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The Science and Prediction of Post-Fire Debris Flows in the Western United States

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Debris flows are among the most destructive hydrological consequences of fires in steep watersheds (Figure 1, Figure 2). The high likelihood of catastrophic wildfires in the western United States and the encroachment of human activities into steep fire-prone areas have created the need to better understand, predict, and mitigate these hazards. This article highlights recent advances in understanding post-fire debris-flow generation and provides an overview of the evolution of hazard assessments in the western United States. Specific emphasis is placed upon free, publicly available tools developed by the U.S. Geological Survey (USGS) and available for analyses in support of Burned Area Emergency Response (BAER) and Emergency Watershed Protection (EWP) program activities. These tools consist of empirical models

Figure 1: Downstream effects of post-fire debris flows in Camarillo Springs, California, downstream of the area burned by the 2013 Springs Fire (12/12/2014).

StreamNotes is an aquatic and riparian systems publication with the objective of facilitating knowledge transfer from research & development and field-based success stories to on-the-ground application, through technical articles, case studies, and news articles. Stream related topics include hydrology, fluvial geomorphology, aquatic biology, riparian plant ecology, and climate change.

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that predict the likelihood, potential volume, and the rainfall intensity-duration thresholds for debris flows in recently burned watersheds.

Fire and Debris-Flow Generation

Wildfire significantly increases the potential for post-fire debris-flow generation in recently burned watersheds by enhancing the discharge and velocity of surface water flow, resulting in higher rates of erosion. While runoff in unburned forested watersheds is typically generated through saturation-excess overland flow processes, runoff in recently burned areas is generated mainly as infiltration-excess (Hortonian) overland flow, which occurs when rainfall rates exceed the infiltration capacity of the soil. The fire-induced physical and chemical changes to soil and vegetation systems, such as decreased raindrop interception, hyper-dry conditions, enhanced hydrophobicity and infiltrated ash, serve to effectively increase the amount of rainfall reaching the surface, decrease the hydraulic conductivity, and decrease the infiltration rate of burned soils, thereby increasing runoff discharge and related erosion. In addition to increased discharge, the runoff velocity in burned areas is often higher after wildfire. Combustion of surface litter reduces surface roughness, time to ponding (i.e., the filling of fine-scale surface depressions) and time to reach pond capacity (i.e., the amount of time needed to overtop fine-scale surface depressions), allowing runoff to flow uninterrupted downslope at higher velocities (Moody and Ebel, 2014; Moody and Martin, 2015). Increased flow depth produces higher shear stresses, inducing rill and gully erosion in areas of concentrated flow. Development and expansion of well-defined rill and gully networks, and enhanced connectivity between hillslopes and gullies, further permits more rapid flow concentration and transfer of water and sediment downslope, which in turn increases discharge, shear stress, and sediment yield (Moody and Kinner, 2006; Neary et al., 2012).

Figure 2: Downstream effects of post-fire debris flows in Mullally Canyon, La Crescenta, California, downstream of the area burned by the 2009 Station Fire (2/6/2010).

Unlike debris flows that initiate from shallow landslides, there is no discrete initiation point or material source in a majority of post-fire debris flows (Parrett, 1987; Meyer and Wells, 1997; Cannon, 2001). Instead, debris-flow initiation in burned areas often results from progressive sediment bulking processes, where infiltration-excess overland flow produced on hillslopes gradually entrains material, ultimately transforming sediment-laden surface water flow to debris flow (Kean et al., 2013). Severe erosion of hillslopes, gullies and channels serves as the primary source of material for the debris flows generated from progressive sediment bulking (Santi et al., 2008; Smith et al., 2012; Staley et al., 2014).

Rainfall and Debris-Flow Generation

The temporal occurrence of post-fire debris flows has been found to closely correlate with pulses of high-intensity rainfall and the generation of infiltration-excess overland flow (Wells, 1987; Gabet, 2003; Cannon et al., 2008; Kean et al., 2011; Staley et al., 2013). Antecedent moisture conditions (e.g., after wildfire, either within single storms or seasonal) have been found to have very little, if any, influence on the likelihood of post-fire debris-flow initiation (Cannon et al., 2008). For example, in a plot-scale field experiment, Wells (1987) was able to initiate small debris flows after only 3 minutes of rainfall at intensities between 12 and 55 mm/h. More recently, field monitoring in the San Gabriel Mountains of southern California recorded the occurrence of post-fire debris flow after 16 minutes of moderate intensity rainfall during the very first rainstorm following wildfire (Kean et al., 2011; Staley et al., 2013). Debris flows have also been generated several months after wildfire after several significant rainstorms (Kean et al., 2011).

Within rainstorms, debris-flow generation has been strongly correlated with short bursts of high-intensity rainfall (Kean et al., 2011; Staley et al., 2013). From precise monitoring of debris-flow timing, Kean et al. (2011) identified a near-zero lag time between the occurrence of short bursts of high-intensity rainfall and the passage of a debris flow at the San Gabriel monitoring site. The best temporal correlation and shortest lag between rainfall intensity and debris-flow initiation was identified for rainfall intensity measured between 5 and 30 minute durations (Kean et al., 2011; Staley et al., 2013). In addition, the first indication of flow in a stream channel (as measured by stage) has frequently been associated with the passage of a debris flow (Kean et al., 2011), rather than a water-dominated flow (i.e., flash flood).

Post-Fire Debris-Flow Prediction

The basic post-fire research findings outlined above have provided the foundation for the development of tools for the prediction of post-fire debris-flow hazards in the western United States. These multivariate statistical models are intended to predict (1) the likelihood of a debris flow at a given location in response to a design storm (Staley et al., 2016; USGS, 2017), (2) potential debris-flow volume (Gartner et al., 2014), and (3) rainfall intensity-duration thresholds (Cannon et al., 2008; Cannon et al., 2011; Staley et al., 2013; Staley et al., 2015; Staley et al., 2017). Specific equations for the calculation of debris-flow likelihood and volume, and the 15-minute rainfall intensity-duration threshold are provided in Table 1.

Post-Fire Debris-Flow Hazard Assessment

Prior to January 2014, most post-fire debris-flow hazard assessments published by the USGS were produced as hard-copy reports accompanied by a series of poster-sized digital maps that displayed post-fire debris-flow probability, expected volume, and combined hazard. Feedback from primary stakeholders, including USFS Burned Area Emergency Response (BAER) teams, the National Weather Service (NWS), and numerous other state and local agencies suggested that this mode of assessment dissemination was antiquated and relatively ineffective

Table 1: Post-fire debris-flow hazard assessment model equations used for predicting likelihood, potential volume, and estimated rainfall intensity-duration threshold.

Model Name	Equation / Variables	Citation
Debris-Flow Likelihood (L)	$X = -3.63 + (0.41 * PropHM23 * i15) + (0.67 \times (dNBR / 1000) * i15) + (0.7 * KFFACT * i15)$ $L = \exp(X) / (1 + \exp(x))$ PropHM23 = Proportion of upslope area burned at high or moderate severity with gradient in excess of 23° dNBR / 1000 = average differenced normalized burn ratio (dNBR) of upslope area, divided by 1000 KFFACT = soil erodibility index of the fine fraction of soils i15 = 15 minute rainfall intensity (mmh^{-1})	Staley et al., 2016
Potential Debris-Flow Volume (V, in m^3)	$\ln(V) = 2.89 + (0.17 \times Relief^{0.5}) + (0.3 \times \ln(HM_{km}) + (0.47 \times i15^{0.5})$ Relief = Upslope relief (m) HM_{km} = Upslope area burned at high or moderate severity (km^2) i15 = 15 minute rainfall intensity (mmh^{-1})	Gartner et al., 2014
Estimated Rainfall Intensity-Duration Threshold (T_{15}, in mmh^{-1})	$T_{15} = (\ln(P / 1\text{-}P) + 3.63) / (0.41 * PropHM23) + (0.67 * (dNBR / 1000)) + (0.7 * KFFACT)$ P = likelihood value used for threshold definition, in this case we use P = 0.5 PropHM23 = Proportion of upslope area burned at high or moderate severity with gradient in excess of 23° dNBR / 1000 = average dNBR of upslope area, divided by 1000 KFFACT = soil erodibility index of the fine fraction of soils	Staley et al., 2017

for the purpose of rapid hazard assessment.

Beginning in January of 2014, the USGS transitioned to a web-based method for disseminating post-fire debris-flow hazard assessment information using a largely automated process to estimate potential debris-flow hazards, including likelihood (Figure 3), estimated volume (Figure 4), and estimated 15-minute rainfall intensity-duration threshold (Figure 5). This new method addressed the feedback from primary stakeholders by reducing the time needed to deliver hazard assessment information to 3–5 business days after receiving required input data (soil burn severity and differenced normalized burn ratio imagery), providing users with both interactive online maps and downloadable, fully attributed geospatial data. With the increased automation, a much greater number of assessments are able to be disseminated to the stakeholders. In addition, the assessments are freely available for Federal, State and local agencies and non-governmental groups or individuals seeking post-fire debris-flow hazard information, provided that geospatial field-validated burn severity data are available. More information and assessment examples may be found on the USGS website for post-fire debris-flow hazard assessment (USGS, 2017). Interactive maps are available for areas burned within the last two years. Downloadable geospatial data are available for all analyzed burn areas, irrespective of fire age.

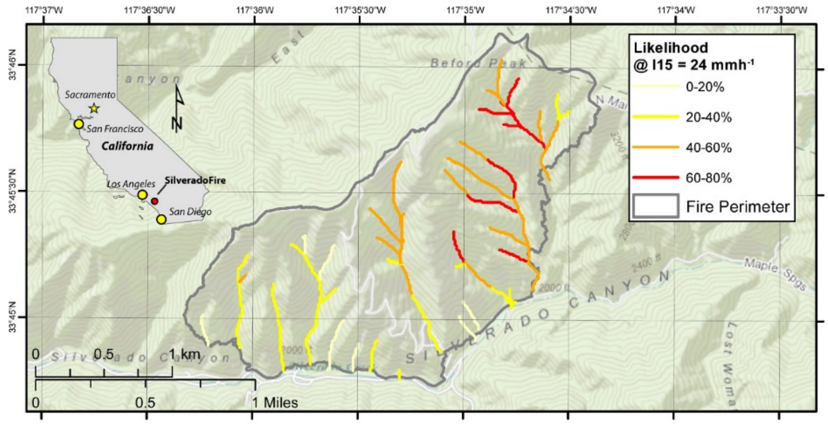

Figure 3: Estimates of post-fire debris-flow likelihood for a rainstorm with a peak 15-minute rainfall intensity of 24 mmh^{-1} in the area burned by the 2014 Silverado fire, Cleveland National Forest.

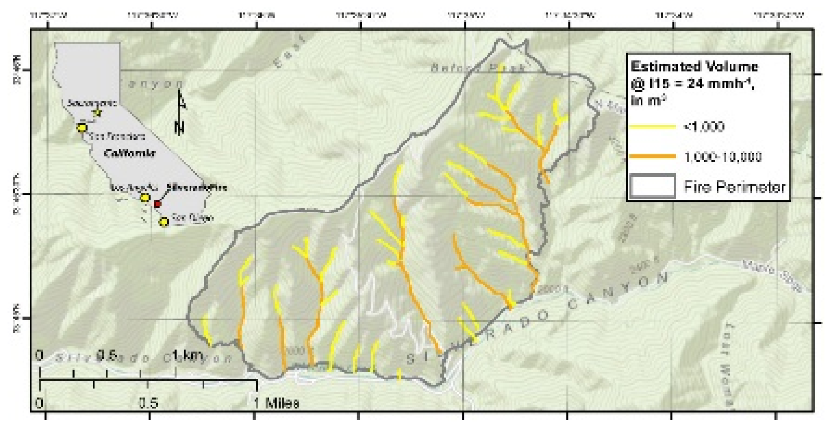

Figure 4: Estimates of post-fire debris-flow volume, in m3, for a rainstorm with a peak 15-minute rainfall intensity of 24 mmh^{-1} in the area burned by the 2014 Silverado fire, Cleveland National Forest.

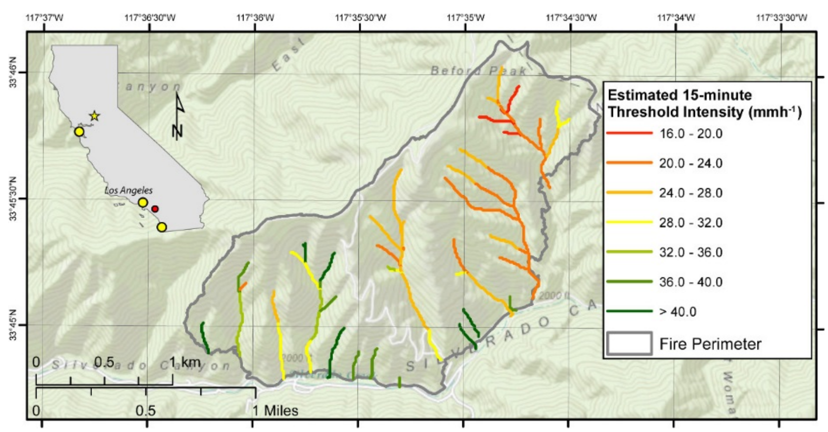

Figure 5: Estimates of the 15-minute rainfall intensity-duration threshold, in mmh^{-1}, for post-fire debris-flow flow generation in the area burned by the 2014 Silverado fire, Cleveland National Forest.

Summary of Hazard and Mitigation Strategies

Debris flows in the first 1-2 years after a wildfire typically do not initiate from infiltration-triggered shallow landslides. Instead, enhanced runoff generation and increased sediment availability promote infiltration-excess overland flow that transitions to debris flow in recently burned steeplands. As such, traditional slope stability modeling may not be appropriate for the prediction of post-fire debris flow initiation (Kean et al., 2011). Consequently, mitigation strategies for debris flow hazards that seek to reduce runoff generation, decrease the volume and velocity of surface flow, laterally contain channelized flow, stabilize stream channels (beds and banks) and encourage deposition in areas of low risk (e.g., along unpopulated stream reaches), as well as the provision of protective measures that deflect debris flow at an oblique angle or trap sediment (e.g., sediment retention basins), should take precedence over strategies designed to increase the near-surface stability of hillslopes (e.g., retaining walls, dewatering systems, or Earth reinforcement systems).

However, the areal extent and extreme gradients of many debris-flow producing watersheds often preclude the implementation of erosion control practices. Post-fire debris flows have been initiated during relatively modest rainfall intensities measured over short durations, with little lag time between the onset of higher rainfall intensity pulses and debris-flow initiation. Real-time monitoring of in situ rainfall rates and flow-stage, or video monitoring of stream channels, may not provide sufficient lead time to issue warnings and implement local evacuations or area closures. Instead, early warning must incorporate both forecast rainfall intensities and monitoring of atmospheric and rainfall conditions upwind of the area of concern [e.g., monitoring rainfall rates to the west of an area of concern during a storm that generally tracks west-to-east). Using physically based models to simulate debris-flow timing (e.g., Rengers et al. (2016)) under potential rainfall scenarios may also provide useful planning information.

Post-fire debris flows have been initiated during the very first rainstorm following wildfire with very little antecedent moisture, and have been documented for several years following wildfire. However, the duration of elevated debris-flow hazard following a fire is poorly understood. Traditionally, recently burned watersheds in the western United States are expected to have enhanced hydrologic and sedimentologic responses to high-intensity rainfall for a period of 2 to 5 years following wildfire. The rate of recovery is dependent upon several factors, including the amount of seasonal rainfall, vegetation regrowth, the recovery of soil properties to pre-fire conditions, and a net decrease in sediment availability. Further research is needed to quantify the relation between declining post-fire debris-flow likelihood and the rate of watershed recovery.

Freely available tools, such as published rainfall intensity-duration thresholds and post-fire debris-flow hazard assessments, can be used to better predict site-specific hazards in areas at high risk of post-fire debris flow. While these tools do not always characterize the local site conditions that may increase (or decrease) debris-flow hazards, they can be used to identify areas of concern and provide a major component in the process of determining site-specific post-fire debris-flow risk.

More Information

Links to modeling results, scientific background, and **assessment requests** are available from the USGS Landslide Program Emergency Assessment of Post-Fire Debris-Flow Hazards website.

Acknowledgements

We would like to acknowledge Hannah E. Pauling, Eric S. Jones, and Francis Rengers (USGS landslide hazards program) for their assistance in conducting post-fire debris-flow hazard assessments. We also are grateful for insightful reviews provided by Jeff Coe, Bill Schulz, and Rex Baum as a part of the internal USGS peer-review process. Finally, we would like to thank Steven Yochum (U.S. Forest Service) for the invitation to participate in this issue of StreamNotes and for editorial comments that have improved this manuscript.

Management Implications

- Post-fire debris flows can be initiated during the very first rainstorm following wildfire with very little antecedent moisture, and have been documented for several years following wildfire.
- Free and publicly available empirical models are available to predict the likelihood, potential volume, and the rainfall intensity-duration thresholds for debris flows in recently burned watersheds.
- Early warning of debris flow hazards during a rain event must incorporate both forecast rainfall intensities and monitoring of atmospheric and rainfall conditions upwind of the area of concern.
- To reduce debris flow hazard, mitigation strategies should seek to reduce runoff generation, decrease the volume and velocity of surface flow, laterally contain channelized flow, stabilize stream channels and encourage deposition in areas of low risk, and/or provide protective measures that deflect debris flow or trap sediment.

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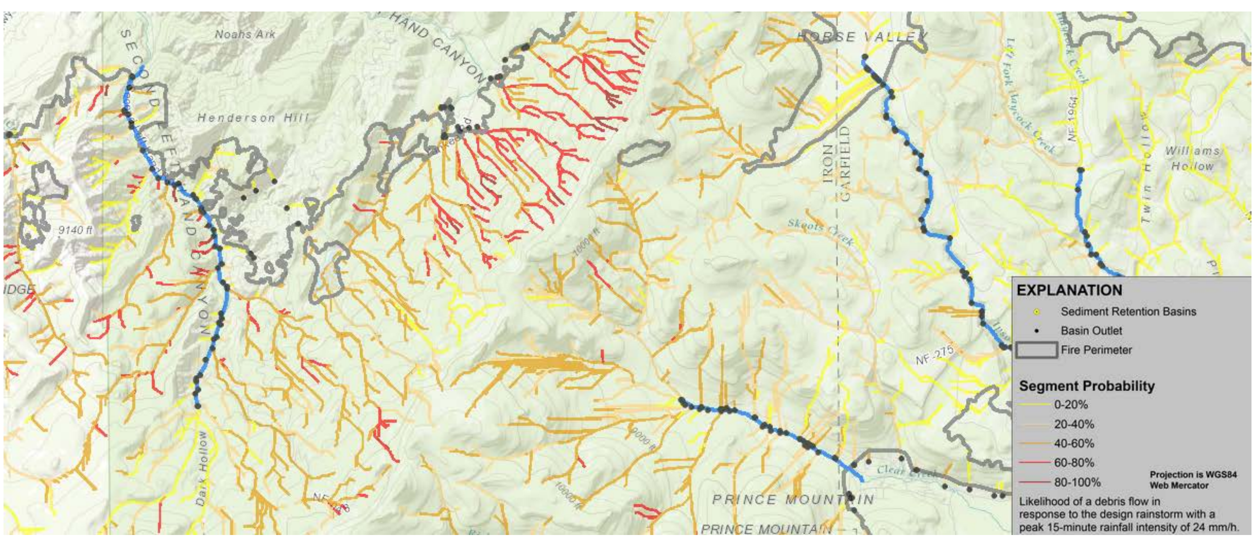
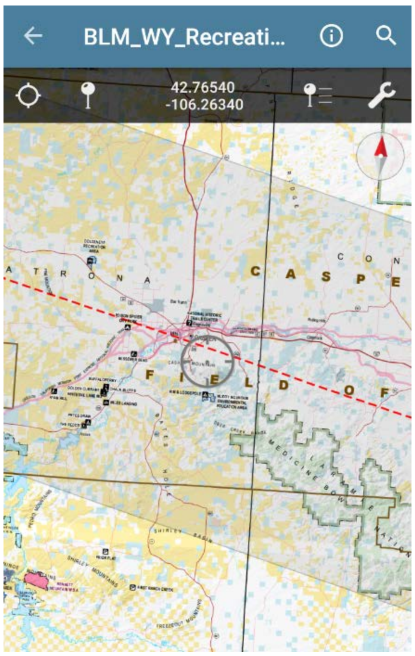


Preliminary hazard assessment, 2017 Brianhead Fire, Iron County, Utah

Notices and Technical Tips

- **Direct technical assistance from applied scientists at the National Stream and Aquatic Ecology Center** is available to help Forest Service field practitioners with managing and restoring streams and riparian corridors. The technical expertise of the Center includes hydrology, fluvial geomorphology, riparian plant ecology, aquatic ecology, climatology, and engineering. If you would like to discuss a specific stream-related resource problem and arrange a field visit, please contact a scientist at the Center or David Levinson, the NSAEC program manager.



- **Viewing georeferenced PDF and GeoTIFF files on a tablet or smartphone** is simple and convenient using the Avenza Maps app. View recent aerial imagery, land ownership boundaries, and other georeferenced files that you exported from ArcGIS or downloaded from Avenza's servers and view them offline in the field. View your location and tracking, a compass, and more. Mark waypoints and export for use in the office. The app is available for Android, Apple, and Windows mobile devices.
- **Have we underestimated the West's super-floods?** As reported in High Country News:

  In the late 1980s, a Japanese scientist named Koji Minoura stumbled on a medieval poem that described a tsunami so large it had swept away a castle and killed a thousand people. Intrigued, Minoura and his team began looking for paleontological evidence of the tsunami beneath rice paddies, and discovered not one but three massive, earthquake-triggered waves that had wracked the Sendai coast over the past three thousand years.

  In a 2001 paper, Minoura concluded that the possibility of another tsunami was significant. But Tokyo Electric Power was slow to respond to the science, leaving the Fukushima Daiichi nuclear power plant unprepared for the 15-meter wave that inundated it in 2011. The wave resulted in a $188 billion natural disaster. More than 20,000 people died.

  For the past several decades, paleo-hydrologist Victor Baker of the University of Arizona has been using techniques similar to Minoura's to study the flood history of the Colorado Plateau. Like Minoura, he's found that floods much larger than any in recorded history are routine occurrences. And like Minoura, he feels his research is being largely ignored by agencies and public utilities with infrastructure in the path of such floods.

- The USFS Pacific Northwest Research Station recently published a Science Findings article on **wildfire-induced added stream complexity and aquatic habitat impacts** (Adaptation to wildfire: A fish story).

  In the Pacific Northwest, native salmon and trout are some of the toughest survivors on the block. Over time, these fish have evolved behavioral adaptations to natural disturbances, and they rely on these disturbances to deliver coarse sediment and wood that become complex stream habitat. Powerful disturbances such as wildfire, postfire landslides, and debris flows may be detrimental to fish populations in the short term, but over time, they enrich instream habitats, enhancing long-term fish survival and productivity.

  Over the past century, dams, roads, and timber harvest practices have contributed to the decline in the amount and complexity of salmon and trout habitat in the Pacific Northwest. New research indicates that wildfire suppression adjacent to streams also may have inadvertently reduced the quality of aquatic habitat. The accumulation of forest fuels also has set the stage for higher-than-normal fire intensity, and perhaps larger fires that may cause extensive damage to local fish populations. This poses a significant problem for isolated and vulnerable fish populations such as bull trout.

Notices and Technical Tips

- An update to Pollock et al. beaver restoration guidebook has been released. This version 2 includes a new chapter on beaver in urban areas, as well as updates throughout this revision of the original 2015 edition.

The Beaver Restoration Guidebook

Working with Beaver to Restore Streams, Wetlands, and Floodplains

Version 2.0, June 30, 2017

Photo credit: Worth A Dam Foundation (martinezbeavers.org)

Prepared by

US Fish and Wildlife Service	Janine Castro
National Oceanic and Atmospheric Administration	Michael Pollock and Chris Jordan
University of Saskatchewan	Gregory Lewallen
US Forest Service	Kent Woodruff

Funded by

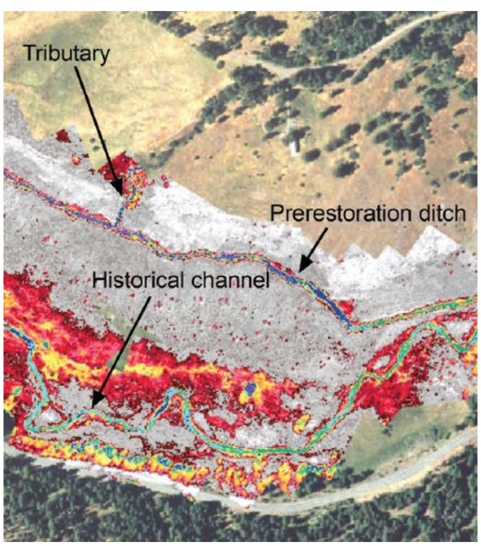
North Pacific Landscape Conservation Cooperative

Version 2.0. Get the latest version at: https://www.fws.gov/oregonfwo/promo.cfm?id=177175812

Increasingly, restoration practitioners are using beaver to accomplish stream, wetland, and floodplain restoration. This is happening because, by constructing dams that impound water and retain sediment, beaver substantially alter the physical, chemical, and biological characteristics of the surrounding river ecosystem, providing benefits to plants, fish, and wildlife. The possible results are many, inclusive of: higher water tables; reconnected and expanded floodplains; more hyporheic exchange; higher summer baseflows; expanded wetlands; improved water quality; greater habitat complexity; more diversity and richness in the populations of plants, birds, fish, amphibians, reptiles, and mammals; and overall increased complexity of the riverine ecosystems.

In many cases these effects are the very same outcomes that have been identified for river restoration projects. Thus, by creating new and more complex habitat in degraded systems, beaver dams (and their human-facilitated analogues) have the potential to help restoration practitioners achieve their objectives. Beaver have become our new partner in habitat restoration.

Yet even though the potential benefits of restoring beaver populations on the landscape are numerous, so, too, is the potential for beaver/human conflicts. These conflicts can arise from an overlap of preferred habitats by both humans and beavers, misunderstandings of how beavers modify their habitats, and a lack of planning or use of adaptive management on restoration projects. Reviewing the information provided in this guidebook will help interested parties approach beaver-based restoration from a more informed perspective*, so that they can manage expectations and increase success.*



- The article **Envisioning, Quantifying, and Managing Thermal Regimes on River Networks** has recently been released by Ashley Steel (Pacific Northwest Research Station) and her collaborators:

Water temperatures fluctuate in time and space, creating diverse thermal regimes on river networks. Temporal variability in these thermal landscapes has important biological and ecological consequences because of nonlinearities in physiological reactions; spatial diversity in thermal landscapes provides aquatic organisms with options to maximize growth and survival. However, human activities and climate change threaten to alter the dynamics of riverine thermal regimes. New data and tools can identify particular facets of the thermal landscape that describe ecological and management concerns and that are linked to human actions. The emerging complexity of thermal landscapes demands innovations in communication, opens the door to exciting research opportunities on the human impacts to and biological consequences of thermal variability, suggests improvements in monitoring programs to better capture empirical patterns, provides a framework for suites of actions to restore and protect the natural processes that drive thermal complexity, and indicates opportunities for better managing thermal landscapes.

Predicting Erosion Risk during Large Floods

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Infrastructure, homes, and businesses are frequently located within stream corridors and are susceptible to damage from inundation or erosion during large floods. While there is general recognition of the dangers of floodwaters due to inundation, as reflected by the FEMA flood hazard mapping program's focus on inundation threats, less consideration has been given to flood-induced geomorphic change (erosion and sediment deposition). Due to erosion of terraces and embankments, roadways and utilities can be cut off (Figure 6), leading to community isolation during an emergency situation, and homes and businesses being heavily damaged or destroyed (Figure 7). Sediment deposition can lead to increased inundation of adjacent structures as well as erosion and channel development in unexpected locations. Therefore, greater understanding of geomorphic change during large floods is needed, to help predict portions of stream corridors that are more hazardous as well as to reduce unintended consequences of development. Using the same hydraulic modeling techniques used for FEMA floodplain mapping, in some situations geomorphic change risk can be quantitatively assessed as a part of planning efforts.

Drawing on observations collected in the wake of the 2013 Colorado Front Range Flood, Yochum et al. (2017) identified unit stream power thresholds for several categories of geomorphic change. The results of this work are relevant to other semi-arid streams, and are summarized in Yochum and Scott (2017) for use by practitioners.

Figure 6: Eradicated US-34 roadway embankment along the Big Thompson River on the Roosevelt National Forest (10/21/2013). Flow direction is away from viewer. Graphic created in ArcGlobe with imagery from the Colorado Department of Transportation and LiDAR data from FEMA and USGS.

Generally, geomorphic hazards along stream corridors consist of gradual adjustments of stream channels during common floods as well as rapid adjustment during larger floods. Both need to be considered for development along stream corridors. During floods, where it occurs geomorphic change generally consists of erosion in locations where valley width and slope are relatively consistent, and deposition and erosion where valley width increases and valley slope decreases. Of value for quantifying the potential for geomorphic change is unit stream power:

$$\omega = \frac{\gamma Q S_f}{w}$$

where ω is unit stream power (W/m^2), γ is the specific weight of water (N/m^3), Q is discharge (m^3/s), S_f is the friction slope (m/m, frequently assumed to be equal to the water surface or channel slope), and w is the flow width (m). Unit

Figure 7: Residence heavily impacted by erosion during the 2013 Colorado Front Range flood, on James Creek in Jamestown (10/29/2013).

stream power is directly proportional to sediment transport conveyance capacity; as power increases, there is greater sediment transport potential and erosion is more likely. Where power decreases, there is less transport potential and sediment deposition is more likely.

Along streams where the valley and floodplain width substantially increase and the valley and stream channel slope substantially decrease, unit stream power can markedly decrease. At these locations deposition frequently occurs, which can lead to local erosion, new channel development, and braiding. At locations where unit stream power is more consistent and elevated, due to high discharges, steep slopes, and narrow flow widths, erosion can be likely.

Using a dataset of 531 reaches on 226 km of streams impacted to various degrees by the 2013 flood, Yochum et al. (2017) developed a framework for describing increasing levels of geomorphic change. Using a precautionary approach to management and design, thresholds for the various levels of geomorphic changes were developed (Figure 8). These thresholds can potentially be utilized in other semiarid climates, though are not appropriate where there are large reductions in unit streams power (where floodplains become substantially wider and less steep) or where channel slope is >3%.

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References

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Management Implications

- Threats due to floods include not only inundation but also erosion, potentially leading to loss of life.
- This erosion can result in damage or the complete loss of roadways and other infrastructure, as well as homes and businesses.
- Local erosion and increased inundation risk associated with deposition can occur where there are large reduction in unit stream power.
- In streams without large reduction in unit stream power and with slopes <3%, thresholds for a variety of geomorphic change were developed for a semi-arid setting. With caution, these thresholds can be utilized in other semi-arid climates to assess risk.

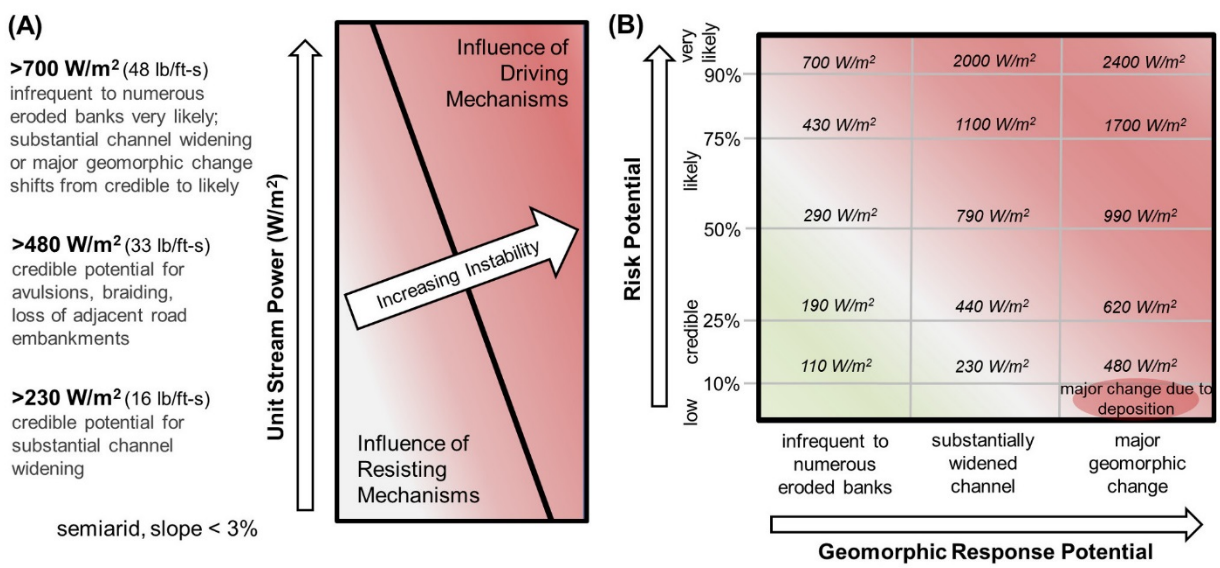

Figure 8: Schematic illustrating conceptual processes and observed thresholds for dominant geomorphic change processes for semiarid streams with slopes <3% during the 2013 Colorado Front Range flood (A) and a risk potential matrix (based on peak flow unit stream power) for three classes of geomorphic adjustments (B). Major geomorphic change refers to avulsions, braiding, or roadway embankments and high terraces eliminated or substantially eroded by erosional and/or depositional processes. The red oval represents stream reaches with major geomorphic change induced by deposition at relatively low unit stream power.