

REVIEW SUMMARY

NATURAL HAZARDS

Cascading land surface hazards as a nexus in the Earth system

Brian J. Yanites*, Marin K. Clark, Joshua J. Roering, A. Joshua West, Dimitrios Zekkos, Jane W. Baldwin, Corina Cerovski-Darriau, Sean F. Gallen, Daniel E. Horton, Eric Kirby, Ben A. Leshchinsky, H. Benjamin Mason, Seulgi Moon, Katherine R. Barnhart, Adam Booth, Jonathan A. Czuba, Scott McCoy, Luke McGuire, Allison Pfeiffer, Jennifer Pierce



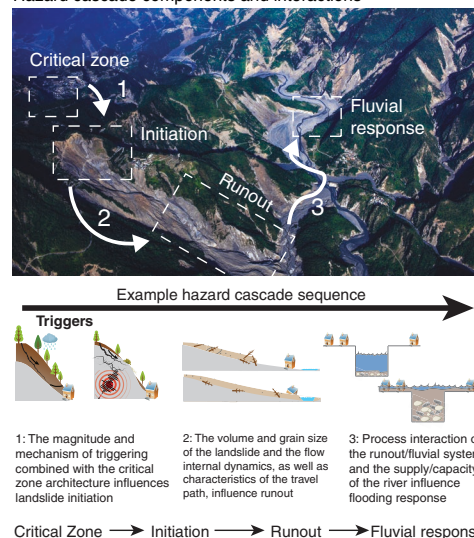
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BACKGROUND: Earth's surface is sculpted by numerous processes that move sediment, ranging from gradual and benign to abrupt and catastrophic. Although infrequent, high-magnitude sediment mobilization events can be hazardous to people and infrastructure, leaving topographic imprints on the landscape and remarkable narratives in the historical record. Hazardous events such as fires, storms, and earthquakes accelerate erosion and sediment transport, increasing landscape sensitivity to subsequent perturbations, thus forming a cascading hazard. Although the redistribution of sediment across Earth's landscape can result in higher risks to vulnerable populations, cascading processes are commonly unaccounted for in hazard assessments. Cascading hazards can occur almost immediately after triggering events, such as coseismic landslides, or over months, years, or even decades after an initial perturbation, such as debris flows after wildfires or flooding in channels alluviated by volcanic debris. Sediment cascades span Earth's surface, from mountaintops to river valleys, where erosion, deposition, and aggradation can lead to a myriad of hazardous processes, including decreased river conveyance capacity, which increases the likelihood of downstream flooding. An improved understanding of the magnitude, frequency, and persistence of cascading hazards is critical given the rapid changes in the frequency and severity of storms, fires, sea-level change, and cryospheric melting, as well as the expansion of high-population-density urban footprints in regions susceptible to solid Earth hazards. Understanding the full consequences and underlying physics of Earth's cascading land surface hazards can help minimize future human and economic losses.

ADVANCES: Recent research reveals crucial surface process interactions that link distinct components of Earth systems on human timescales (seconds to centuries) and give rise to cascading hazards. For example, solid Earth processes, such as earthquakes and volcanic eruptions, can generate widespread deformation and stress changes that affect rock strength and susceptibility to mass wasting. Likewise, the atmospheric triggering of hazards because of extreme precipitation, drought, and warming varies regionally and can be amplified or dampened depending on topography, geologic materials, and seismic activity, which are tied to the tectonic history of a region. New models capable of linking atmospheric forcings and solid Earth phenomena to land surface processes provide critical tools for quantifying how different Earth systems interact to initiate and sustain cascading hazards. Advances in high-resolution remote sensing tools provide accurate and extensive datasets to calibrate and validate models. Moreover, recent advances in critical zone science illuminate how the coupling of hydrologic, geologic, and biologic processes modifies near-surface material properties, altering their susceptibility to land surface hazards. These methodological and theoretical advances provide an opportunity to anticipate and forecast how the interaction of Earth systems affects land surface hazards in a changing world.

OUTLOOK: The science of land surface processes—encompassing the atmospheric, hydrospheric, biospheric, and solid Earth system sciences—is well positioned to advance our ability to forecast cascading hazards

Hazard cascade components and interactions



A photograph and a schematic illustration of how the interaction of Earth systems through surface process controls the emergence and persistence of cascading hazards. Processes at and near Earth's surface influence the strength and thickness of near-surface Earth materials, affecting how the mobilization of hillslope sediment will respond to triggers. The dynamics of the runout of this mobilized sediment can vary substantially owing to the interconnected upslope processes. As sediment works through fluvial systems, high sediment loads increase flood hazards and destabilize adjacent hillslopes, leading to further sediment mobilization. [Photo by Chi Po-lin and provided by the Chi Po-lin Foundation, copyright Above Taiwan Cinema]

and enhance societal resilience through improved risk assessment and management. However, to achieve such advances, cross-disciplinary research teams are needed to address new research paradigms such as “How do different Earth systems interact to influence the magnitude, frequency, and longevity of impactful events?” Addressing these inherently complex and multidisciplinary questions requires a holistic approach to cascading hazard science that considers the impact of trigger magnitude, the influence of preconditioning along the cascade pathway from critical zone processes, and the interaction of processes along the cascade. Such advances can help interpret the emergence and persistence of cascading hazards and anticipate how they will be influenced by climate and land use changes. Linking Earth systems within a cascading hazard framework can inform theories, mechanistic models, and data analyses capable of quantifying the hazards of cascading processes on the ever-evolving Earth's surface, ultimately strengthening community resiliency and sustainability. □

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Cascading land surface hazards as a nexus in the Earth system

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This Review synthesizes progress and outlines a new framework for understanding how land surface hazards interact and propagate as sediment cascades across Earth's surface, influenced by interactions among the atmosphere, biosphere, hydrosphere, and solid Earth. Recent research highlights a gap in understanding these interactions on human timescales, given rapid climatic change and urban expansion into hazard-prone zones. We review how surface processes such as coseismic landslides and post-fire debris flows form a complex sequence of events that exacerbate hazard susceptibility. Moreover, innovations in modeling, remote sensing, and critical zone science can offer new opportunities for quantifying cascading hazards. Looking forward, societal resilience can increase by transforming our understanding of cascading hazards through advances in integrating data into comprehensive models that link across Earth systems.

Processes that shape Earth's surface range from gradual and benign to abrupt and destructive. Such processes can pose hazards to life and property and leave topographic imprints on the landscape (1–3). These events increasingly affect human life and infrastructure (Fig. 1) (4), with changes in the frequency of land surface events expected because of climate change and the expansion of populations into more hazardous areas (5–10). When one extreme event occurs, the probability of coincident or subsequent hazardous land surface events often increases, resulting in a higher risk to communities and the amplification of the impact on Earth's surface (11), initiating a “cascading hazard” (12–17). Subsequent events can occur almost immediately, such as coseismic landslides (18) or river bank instability during flooding (19), whereas others can occur months, years, or even decades after an initial event, such as debris flows after wildfires (7, 20, 21) or flooding from mass movement-driven river damming or aggradation (22–25). However, we currently lack standardized approaches for incorporating land

surface processes within a mechanistic framework to quantify the persistent surface disturbances that result from an event on timescales relevant to hazard mitigation (26). A grand challenge in advancing knowledge of cascading hazards is the integration across Earth systems by linking mechanistic models and observations to include relevant solid Earth, land surface, and atmospheric processes (27). Recent advances in computational and observational approaches now provide the tools necessary for geoscientists to build a holistic, multihazard approach to advance the understanding and prediction of the consequences of extreme events across Earth's surface.

The process interactions leading to cascading hazards can emerge from triggers in different Earth system components on timescales relevant to hazards and societal impacts (seconds to centuries) (14, 23, 28–30). For example, solid Earth processes, such as earthquakes and volcanoes, generate cascading impacts, notably landslides and sediment loading in rivers, which reduce river channel conveyance and cause flooding (24, 25, 28). These cascading effects are linked to weather and climate, as illustrated by the enhanced debris flow activity in the years after the 2008 moment magnitude (M_w) 7.9 Wenchuan earthquake in China and 2015 M_w 7.8 Ghorhka earthquake sequence in Nepal (29, 30). Atmospheric conditions such as precipitation, drought-driven fire, and changing temperatures can also trigger hazards, which in turn are amplified or dampened by the topographic, tectonic, and seismic history of a region (31–33). For example, the 2018 Montecito post-fire debris flows in southern California were affected by geologic substrate controls on sediment accumulation (34). Advances in critical zone science further illustrate the role of Earth system interaction through the hydrologic and biologic processes that modulate near-surface properties, altering susceptibility to solid Earth and atmosphere-triggered land surface hazards (35, 36).

The geoscience community has an opportunity to advance the science of cascading land surface hazards by leveraging emerging observational and modeling technologies. The proliferation of high-frequency satellite imagery (37, 38), light detection and ranging (LIDAR) (39, 40), uncrewed aerial vehicles (UAVs) (41), and in situ instrumentation networks (42, 43) enable the detailed spatial and temporal observations necessary to quantify the scale of cascading hazards. Advances in landscape evolution modeling (44, 45), although not originally developed to capture the dynamics of processes that lead to hazards on timescales relevant to societal impact, provide a critical foundation for quantifying process interactions across Earth's surface. Further integration of numerical models across hazard components is also emerging as a powerful tool to understand the interactions between Earth systems, including the atmosphere, solid Earth, and critical zone, with geomorphic processes that control the emergence of cascading hazards (23, 46, 47).

These technological advances allow for improved data-model integration, calibration, and validation, facilitating better forecasts of hazard trajectories in a rapidly changing world (47). Such progress establishes a clear connection among processes that occur on hillslopes to valley bottoms and mountain fronts, prompting critical questions such as, “When and why do landslides and other abrupt sediment transport events near mountain tops influence the frequency of hazards within and beyond mountain fronts?” Addressing such questions requires a systematic approach that capitalizes on technological advances and considers the interactions among Earth systems across timescales that span seconds to centuries. But understanding and forecasting cascading hazards from their triggers to their ultimate impacts necessitates a framework that also examines and embraces Earth system interactions and feedbacks.

We require a paradigm shift that frames the interconnections of surface hazards in terms of Earth system interactions. Thus, in this Review we reframe the question more generally to ask, “How do different Earth systems interact to influence the magnitude and frequency of land surface events and the emergence of cascading hazards?” We

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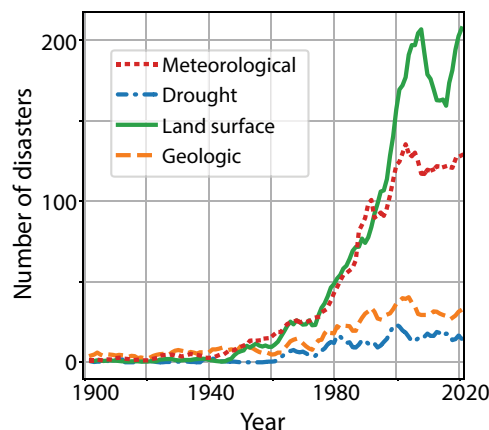


Fig. 1. Frequency of land surface disasters compared with other meteorological and geologic disasters. Data are from EM-DAT (201,202), updated from (4). Events are included in EM-DAT if they result in at least 10 deaths, 100 people affected (injured or homeless), or a call for international assistance or emergency declaration. Such criteria likely undercount localized mass movement events, which affect only a few people per event and are therefore not included in this analysis. Land surface hazards include mass movements (rockfall, landslides, mudslides, and avalanches) and floods (riverine and flash floods). Geologic events include earthquakes, tsunamis, and volcanic events. Meteorological events include cyclones, tornadoes, hail, storms, sand or dust storms, heat waves, and cold waves.

highlight key scientific gaps, challenges, and opportunities that collaborative initiatives across Earth system science disciplines can address in the coming decade. This Review differs from others on cascading hazards (17, 48–50) in that we focus on a mechanistic understanding of how different Earth systems and the resulting land surface processes interact over a broad range of spatial and temporal scales that lead to the emergence of cascading hazards. We restrict our focus to the hazard science dimension because it is the first step toward a holistic treatment of the consequences of natural hazards for communities, infrastructure, and ecosystems that underpin risk.

Definition of cascading hazards

Mechanistically, cascading land surface hazards are a linked chain of processes that move water and sediment across Earth's surface with the potential to cause harm to life or property. Although these processes often link in the downslope direction, events such as landslide dams (51) or fluvial undercutting of hillslopes can also affect upslope hazards (52). We distinguish cascading from compound hazards with the simple definition that with cascading hazards, one event directly affects the probability of another event, whereas compounding hazard refers to the occurrence and amplification of events that are statistically independent. Cascades are initiated when a triggering mechanism alters the state of the landscape (for example, changes in the moisture content of the critical zone or ground shaking during an earthquake), and this state change modifies the likelihood of a surface process that poses a hazard (for example, the landslide probability increases because of the altered state). For example, shaking during earthquakes destabilizes hillslopes (3), which can change the likelihood of landslides for years after the event, likely because of weakening of the substrate in the critical zone (Fig. 2A) (29, 53–55). Wildfire provides another example because it can change vegetative cover, sediment availability, and the hydrologic properties of the soil for years, making steep landscapes more susceptible to runoff-generated debris flows during rainstorms in the first several years after fire relative to the pre-wildfire conditions (Fig. 2B) (20, 56). Once material is mobilized on the land surface, the chain of processes and their interaction

across the surface continue to influence downslope processes and events, further affecting the likelihood of potentially hazardous events (Fig. 2C) (56, 57).

The M_w 8.7 1950 Assam Earthquake in eastern India provides an exemplary case study of a long-lasting cascading hazard. This earthquake resulted in catastrophic sediment loading from landslides. The sediment pulse traveled slowly through the river system, leading to cascading hazards such as aggradation, flooding, and avulsions in Bangladesh more than 20 years after the earthquake (58), which is similar to the timescales of the fluvial sediment responses in other observed earthquake-induced landslide events (54, 59, 60). Although many examples of cascading hazards in steep landscapes exist, we emphasize that lower-relief continental interiors and coastal regions are also subject to cascading hazards. For example, river floods can steepen local bluffs that line floodplains, leading to hazardous landslides (61), and submarine landslides can trigger tsunamis (62). Similarly, enhanced sediment transport in the years immediately after a wildfire can pose water quality and sedimentation hazards across a range of geologic and climatic settings, even in the absence of mass movements (63, 64).

A critical challenge in the cascading hazards science community is forecasting or predicting how the frequency–magnitude relationship of a particular process changes through time and in response to other events (Fig. 2). Many hazardous processes are characterized by some quantifiable magnitude, such as the moment magnitude scale for an earthquake (65), Saffir–Simpson scale for hurricanes (66), river stage for flooding (67), or the volume of material for landslides (68). Past and ongoing work has focused on understanding the controls on the statistical scaling of the frequency of events of a particular size (68–70). These frequency–magnitude relationships are defined for different regions and underpin hazard mitigation plans (71) and insurance rates (72). In the context of cascading hazards, however, frequency–magnitude relationships are not static as is traditionally assumed but rather evolve in time and space in response to previous events, local preconditioning processes, and upslope process interactions (73). Given the rapidly changing climate (74) and continued land surface modification by human activities (75), recognition of nonstationarity in the estimation of land surface hazards is likely to become more prominent, as already suggested for hydrologic time-series in water resource research (76, 77). The potential consequences of land surface cascading hazards are gaining attention from government (78, 79) and private sector stakeholders (80) as hazard researchers and practitioners become increasingly aware of the need to plan beyond individual events as an isolated or singular phenomenon.

Technological advances

Overcoming the challenge of understanding how frequency–magnitude relationships change during cascading hazards requires advances in both observational datasets and numerical modeling (Fig. 3). Although fundamental and ongoing work on the immediate connections between events have paved the way for cascading hazards science, few studies track the evolution of the hazard systems over longer periods or at sufficient resolution to resolve how land surface events are connected to processes that have occurred years or even decades beforehand (81). Likewise, the ability to quantify process interactions across the land surface has been limited by both the infrequent acquisition and low-resolution spatial data, which hampers the ability to track sediment mobilization from ridgetops to valley bottoms. However, an ongoing revolution in data from new satellite constellations is now providing imagery at finer spatial (from multimeter to submeter resolutions) and temporal resolutions. This allows the production of high-resolution maps of surface changes after events, and repeat imagery collection captures ongoing surface changes as the cascade develops (Fig. 4). For example, such satellite imagery was crucial for identifying the cause of the 2021 Chamoli rock and ice avalanche in the Himalaya

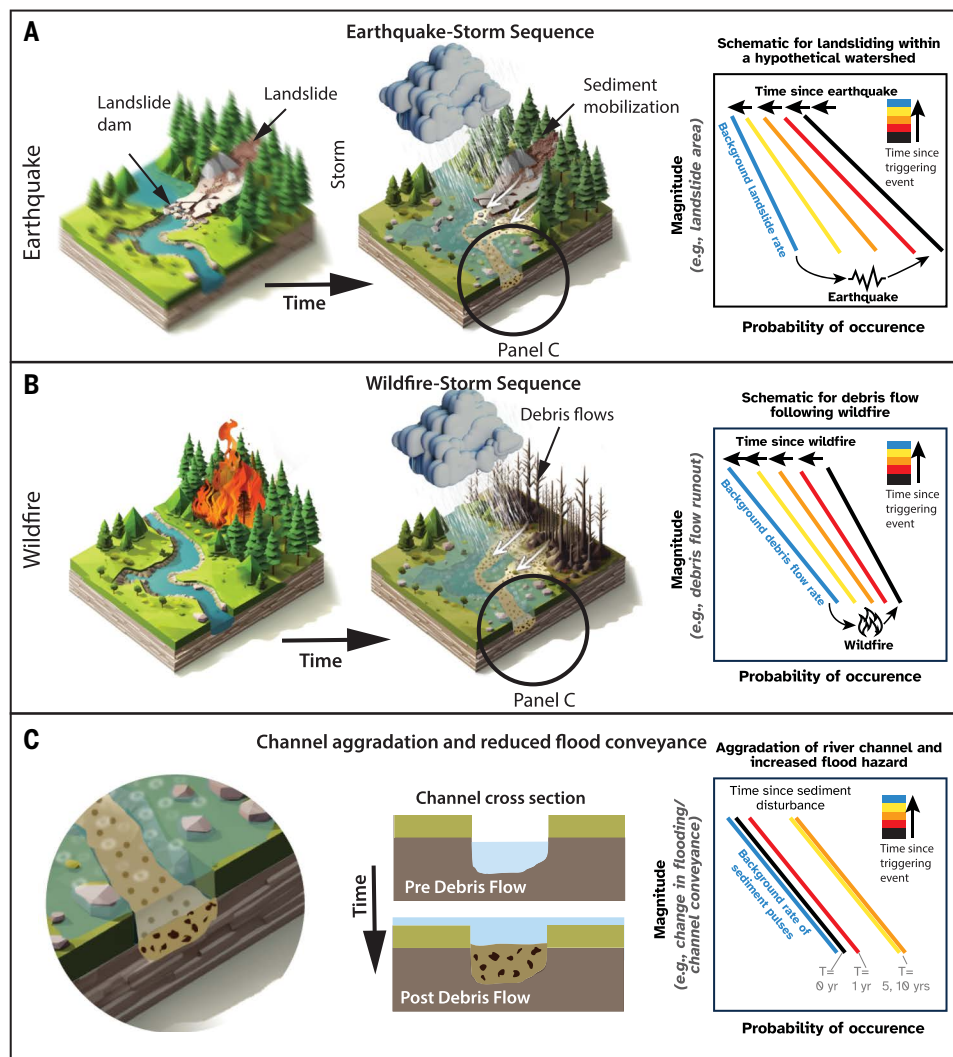


Fig. 2. Conceptual figure of cascading hazards and their influence on frequency–magnitude space. (A) An earthquake can drive landsliding immediately during the earthquake, and the elevated probability of landslide events persists well after the earthquake. (B) The occurrence of a wildfire increases the probability of runoff-generated debris flows. This increased hazard persists until soil and vegetation can reestablish, promoting greater infiltration and resistance to erosion across the landscape. (C) Cascading hazards downstream are delayed relative to the original trigger [for example, (A) earthquake or (B) wildfire], in which the maximum increase in a hazard occurs some time ($T = 10$ years in this case) after the triggering event rather than immediately because it takes time for the river to mobilize and transport the material downstream [(A) and (B)]. A challenge in the cascading-hazard community is quantifying how the frequency–magnitude curves change in response to factors such as the magnitude of the trigger as well as post-event critical zone processes and landscape characteristics (transport and storage zones), leading to questions such as whether the curves merely translate in frequency–magnitude space as depicted in (C), or whether there are changes in the slope of the relationship between the magnitude and probability change through time as depicted in (A) and (B).

that led to catastrophic flooding (14). LIDAR-based studies of hazards before and after events also provide crucial snapshots for quantifying mass fluxes and topographic changes (34, 82, 83), which proved essential in understanding the devastating 2014 Oso landslide in Washington state (84). Additionally, sensor miniaturization allows UAVs to be equipped with multiple sensors tuned to the specific measurements that are critical to capturing fundamental processes, and these UAVs can be flown essentially on demand by the investigator (41). UAVs equipped with optical and LIDAR sensors can be used to generate centimeter- to decimeter-scale three-dimensional (3D) models of the Earth's surface, enhancing quantification of topographic changes,

identification of the size and geometry of landslides, assessment of landslide mobility, sediment grain size measurement, river aggradation analysis, and optical characterization of the materials involved.

Linking process models across Earth's system and geomorphic process domains is also a burgeoning and exciting area of research in cascading hazards (23, 47, 82). Numerical modeling of cascading hazards is critical given that (i) extreme events are, by definition, rare; (ii) observations of extreme events are even rarer; and (iii) the nonstationarity of the systems (such as climate change) needs to be accounted for in probability estimates (constraints on observed past frequencies do not translate to future probability). Maturing process modeling approaches are ripe for integration into a cascading hazard framework. For example, the numerical architecture exists to link atmospheric and land surface models to simulate the evolution of cascading hazards across multiple process domains [for example, (47)]. Convection-resolving ensembles of atmospheric simulations, such as West-WRF (Weather Research and Forecasting), allow for probabilistic predictions of weather events that can be coupled with catchment-level post-fire debris flow likelihood models (85). Additionally, advances in post-wildfire debris flow modeling (82, 86) can provide inputs into sediment routing and river dynamics models (23, 87) to assess the evolution and impact of post-fire sediment pulses (86). Another important example of using coupled process modeling to understand cascading hazards is modeling two-phase solid-fluid mixtures to understand the evolution of landslide runout (88) and the interaction of runout and fluvial flooding (19). These coupled models hold promise for integration into other conceptual or mathematical frameworks for the assessment of cascading hazards (89). To advance land surface hazard science, models integrated across process domains and data collected at high spatial resolutions and over long durations need to converge to predict how a given event will affect the probability of subsequent events.

Cascading hazard components and Earth system interaction

We focus on cascades in steep landscapes that originate on hillslopes and transfer sediment to fluvial systems. The cascade initiates with a trigger that leads to the mobilization of sediment by hillslope processes—often landslides and debris flows—that transit the landscape. This transit leads to additional hazards associated with mass movement, runout, and the eventual deposition of sediment in adjacent river channels that can exacerbate river flooding owing to reduced channel conveyance (Fig. 5). Abrupt changes in channel morphology or damming of rivers can also propagate signals upstream in a fluvial system. Advances in technology are revolutionizing our ability to study three

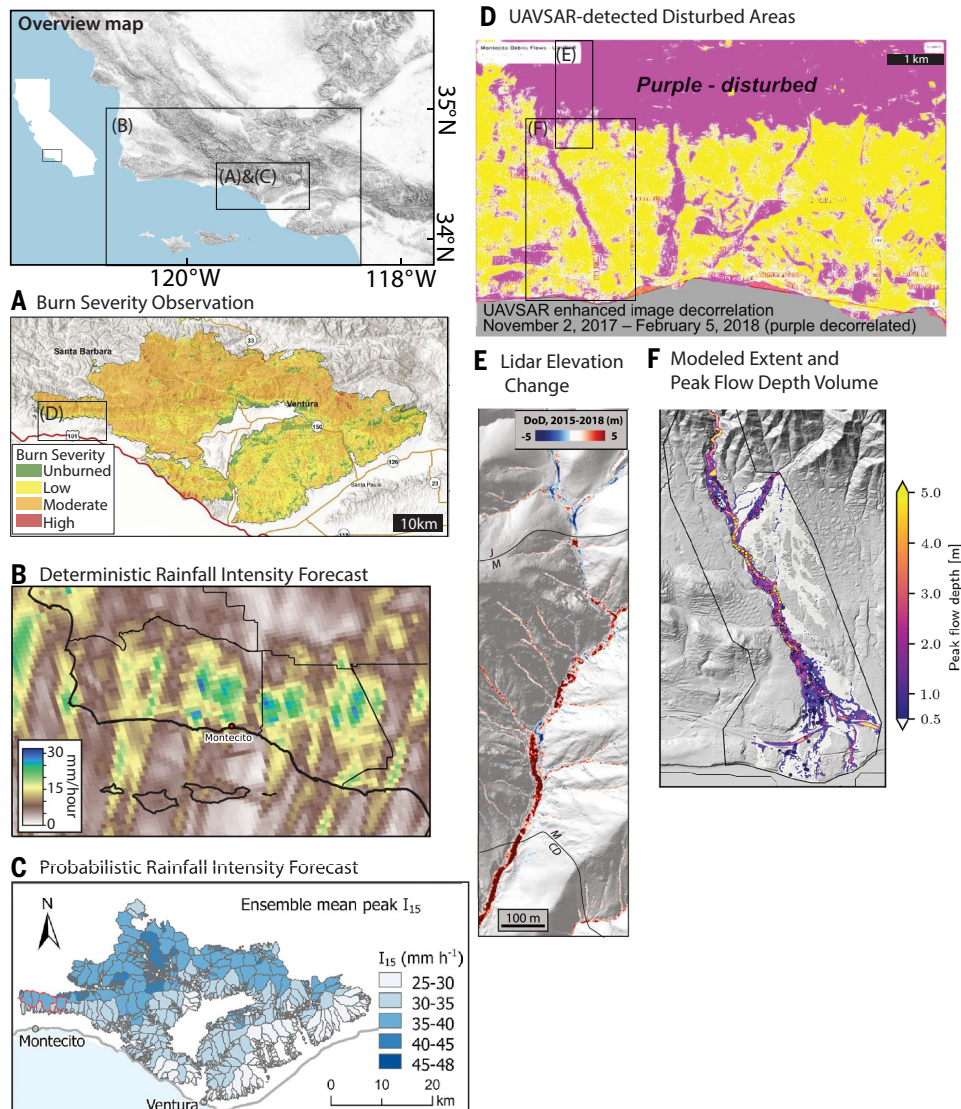


Fig. 3. The 2017 Thomas Fire and subsequent debris flows in southern California illustrate the increasing capability of cascading hazard science owing to advances in prediction, observation, and hindcast technologies. Observations can provide rapid quantification of burn severity across the landscape at high spatial resolutions. (A) Image modified from (203), depicting burn severity as mapped by the Burned Area Emergency Team with weather models that forecast rainfall intensity over the same region as in (B) and (C). (B) Data from the deterministic High Resolution Rapid Refresh (HRRR) meteorological forecast, showing a deterministic map of maximum 1-hour rainfall intensity for 9 January 2018 (204). (C) At a more local scale, the image is modified from (87) and illustrates a mean peak 15-min intensity from a 100-member WRF model realization ensemble. (D and E) Airborne observations provide (D) high-resolution maps of where the land surface has been disturbed and (E) estimates of the magnitude of erosion and deposition. (D) Image modified from (205), showing areas of decorrelation in Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data before and after the debris flows. (E) Image modified from (34), showing LIDAR-derived estimates of surface elevation change at 1 m resolution based on 2015 (pre-fire) and 2018 (post-debris flows) datasets. (F) Image modified from (82), showing a model of Montecito inundation by debris flows. Advances in surface process modeling can predict patterns of land surface disturbance.

critical aspects of cascading hazards: (i) the evolution of material properties of Earth's surface, (ii) the imprint of the triggering events on Earth's surface, and (iii) the interaction of processes that cause the emergence and propagation of cascading hazards (Fig. 5).

Earth system interactions in the critical zone and hazard preconditioning

In the critical zone, dynamic interactions among the biosphere, hydrosphere, and geosphere work to convert solid rock into transportable

fragments of rock and soil (90). Advances in critical zone science over the past few decades have transformed our understanding of how landscape properties vary in space and time (91) and how the critical zone modulates the landscape response to atmospheric and solid Earth triggering of cascading hazards. The transformation of rock into weathered regolith and soil greatly diminishes the mechanical strength of the upper few meters to tens of meters of the near-surface environment by several orders of magnitude (92). Subsurface stress fields change as rocks are exhumed from depth to the surface, especially in the presence of topography, and alter the rock mass physical and hydraulic properties (93, 94), preconditioning instability at the near surface. Vegetation cover modulates the timing and amount of atmospheric water that reaches that underlying rock mass. Once water infiltrates, the deep critical zone can influence the groundwater flow pathways and induce variations in hydraulic response during rainstorm events, potentially influencing saturation patterns and landslide initiations (95–97). Last, the type and density of vegetation cover and root depth, the soil cohesion and texture, and the slope angle all influence the balance between driving and resisting forces on hillslopes.

The interaction of Earth systems influences the processes and properties of the critical zone that are integral to predicting the land surface response to atmospheric and geospheric triggers. The critical zone influences the location, timing, and magnitude of cascading hazards and also shapes the landscape's response after events. Dynamic alterations in near-surface material properties after wildfires, severe earthquakes, and anthropogenic forces can transiently increase the potential for landslides and subsequent hydrologic hazards, such as flooding (98). For example, local variability in bedrock properties and site conditions can induce spatial variations in strong ground motion during earthquakes, leading to varying densities, distributions, and characteristics of earthquake-induced landslides (18, 36, 99, 100). Additionally, sediment size distributions and fracture patterns within the critical zone can influence the

rheological properties of debris flows; control bed materials in channels; and induce inundation, aggradation, and damming (101–104). The post-Thomas fire debris flow event near Montecito, California, in 2018 showed that different sediment characteristics, particularly those of shale and sandstone lithologies, influenced the extent of rainfall-driven rill erosion, sediment volume, delivery rates, size distributions, and rheology of the water-sediment mixture in the debris flow (34, 103, 105), factors that can affect the magnitude and destructive impact of the flow runoff.

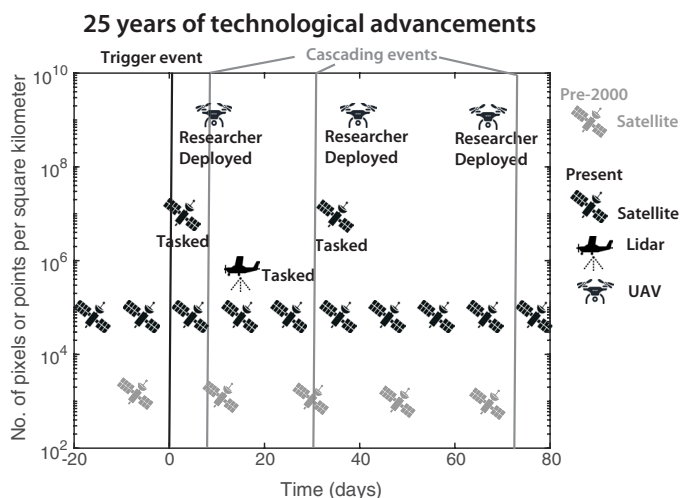


Fig. 4. Schematic illustration of a hypothetical cascading event to illustrate how the evolution of remote observation technologies for cascading hazard science has changed data availability over the past 20 years. The proliferation of commercial and government satellites has increased the spatial and temporal resolutions of imagery (optical and radar), allowing the isolation of surface response to specific trigger events separated from follow-on events such as storms or aftershocks (in the case of seismic triggering). Satellites capable of capturing high-spatial-resolution images (for example, 30 cm satellite resolution) can be tasked in the days after an event. LIDAR provides the ability to generate 3D maps of the surface through vegetation and has only become widely available and used in the past 15 years. Airborne LIDAR campaigns can be mobilized within days to weeks of an event. UAVs allow researchers to capture extremely high-resolution imagery or LIDAR as needed for surface characterization. These technologies offer trade-offs between spatial coverage and resolution.

Trigger events

Trigger events contribute to surface failure by driving a system to exceed a threshold and generate a hazardous process. Natural triggers (those not associated with anthropogenic forcing) can be broadly categorized into two categories: atmospheric or geospheric. We focus on these categories individually but acknowledge that atmospheric and geospheric systems are often intertwined and precondition the initiation of other events. The M_w 6.6 September 2018 Hokkaido Eastern Iwate Earthquake in Japan, for example, occurred 1 day after the passage of 2018 Typhoon Jebi and generated thousands of earthquake-induced landslides on saturated slopes (106). Anthropogenic forcings, such as land use and urban expansion into hilly terrain, can also accelerate land surface hazards, but the focus below is on natural triggers arising from the Earth system.

Atmospheric events: The climate system and associated weather events (such as storms) are primary drivers of natural hazards across Earth's surface. Precipitation is particularly important to land surface hazards. For example, in 2009 in Taiwan the island topography and low-level convergence affected the path of tropical cyclone Morakot, causing it to stall over the southern portion of the island. Rain gauges in mountainous areas recorded 1.5 to >3 m of rain over a 96-hour period (107). This deluge generated >20,000 landslides (108); this landslide-derived sediment is still propagating through the river system and increasing river stages (33). Extraordinary examples highlight a clear emergence of cascading hazards, but questions remain about the rainfall intensity and duration required to trigger mass movements, which vary by mass movement type and region and are influenced by the longer-term rainfall history (109, 110) and critical zone processes (36). Improved observations of mass movement catalogs (111) and detailed precipitation

histories, achieved through modeling and observation, can clarify how precipitation characteristics contribute to the emergence of cascading hazards (97, 112).

A lack of precipitation can also influence the likelihood of cascading hazards. Meteorological drought, driven by natural variability and anthropogenic influences, enhances the probability of wildfire (6, 113). Wildfires can alter vegetation and the hydrologic properties of the soil, creating surface and soil conditions that are more susceptible to generating rainfall-driven debris flows relative to conditions before the wildfire (56, 98). For example, after wildfires in 2007 in Greece, the magnitude of rainfall intensity-duration thresholds associated with debris flow initiation dropped by ~50% (114), which is similar to observations in the southwestern United States (115). Severely burned hillslopes in small (<10 km²) drainage basins can produce large-magnitude debris flows after average-magnitude (<2-year return interval) rainfall events (116). This drought, wildfire, rainfall, and debris flow cascade could be exacerbated in the future by projected increases in extreme rainfall after wildfire in some debris flow-prone regions (9, 117), highlighting the nonstationarity of cascading hazards. Using a combination of climate, fire, and erosion models, Sankey *et al.* (64) projected that by the decade of 2041–2050, post-fire sedimentation will increase by more than 10% in nearly 90% of watersheds and by more than 100% in more than one-third of watersheds in the western United States. Recent evidence also suggests that this hazard chain can extend further to affect water resources, with burned areas experiencing enhanced streamflow, large sediment loads, and reduced reservoir water quality (23, 118, 119).

Although many surface hazards are triggered by precipitation, temperature change can also contribute to the triggering of cascading hazards. Rapid snowmelt and rain-on-snow events, driven by shifts to earlier increases in springtime temperature and spring season heatwaves, can trigger extensive flooding and landslides, especially after warm rainfall (120). Frost weathering can supply debris flow channels with mobile grains (121, 122). Permafrost thaw is rapidly preconditioning ground failure from rainfall and earthquakes in Arctic latitudes and high mountain environments (123, 124) by weakening ice-filled joints or raising subsurface pore water pressures (31). Global warming has been implicated in recent increases in the frequency of glacial lake outburst floods (GLOFs) (8, 125, 126). Such events can lead to a cascade by undermining adjacent hillslopes along the flow path and ultimately alter the local channel morphology, leading to along-channel landslides (52). The addition of sediment to river channels can also drive morphodynamics that leads to channel avulsions and delta instability (127).

Geospheric events: The solid Earth triggers cascading hazards in a number of ways, including earthquake-induced widespread failure of hillslopes (18), volcanic eruptions blanketing landscapes with highly erodible sediment (128), and fault ruptures shifting topography, altering river erosion, sedimentation, and flood characteristics (129). In each case, the impact of the initial trigger can alter the state of the system by preconditioning or generating cascading hazards. Moreover, the intrinsic properties of Earth materials are altered by topographic stresses (93), deformation (such as fracturing) (94), and chemical weathering (130), which is influenced by interactions among the atmosphere, hydrosphere, and biosphere.

Strong earthquake motions alter the strength and hydrological conditions of the near-surface environment (131, 132). Observations show that an increase in landslide density proximal to large faults imparts an important control on earthquake- and rainfall-triggered landslide events. This suggests that the stronger ground motions observed close to faults cause temporary near-surface reduction in material strength, or that longer-term accumulation of high fracture density and rock damage proximal to major structures imparts a substantial control on near-surface rock strength (100, 133). Furthermore, several studies have shown that rainfall-triggered landslide rates increase after large earthquakes and exponentially decay to “background rates” within months

Triggers/Forcings

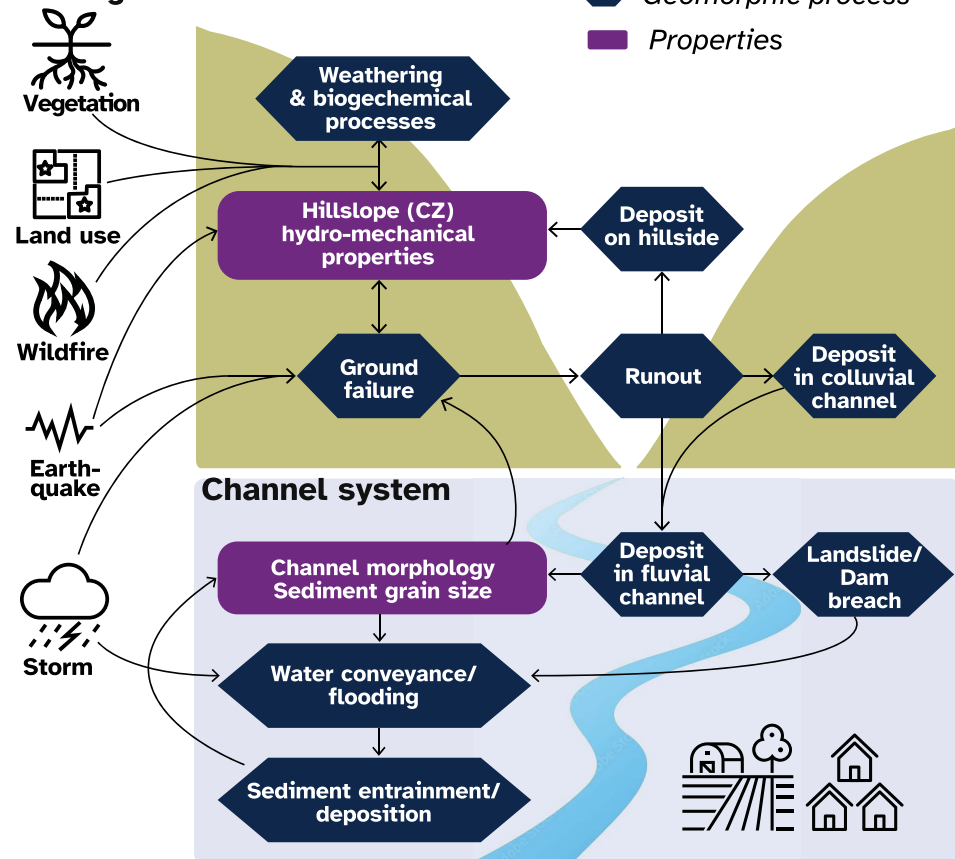


Fig. 5. System and process interactions illustrated in a flow diagram. Critical zone processes alter material properties on hillslopes that influence the landscape susceptibility to trigger events and other forcings. The mobilization of sediment on hillslopes by mass movements results in runout and eventual deposition, either on the hillslopes or in adjacent river channels. The addition of sediment to river channels can lead to damming or aggradation, which can increase flood hazards, impair water quality, and exacerbate reservoir sedimentation (63). Alterations to channel morphology, including abrupt incision events, can also trigger ground failure, exemplifying feedbacks within the hillslope and channel system.

to years after the event (53, 133, 134, 135). Ambient noise interferometry reveals a transient reduction in near-surface seismic velocity, suggesting a temporary weakening of the near-surface layer of the critical zone due to the settling of granular material over time (136). The mechanisms that cause strength reduction during earthquakes and the potential recovery to pre-event conditions, however, remain debated.

Volcanic processes generate enormous amounts of highly erodible sediment across large expanses of landscapes (128). The sediment loading itself changes landscape-wide erosion rates as the newly deposited material is eroded in the months to decades after an event (28, 127–139). The erodible sediment on hillsides elevates the post-eruption rates of mass wasting, and the sediment loading fundamentally alters sediment transport, river hydraulics, and pathways, affecting water quality and flood hazards. After the 1980 Mount St. Helens eruption, the ports of Portland, Oregon, closed for 2 weeks and were affected for 6 months by sediment aggradation that disrupted shipping lanes. Continued sediment management occurs today largely through the maintenance of a large sediment retention structure (140). Eruptions can also have major impacts on processes that take years to be realized. For example, the 2008 Chaiten and 2011 Puyehue-Cordon Caulle volcanic eruptions in southern Chile showed that on forested hillsides, elevated landslide

rates persisted for 2 to 6 years after the event (141) because of reduced shear strength associated with tree root decay. Volcanic material can also mobilize into lahars, generating devastating high-mobility flows, such as the 1985 Nevada del Ruiz event in Columbia, which killed more than 25,000 people (142). In the years after the 1991 eruption of Mt. Pinatubo in the Philippines, lahars were the primary post-eruption hazards in that region (139, 143). Lahars in the recent geologic past covered parts of the Seattle metropolitan area in Washington state (144), and the risk of future lahars in the region persists (88).

Land surface processes and their interactions

Anticipating the impacts of cascading land surface hazards requires an understanding of geomorphic processes and their interactions. Cascades in steep landscapes often originate on hillslopes when sediment is mobilized by mass movements and subsequently transported through fluvial systems. There, the material can lead to enhanced river flooding or damming events (18, 19, 24, 25, 51, 145), which pose a risk of catastrophic failure. How one process and its dynamics influence the next in the sequence is critical to anticipating the emergence, magnitude, and temporal persistence of cascading hazards.

Initiation: Mass movements are a primary driver of sediment mobilization during atmospheric or geospheric disturbances and are directly influenced by critical zone processes. Topography, bedrock, vegetation, and critical zone architecture are coupled and coevolve in response to the stresses and forcings that are imposed on hillslopes susceptible to mass movements.

The state of internal stresses and associated weaknesses within a hillslope, which evolve with weathering, are fundamental controls on landslide initiation, and destabilizing stresses tend to increase with slope and relief. However, initiation can manifest in numerous forms to produce a broad range of ground failure types and depths that range from shallow debris flows and soil or rock slides to deep-seated bedrock landslides. Generally, volume-area scaling relationships suggest that shallower landslides in soils increase in volume by increasing in area with a relatively constant depth, whereas deep-seated landslides in bedrock follow geometric scaling (146). For example, shallow landslides tend to initiate rapidly within weathered rock and soil, often exhibiting precursory motion that is outside the spatial and temporal scales of standard observation. Deep-seated landslides tend to occur primarily in bedrock; however, the mechanisms of initiation are a continuum because precursory motion may result in runaway failure, steady creep, or in some cases, dormancy (147). These behaviors may vary substantially over a given deep-seated landslide, both spatially and temporally, but their controls are poorly constrained.

The varied initiation behavior between shallow and deep-seated landslides depends on topography, weathering, geologic setting, vegetation, and forcing. Shallow landslide debris exhibits notable mobility owing to loss of frictional strength; contraction of loose, saturated

material (148); and loss of vegetation root strength upon deformation (149). Vegetation is considered an important factor in shallow landslides: The forest canopy intercepts precipitation (140, 141), evapotranspiration modulates groundwater (142, 143), and roots reinforce surface materials (140, 147) but also cause physical damage to the parent rock that facilitates enhanced chemical weathering (35). The evolution and variability of vegetation as a control on preconditioning shallow landslides remains a key knowledge gap. The role of vegetation in deep-seated landslides is less clear because the stresses that drive failure are much greater than root strength (150), and hydrological changes from land cover change are poorly constrained at the scale of a landslide. Hillslope stability also depends on the underlying geology, past disturbances, and weathering processes (151) that have occurred before the disturbance (36). For example, shallow landslides tend to occur in highly weathered, cohesionless materials that respond to pore pressures stemming from short-duration, high-intensity precipitation events or snowmelt (152, 153). However, questions remain as to the relevance of antecedent moisture in preconditioning shallow landslide initiation (154). Deep-seated landslides often exist in a weakened state after substantial deformation (151), moving slowly because of residual friction, although the mechanisms behind this creep are debated (155). These landslides may not fail immediately after heavy rain or earthquakes but instead accelerate over time (156, 157). On the contrary, progressive, “first-time” failures in bedrock may yield catastrophic failure from runaway weakening of intact rock mass and associated loss of strength through fracture, excess pore pressure generation, and even shear heating (158, 159). However, knowledge of how critical zone architecture controls these mechanical thresholds of weakening, or the evolution of hydrological systems within deep-seated landslides, is largely unknown. Substantial uncertainties remain as to the interplay of governing processes and forcings that control the initiation of mass movements. These unknowns include how the different aspects of the atmosphere, geosphere, and critical zone influence initiation mechanisms and thresholds of mass movements that lead to cascading hazards (20).

Runout: Although mass wasting initiates on hillslopes, the ensuing runout of debris to colluvial and fluvial channels can entrain material, aggrade channels, dam rivers, and inundate communities. Within an individual event, the proportion of solid and fluid components is a key control on runout behavior, and streamwise changes in this proportion can result in mass wasting events that transition into floods (160). Theory on the physics of granular flows and fluid-particle interactions that govern runout has advanced in recent years (161), although much is unknown about how these flows interact with the complex topography and materials found in real landscapes. Many landslide runout studies show that travel distance and inundation area scale with volume, although these measures of runout can vary considerably among debris flows with similar volumes in different settings, especially for smaller debris flows (162–164). Debris flow volume depends on the initial failure volume of the landslide and the entrainment and disentrainment of sediment along the flow path. Entrainment rates are highly variable both within and among debris flow-triggering events, with a documented range of 0 to 70 m³/m, and a debris flow’s volume may increase by orders of magnitude from initiation to deposition (165). The grain size, bed material, and flow hydraulics serve as key controls on the potential for entrainment (166), and this bed material originates from sediment production in the critical zone on adjacent hillslopes. Thus, in addition to the ratio of solids to liquids in a flow, runout behavior also depends on the abundance and grain size of sediment delivered to channels (167), which can change abruptly after a disturbance (122, 168); seasonally with frost-driven weathering (121); or on decadal or longer timescales owing to the production of material through volcanism, weathering, erosion from adjacent hillslopes, and other mechanisms (169, 170). The travel distance of

dry granular flows strongly depends on substrate roughness relative to the volume and grain size of the flow. Debris flow mobility also depends on the geometry of the channel network being traversed (171) and maintenance of high pore-fluid pressures, with low pore pressure diffusivity owing to fine-grained sediment being a critical property of debris flow material (172). In these flows, coarse debris, including boulders and large wood, are dynamically segregated to the front and lateral margins of the flow, which often results in damage and destruction (101).

Several knowledge gaps constrain our ability to predict the hazards of mass movement runout. For example, how the initial size of mass movements (167) control runout and how different mixtures of water and sediment generate debris flows are active research topics (162, 173, 174). Initial grain size of the failure or in-channel sediment is a critical component of the runout process (167), yet the controls on the production and size of sediment that provides bed material in landslide-prone channels is a critical and on-going research direction (175, 176). Critical zone processes influence the grain sizes of landslides, but how these processes and resulting grain sizes vary across different environments remains poorly constrained (172). Last, we know little about the physical controls on the size of debris fans that get deposited at the end of a runout, which is a particularly notable knowledge gap given the frequent societal development on such fans. The grain size and deposition problems of runout are critical for predicting cascading hazards because the distribution and physical properties of landslide deposits are key for determining how fluvial systems respond to landslide initiation and runout.

Fluvial system: The fluvial component of the hazard cascade can transmit cascading hazards for hundreds of kilometers (58). These fluvial processes are influenced by channel morphology, which reflects the regional geologic history, and climate, which links Earth systems in the trajectory and longevity of cascading hazards. The potential for cascading hazards to persist in a fluvial system depends on the volume and sediment characteristics of the mass movement deposit(s) relative to the channel transport capacity, which dictates any resulting morphological changes and alterations to downstream flood risk (24, 25, 177). Grain size, water discharge, and channel morphology (width, slope, and roughness) all affect the local transport capacity of a river system (178, 179). The runout deposit volume and grain size set the initial perturbation to the fluvial system. If the grain size or volume of the deposit is small relative to the capacity of the receiving fluvial system, then the sediment will be transferred efficiently downstream. Alternatively, if the grain size or volume of the deposit is large, then the incoming sediment will be deposited, potentially forming a large fan or landslide dam. Whether such deposits translate downstream in a wave or disperse in place depends on factors such as the runout grain size as well as the existence of other downslope channel constrictions, which can localize aggradation of sediment transiting the fluvial network (83, 178). The effects of mass movement deposition can also extend upstream as additional sediment is deposited either as lake fill behind a dam or as fluvial aggradation in a zone of decreased channel gradient upstream of a channel constriction. Landslide dams can trigger delayed and sometimes catastrophic hazards downstream when they fail (180). In situations in which the mass movement deposit is mobilized by the fluvial system, the reworked material can affect the downstream channel morphology (181), undermine adjacent hillslopes (52), and increase flooding potential over a geographic area much larger than that affected by the initial mass movement and runout (182). Although these generalized patterns are clear, uncertainty in quantitative predictions of sediment transport can exceed an order of magnitude (183), with recent work progressively revealing greater complexity, including the variability of the threshold for grain motion with flow history, sediment supply, and grain-scale bed structure (184, 185); temporal fluctuations in transport even at constant flow (183); and

hysteresis in bedload transport (186). Improvements in our ability to accurately predict sediment transport in real rivers over long distances would be a great benefit to morphodynamic predictions of cascading hazards in fluvial systems.

Even with these uncertainties, modeling is becoming a critical tool for understanding how the river system redistributes this incoming sediment supply (180, 187), changes channel morphology in response to landslides (182), and the degree to which this sediment redistribution changes channel conveyance and flooding or avulsion potential (22, 125). Sediment pulse transport in rivers has been modeled extensively by using 1D morphodynamic models with reach-scale hydraulic forcing (178), with recent work introducing Lagrangian approaches to tracking sediment from source to sink (188). These models have the benefit of computational efficiency but have limited ability to capture subreach-scale morphologic changes. Yet higher-fidelity morphodynamic models, such as Delft3D, must be carefully tuned to a relatively shorter reach and are ill-suited to the high-gradient systems often involved in a hazard cascade (189). Existing sediment transport and morphodynamic models do not have a mechanism for handling rapid geomorphic change that can be brought about by extreme stream and hyperconcentrated flows that can accompany cascading hazards. This includes debris build-up and rapid changes in channel width, both of which cannot easily be parameterized from boundary shear stress or sediment transport capacity. Other work has focused on multiphase modeling of landslide and flood interactions, demonstrating the potential for amplification of flood hazards through landslide sediment delivery by means of mechanisms such as bulking of the flow and even temporary damming and dam failure during a flood event (19, 145). Further work could help to understand and model the complex interaction of sediment and water along the continuum from debris flows to clearwater flows that transport sediment as bedload (160).

How long do cascading hazards last?

Anticipating the impact of a triggering event through the entire cascade requires understanding the timescale over which associated hazards remain elevated above background rates after the triggering event (Fig. 6). Evaluating this requires an approach that considers the magnitude of the trigger and its effects on surface processes and materials, the preconditioning and response of the surface materials through critical zone processes, and the dynamic interaction of the chain of surface processes that constitute a cascading hazard. We present a conceptual framework that uses a hazard index to represent the magnitude of a hazard and visualize how it changes over time after a triggering event. The dynamic index illustrated in Fig. 6 should reflect the integrated change in probability for subsequent hazardous events (Fig. 2). By capitalizing on the emerging observational and modeling technologies (Figs. 3 and 4), the science is well positioned to fill knowledge gaps in the coming decade related to anticipating how these cascading hazards emerge. Specifically, predictions of probability change in response to different triggering events or critical zone evolution throughout the cascade. We view quantifying the changing probability-magnitude space through modeling and observation as the grand challenge of cascading hazard science.

This framework can be used to characterize different post-trigger responses, how they vary from one hazard type to another, and how they are influenced by natural and human (such as hazard mitigation actions) forcings, which could assist with the development of quantitative models and identification of factors that control the magnitude and temporal persistence of cascading hazards. Hazard magnitude can peak immediately after a trigger, as with coseismic landslides, or years to decades after the trigger, as with shallow landslides after wildfire (20). However, forecasting hazard index trajectories and explaining variability across climatic and geologic settings has been limited by two key factors. First, there is a paucity of long-term observations of cascading hazards that extend beyond a few years after the triggering

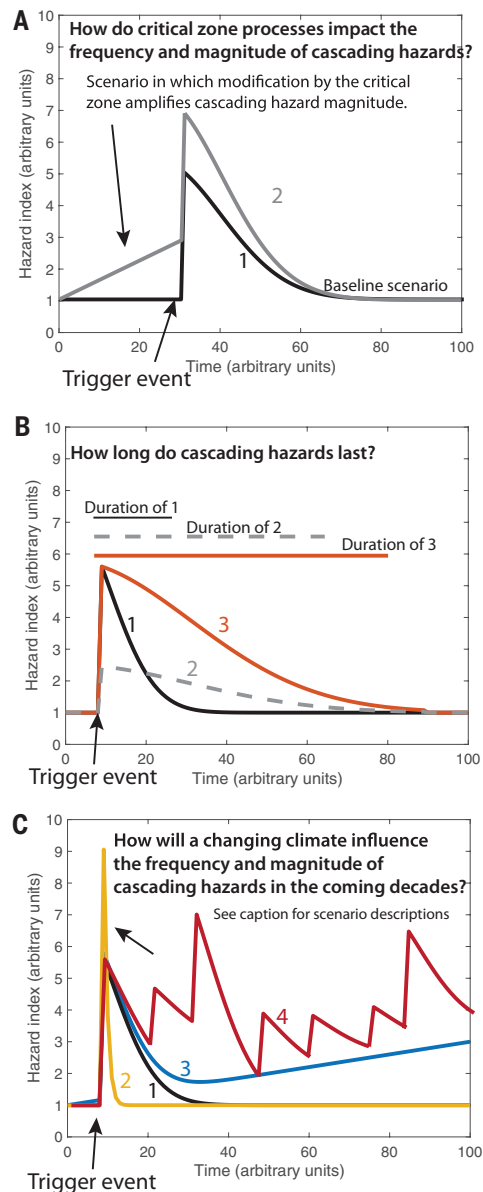


Fig. 6. A conceptual framework based on a hazard index, which quantifies hazard magnitude, can be used to visualize the range of trajectories for the magnitude of cascading hazards after a triggering event. (A) How do critical zone processes affect the magnitude of cascading hazards? Two scenarios: (i) A baseline scenario in which a triggering event occurs (such as an earthquake or wildfire) with a gradual decay in the subsequent hazard (such as landslides or debris flows) over time. (ii) Scenario in which the background hazard probability is increasing because of changing critical zone hillslope properties that diminish material strength. **(B)** How long do cascading hazards last? Three scenarios: (i) A baseline scenario in which a triggering event occurs (such as an earthquake or wildfire) with a gradual decay in subsequent hazards (such as landslides or debris flows) over time. (ii) Scenario in which hazards are not as likely (lower peak hazard index), but the hazard remains elevated for a longer time. (iii) Scenario in which the peak hazard magnitude is the same as the baseline (i), but the temporal persistence of the hazard is greater. **(C)** How will a changing climate influence the frequency and magnitude of cascading hazards in the coming decade? Four scenarios: (i) A baseline scenario. (ii) Climate change increases the immediate hazard after a triggering event, but the landscape responds quickly (for example, from increased rates of sediment transport) and returns to the background index in a short time. (iii) Ongoing climate change is altering the background hazard index, and thus after a triggering event, the hazard index never returns to the original level. (iv) Ongoing climate change is increasing the frequency of events so that the system does not have time to recover to the background state.

events. A few exceptions exist [for example, the 1980 Mount Saint Helens eruption in Washington state, which has been monitored now for many decades (190)], but most studies focus on the immediate secondary impacts of triggering events (for example, post-wildfire debris flows and coseismic landslides). Second, models are often compartmentalized by process and do not link over the spatial and temporal scales needed to consider the legacy of triggering events and interacting processes that control the magnitude and temporal persistence of cascading hazards. The integration of new and existing tools to quantify sediment movement throughout cascading hazards can inform a focus on the “long-tail” response to the original event. With an advanced understanding of relevant process domain interactions and representations of these interactions in quantitative model frameworks, the attribution of events to specific triggers can help illuminate the interconnected nature of Earth’s surface and inform hazard mitigation strategies.

How will climate change influence the emergence, magnitude, and persistence of cascading hazards?

Climate change can modify cascading hazards in multiple ways. Perhaps most commonly, hazard-triggering events are anticipated to become more frequent. In California alone, extreme precipitation from atmospheric rivers is projected to increase by 10 to 40% in the coming decades (191), flood risks from rain-on-snow events are predicted to increase by 20 to 200% (192), and wildfire burn areas are predicted to increase by 3 to 52% (193). However, climate projections in the Alps suggest that debris flow occurrence may drop by 20% (170). More generally, climate-driven changes in extreme precipitation (194) and fire activity (195) are primed to change the frequency and intensity of land surface hazards and their cascades around the world.

Interactions within cascading hazards can exacerbate the effects of climate change (170). Precipitation patterns influence the land surface response to solid Earth triggering events—for example, by determining when and where debris flows and landslides occur in the months to years after an earthquake (30) and by controlling the mobilization and dispersal of sediment through a watershed (60, 182). Moreover, precipitation and thawing permafrost drive the weathering and erosion that reshape the critical zone, potentially weakening surface materials (196). Precipitation also influences vegetation, which can act to stabilize surfaces by increasing near-surface cohesion through root structures (197). Increases in fire frequency to return intervals that are less than the timescale needed for geomorphic systems to return to a pre-fire baseline can lead to scenarios in which post-fire debris-flow hazards depend not only on the most recent fire but also on recent fire history (Fig. 6C) (198). Similarly, the magnitude of fire-enhanced sediment pulses from recently burned watersheds in the Transverse Ranges of Southern California is controlled by interactions between fire frequency and critical zone process that are influenced by climate, including the rate of soil production and the timescale associated with the reestablishment of vegetation on hillslopes (199). These effects can reshape the template for land surface hazards over years to decades (Fig. 6C).

Several major knowledge gaps limit hazard forecasts in a changing climate. For example, much work has been done to quantify rainfall thresholds for landslide initiation in specific locations. These rainfall thresholds are typically viewed in the context of a stationary climate, but rates of exceeding thresholds can change substantially over time. More attention is needed to constrain how the frequency at which these thresholds have been exceeded has changed in present-day climate conditions—a natural if imperfect starting point for assessing how climate change may affect future triggering behavior. Accurate long-term forecasts will require considering the evolution of the critical zone, such as changes in sediment production and surface properties that control sediment mobilization and transport, in response to changes in the magnitude and frequency of triggers (200). Uncertainty

in climate predictions, especially when it comes to the variables that control both triggering and other cascading processes (such as precipitation), represents an additional challenge to forecasting hazards and motivates greater coordination between geomorphologists and climatologists (170). Providing requisite information for anticipating land surface hazards in a changing climate will depend on a cross-disciplinary research effort that recognizes the nonstationary nature of these hazards and the multiple interacting elements of cascading hazards.

Conclusions and outlook

Cascading land surface hazards will likely change in magnitude and frequency in the coming decades, with expected increases in many locations. Advances in forecasting cascading hazards can help to build a more resilient future. The framework presented in this Review of a cross-disciplinary approach in which atmospheric scientists, geologists, geomorphologists, engineers, and others work to improve theory, modeling, and observations of cascading hazards provides a path toward developing actionable plans for communities to prepare for cascading hazards. As the science of cascading hazards matures in the coming decades through observational and modeling advances, we see the utility of a cascading hazards index that provides local communities context for the potential emergence and persistence of cascading hazards (17). This index could synthesize process-based data and models and provide actionable, site-specific information concerning how land surface hazards and risk evolve in response to a triggering event. Such an approach will undoubtedly rely on advances in observational and modeling platforms and will need to account for preconditioning processes in the critical zone, mechanistic understanding of process interactions along the cascade, and incorporate cross-disciplinary modeling approaches that can account for factors such as the nonstationarity of climate change.

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