope storage-drainage concept from disturbance hydrology (Ebel and Mirus, 2014) to the hydrologic cause-trigger concept proposed for improving hydrologic process representation in landslide early warning thresholds (Bogaard and Greco, 2018).

2. Contrasting Debris-Flow Initiation Mechanisms

Debris flows involve substantial water contents with entrained sediment to maintain high pore-water pressures that enhance mobility (Iverson, 1997), and thus they are largely associated with rainfall triggering events. The high risk typically associated with debris flows has prompted an abundance of studies to identify critical rainfall thresholds for specific regions or conditions. However, when investigating the regional variations between rainfall triggering events, it becomes apparent that different underlying hydrological processes may dominate, depending on the hydroclimatic setting. In some regions, debris flows are associated with prolonged heavy rainfall, where steady infiltration into water-logged soils results in catastrophic and widespread slope failures (Crosta and Dal Negro, 2003; Coe et al., 2014; Wooten et al., 2016). In contrast, debris flows are also triggered in arid or semiarid settings and in areas disturbed by wildfire after only a brief period of higher rainfall intensity without distinct correlation to the initial moisture conditions (Cannon, 2001; Kean et al., 2011; Staley et al., 2013). These contrasting rainfall-triggering conditions reflect different hydrological processes and corresponding debris-flow initiation mechanisms (Cannon et al., 2001), which may also exhibit different geomorphic features (Morino et al., 2018; Staley et al., 2019). However, both initiation mechanisms tend to require steep terrain with available mobile regolith.

In the case of wildfires, changes in near-surface hydraulic properties promote infiltration excess runoff (Moody et al., 2013), which can trigger rapid mobilization of available sediment and debris in stream channels within burn affected areas (Kean et al., 2013). This frequent phenomenon across arid and semiarid regions of the western United States has informed the development of short-duration rainfall intensity thresholds and other empirical metrics for rapid burn-area hazard assessments (Cannon et al., 2011; Staley et al., 2013). This empirical approach has been used in conjunction with quantitative precipitation forecasts to provide situational awareness of potential hazards in advance of incoming storms across the western United States (Oakley et al., 2017; Staley et al., 2017). Subsequent research has focused on distributed numerical models parameterized with measured (or measurable) soil properties to simulate the coupled surface and subsurface hydrological processes in burned areas (Ebel et al., 2016; McGuire et al., 2018). In southern California a more simplified process-based model of infiltration-excess runoff also compares well to measured debris-flow timing (Rengers et al., 2016).

Recent fires in more humid regions in Oregon and North Carolina created a need for U.S. Geological Survey (USGS) post-fire hazard assessments that were developed with the same empirical methods that assumes infiltration-excess runoff (https://landslides.usgs.gov/hazards/postfire_debrisflow/). Neither the empirical approach nor process-based modeling of post-fire debris flows have been rigorously evaluated in these humid settings, so it remains unclear how broadly transferrable either approach is to these types of environments where wildfire is typically infrequent and less severe. In Australia, the enhancement of post-fire runoff response correlates with aridity (Van der Sant et al., 2018), which indicates that the post-disturbance impacts are strongly related to hydroclimatic setting. In the semiarid western U.S. streamflow has increased significantly following wildfire, but in the humid southeast no change in streamflow was observed following prescribed fires, because they are characterized by low fire severity and generally cover less than 20% of a basin, a critical threshold for fire impacts on streamflow (Hallema et al., 2018). Thus, wildfire and other disturbances may not have a universal impact on debris-flow hazards across different geographic regions.

3. Monitoring Post-Disturbance Hydrologic Response

Limited observations of pre-and-post disturbance conditions is a major challenge in disturbance hydrology (Ebel and Mirus, 2014; Mirus et al., 2017a). Fortuitously, three USGS landslide monitoring sites in western North Carolina with similar instrument configurations (https://usgs.gov/natural-hazards/landslide-hazards/monitoring) provide an opportunity to directly examine the impacts of wildfire on hillslope hydrologic response in steep terrain that is particularly prone to debris flows. In 2016, prolonged drought contributed to numerous wildfires in the southern Appalachian Mountains. The Poplar Cove monitoring site was burned by the Knob Fire in November 2016, while the Mooney Gap and Bent Creek sites were not directly impacted by the various wildfires in the region. At Poplar Cove the duff groundcover and understory vegetation were largely incinerated, but the soils were relatively undisturbed and the larger trees on the hillslope survived the fire (Fig. 1). Site visits to the nearby Party Rock, Chimney Tops II, Rock Mountain, Tellico, and Maple Springs fires in North Carolina, Tennessee, and Georgia confirmed that the limited impacts of relatively low burn severity observed at Poplar Cove were common across the southern Blue Ridge physiographic province of the Appalachian region.

Fig. 1. The Poplar Cove monitoring site before and after the November 2016 Knob Fire: (a) during summer 2014, and (b) on March 9, 2017.

Regrettably, some of the instrumentation at Poplar Cove was damaged by the Knob Fire, and instruments at Mooney Gap were disturbed by wildlife following the fire, so the otherwise continuous data were disrupted for several months until we repaired the instruments during a site visit in early March 2017. Despite this data loss, comparison of the hillslope hydrologic response time series for shallower soil moisture and deeper pore-water pressure from all three sites before and after the wildfire reveals no clear impacts on infiltration events during the fall and winter months when soils remain wetter (Fig. 2). Similarly, field observations during the site visit did not reveal impacts on hydrophobicity or infiltration capacity. During the transition from spring to summer, when increased evapotranspiration rates lead to gradual and sustained drying, the pore pressures and soil water contents at Poplar Cove displayed similar drainage to the other two sites in the year before the fire. After the fire, deeper pore-water pressures at Poplar Cove exhibit a prolonged drainage that is likely the result of decreased interception and lower transpiration by the canopy and understory vegetation in the disturbed area. Considering that debris flows in the southern and central Appalachians are often infiltration triggered during hurricanes and tropical storm events in the summer and early fall, this delayed drainage has potentially important implications for slope stability.

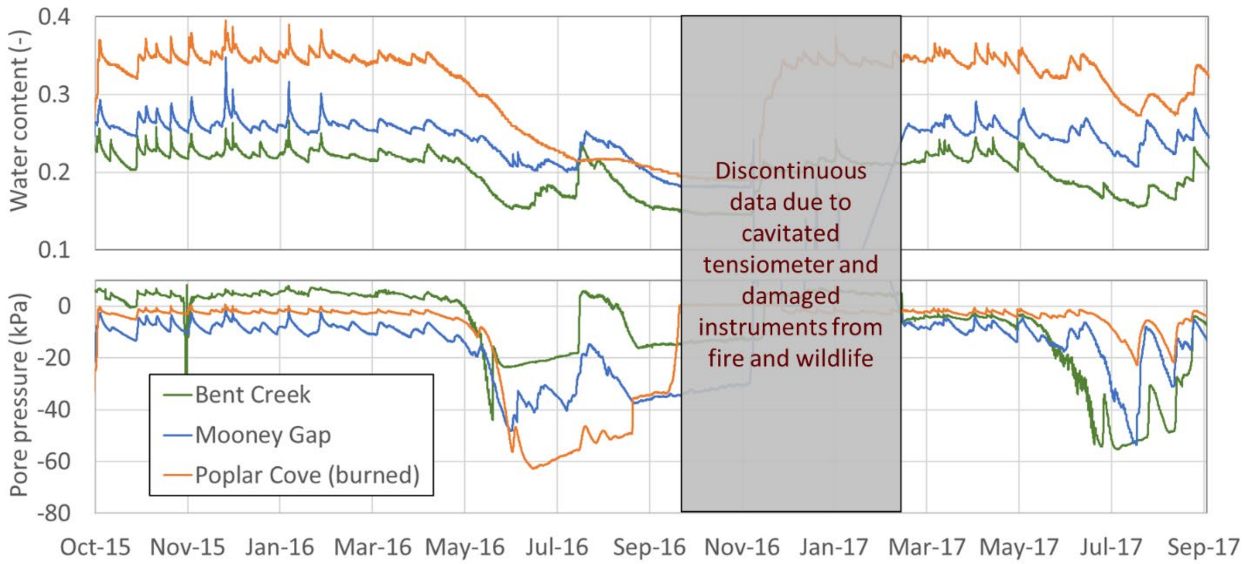

Fig. 2. Time-series of tensiometer measured pore-water pressures at the burned (Poplar Cove, orange line) and unburned (Mooney Gap, blue line; Bent Creek, green line) sites in western North Carolina, measured before and after the November 2016 Knob Fire. Instruments at Poplar Cove and Mooney Gap were damaged during and shortly after the wildfire, which disrupted continuous data collection through March 9, 2017.

Despite the temporary increase in susceptibility to infiltration-triggered debris flows during the early-mid summer of 2017, there were no reports of debris flows in the numerous burn areas since the 2016 wildfires. This lack of reported debris flows is not entirely consistent with our measured rainfall relative to the 15-minute rainfall thresholds indicating 50% probability of runoff-generated debris flows calculated for the USGS post-fire hazard assessments (Fig. 3). However, these thresholds assume the infiltration-excess runoff mechanism triggers debris flows, rather than subsurface pore-pressure development. In contrast, hillslope hydrologic monitoring data suggest that antecedent soil moisture is affected by the fire rather than infiltration rates. Therefore, a more complex conceptual model may be needed to fully assess post-disturbance impacts on hydrologic response and debris-flow hazards. For either runoff or infiltration triggered debris-flow initiation mechanisms, the extent of the impacts of wildfire disturbance were not sufficiently severe to lower debris-flow initiation thresholds to levels below the measured storms in 2016-2017.

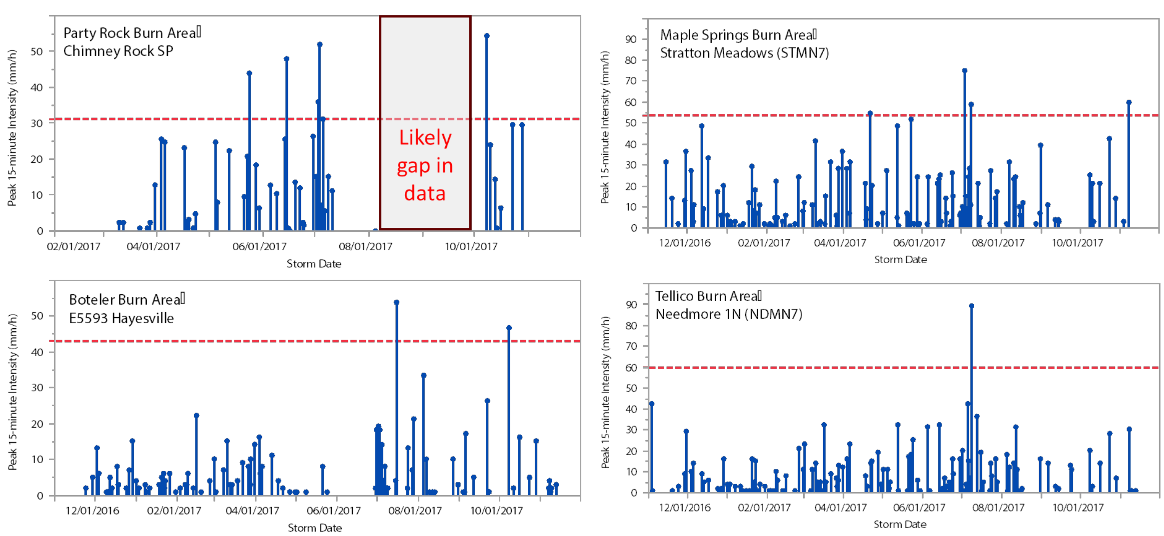

Fig. 3. Time-series of 15-minute peak rainfall intensity measured in areas that burned in November 2016 across North Carolina, relative to USGS calculated thresholds for 50% probability of post-fire debris flows (dashed red line). Gap in data at Chimney Rock fire likely due to clogged rain gage.

4. Disturbance Severity and Recovery of Hydrologic Function

Disturbances are abrupt, but inherently transient phenomena; following a disturbance, hydrologic functioning of a landscape generally recovers or shifts to a new equilibrium (Ebel and Mirus, 2014). When assessing the impacts of disturbances on debris-flow hazards, the magnitude of the disturbance impacts as well as the timescales of the disturbance-recovery cycle and disturbance recurrence interval are relevant.

After several years, soil hydraulic properties altered by wildfire gradually return towards pre-disturbance conditions (McGuire et al., 2016; Ebel and Martin, 2017; Chandler et al., 2018), vegetation canopy regrows, and evapotranspiration recovers (Poon and Kinoshita, 2015; Kinoshita and Hogue, 2018). Similarly, several years after timber harvesting forests regrow and establish some root strength to stabilize slopes, though long-term impacts of anthropogenic disturbances may persist for centuries (Schmidt et al., 2001). Landslide deposits also recover from the disturbance impacts through the processes of pedogenesis, bioturbation, and revegetation (Mirus et al., 2017b), though indications are the timescale of recovery may take several decades (Samia et al., 2017).

The magnitude of disturbance impacts, which influences changes in hydrologic function from the pre-disturbed (or normal) to the disturbed state, can be conceptualized in terms of changes that promote either runoff connectivity or available subsurface storage (Ebel and Mirus, 2014). Runoff generation mechanisms include those governed by the ratio of unsaturated storage capacity versus the cumulative storm totals (i.e. subsurface stormflow and saturation excess overland flow), and the ratio of infiltration capacity to rainfall intensity (i.e. infiltration excess overland flow) (Mirus and Loague, 2013). Similar hydrologic end-members of limited infiltration capacity and limited unsaturated storage can represent the continuum of disturbance impacts on debris-flow initiation potential. Assuming hillslope systems evolve within their hydroclimatic setting to drain water during typical storm events, and also retain water between storms to support vegetation, one can characterize how disturbances contribute to a hillslope water imbalance.

Both of these contrasting impacts can decrease the factor of safety for debris-flow initiation, but in opposite ways, which is demonstrated for burned and unburned sites in different hydroclimatic settings (Fig. 4). In southern California, increased burn severity promotes connectivity of infiltration-excess runoff generated on hillslopes into sediment-laden channels where debris flows initiate (McGuire, et al. 2018), but vegetation recovers rapidly increasing transpiration and root strength. In contrast, a landslide on the coastal bluffs of Puget Sound in Washington reduced subsurface drainage relative to neighboring vegetated hillslopes, which creates a storage imbalance that promoted prolonged susceptibility to recurring slope failures (Mirus et al., 2017b). Our North Carolina monitoring data reveal that for the low severity burn, the disturbed landscape retains more moisture (Fig. 3) and remains more susceptible to infiltration-triggered debris flows during the subsequent hurricane season. The conceptual diagram relating these cases in Fig. 4 illustrates how shifts in hydrologic processes due to the immediate impacts of wildfire may differ with hydroclimatic settings, but also that different disturbances can result in similar decreases in factor of safety with variable recovery timescales and trajectories.

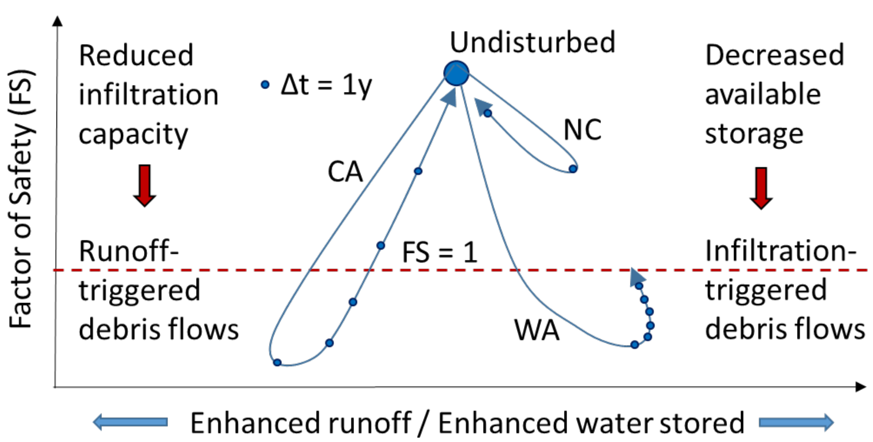

Fig. 4. Conceptual diagram of disturbance impacts on runoff connectivity versus available subsurface storage, and the resulting changes in factor of safety. In undisturbed settings water retention and drainage are balanced to maintain slope stability for a typical storm event (large circle). In different post-disturbance environments changes in hydrologic function reduce factor of safety and recovery rates depending on the hydroclimatic settings (blue arrows): California wildfire, (CA), North Carolina wildfire (NC), and Washington landslide disturbance (WA).

5. Vulnerability and Resilience to Disturbances of Different Magnitude

For a given site or area, the timescale of the disturbance-recovery cycle for a different type and/or severity of disturbance is important for assessing temporal persistence of elevated debris-flow hazards. The vulnerability to post-disturbance debris flows is related to the return period of the corresponding triggering storm event, and the resilience is related to the recurrence interval for the disturbance of interest. A disturbed system where the recovery time is much slower than the recurrence interval for triggering storm event is highly vulnerable to debris flows, whereas a system that recovers rapidly or infrequently experiences potential triggering events is less vulnerable. A system where the recovery time is slower than the return period of the disturbance will experience ongoing disturbance impacts, whereas a resilient system will tend to recover faster than the recurrence interval of the disturbance. The potential utility of these concepts is illustrated in Fig. 5 with the three example disturbances from monitoring sites in southern California, western North Carolina, and Puget Sound, Washington. These concepts in Fig. 5 can also be expressed as non-dimensional ratios to quantitatively define vulnerability and resilience. Disturbance magnitude is more difficult to quantify, but it could be expressed as the ratio of change in hydrologic function from the original, undisturbed state.

Burn severity is one proxy for disturbance magnitude that dominates the likelihood of debris flows in empirical models (Staley et al, 2013) and is conceptually related to the changes in hydrophobicity and other hydraulic properties in process-based models (McGuire et al., 2018; Rengers et al., 2016). Wildfire with moderate to high burn severity on steep terrain will drastically lower the 15-minute rainfall intensity associated with runoff-triggered debris flows. In the Western U.S., the severity of wildfire impacts on hydraulic properties and the frequent recurrence of moderate intensity rainfall events means that post-fire debris flows are likely to occur before the system can recover. In southern California wildfire recurrence interval is on the order of several decades, post-fire recovery is on the order of several years, and the return period of a critical storm for post-fire debris flows is on the order of every year or less. Therefore, areas that do burn are quite likely to experience post-fire debris flows prior to recovery. Thus, within this framework Southern California is classified as system that is resilient, but vulnerable to runoff-triggered post-fire debris flows. However, the decay in water repellency varies and recovery timescale of other soil hydraulic properties and vegetation following wildfire varies by region (Dyrness, 1976; Wondzell and King, 2003; Larsen et al., 2009).

In North Carolina, even low-severity wildfire is infrequent and repeated site visits to burn areas in 2017 and 2018 confirmed that the understory vegetation and duff layer recovered rapidly due to the uniform distribution of rainfall throughout the year. These observations combined with minimal differences between burned and unburned hydrologic response only two years after the Knob Fire suggests that the southern Appalachians are not particularly vulnerable, and also quite resilient to post-fire debris flows. During a typical year in Puget Sound, multiple landslide-triggering storms occur along the coastal bluffs between December and April, but insufficient data exists to distinguish between storms that trigger repeated failures versus those that initiate new failures. Assuming a 25-year recovery time determined for first-time landslides elsewhere (Samia et al., 2017), the Puget Sound system is highly vulnerable and not particularly resilient to landslide disturbances. Of course, changes in climate can impact the recurrence interval and recovery timescale of disturbances such as wildfire, as well as the return period for a storm of given intensity or duration, all of which could also be accommodated within the vulnerability and resilience conceptual framework. For example, shorter return periods of severe storms and increased frequency of wildfire would result in more vulnerable and less resilient systems, respectively.

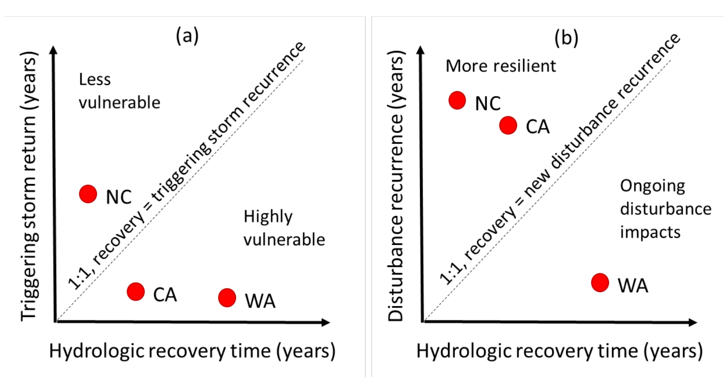

Fig. 5. Plots comparing the timescales of disturbance-recovery cycles for NC, CA, and WA, relative to the (a) return period of a post-disturbance debris-flow triggering storm to illustrate the concept of vulnerability, and (b) recurrence interval of the same disturbance to illustrate resilience.

6. Conclusions

We propose a conceptual framework to assess possible variability in how disturbances impact hydrologic process and corresponding debris-flow initiation thresholds across different geographic regions. Increases or decreases in hillslope runoff connectivity or subsurface drainage provide a metric for assessing the magnitude of disturbance impacts on two contrasting debris-flow initiation mechanisms. These qualitative concepts can be related to quantitative measurements of changes in infiltration or available soil moisture storage capacity in undisturbed and post-disturbance settings, and the corresponding reduction in rainfall triggering conditions for a given hydroclimatic setting. The timescales of the disturbance-recovery cycle relative to the return period for corresponding debris-flow triggering storm and recurrence interval for that disturbance provide metrics for assessing the vulnerability versus the resilience of the system. Examples from USGS monitoring sites in contrasting disturbed settings across the U.S. illustrate the utility of this conceptual framework for understanding how disturbances may impact debris flow hazards. In the context of climate and land-use change, and increasing wildfire disturbances, this conceptual framework can inform future data collection efforts and improved modeling of thresholds for post-disturbance debris-flow hazards.

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