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Post-disturbance sediment recovery: Implications for watershed resilience

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ABSTRACT

Sediment recovery following disturbances is a measure of the time required to attain pre-disturbance sediment fluxes. Insight into the controls on recovery processes and pathways builds understanding of geomorphic resilience. We assess post-disturbance sediment recovery in three small (1.5–100 km^2), largely unaltered watersheds within the northern Colorado Rocky Mountains affected by wildfires, floods, and debris flows. Disturbance regimes span 10^2 (floods, debris flows) to 10^3 years (wildfires). For all case studies, event sediment recovery followed a nonlinear pattern: initial high sediment flux during single precipitation events or high annual snowmelt runoff followed by decreasing sediment fluxes over time. Disturbance interactions were evaluated after a high-severity fire within the South Fork Cache la Poudre basin was followed by an extreme flood one year post-fire. This compound disturbance hastened suspended sediment recovery to pre-fire concentrations 3 years after the fire. Wildfires over the last 1900 YBP in the South Fork basin indicate fire recurrence intervals of ~600 years. Debris flows within the upper Colorado River basin over the last two centuries have shifted the baseline of sediment recovery caused by anthropogenic activities that increased debris flow frequency. An extreme flood on North St. Vrain Creek with an impounding reservoir resulted in extreme sedimentation that led to a physical state change. We introduce an index of resilience as *sediment recovery/disturbance recurrence interval*, providing a relative comparison between sites. Sediment recovery and channel form resilience may be inversely related because of high or low physical complexity in streams. We propose management guidelines to enhance geomorphic resilience by promoting natural processes that maintain physical complexity. Finally, sediment connectivity within watersheds is an additional factor to consider when establishing restoration treatment priorities.

1. Introduction

Assessing watershed response and recovery to extreme events provides insight into landscape resilience, a concept that has gained much interest as human activities continue to fundamentally alter Earth's surface (Hooke, 2000; Sanderson et al., 2002; Hooke et al., 2012). The predicted increase in extreme events (disturbances) accompanying climate change (Coumou and Rahmstorf, 2012) is anticipated to alter the resilience of geomorphic systems and their ability to recover after disturbance. A working definition of *disturbance* is any force that tends to move a system far from a given equilibrium or steady state (Tabacchi et al., 2009). Disturbances to rivers may include large hydrological events that promote the erosion, transport, and deposition of large amounts of sediment or disturbances that directly affect vegetation, such as wildfire, insect/pathogen outbreak, or drought-related dieoff that reduces hillslope stability, lowers substrate cohesiveness, and increases sediment loads (Corenblit et al., 2007). Of particular concern are disturbances that enhance sediment delivery from hillslopes to channels because of the effects of increased sedimentation on aquatic ecosystems (Newcombe and Macdonald, 2011), channel and floodplain morphology and hence flooding, water resource management including water quality (Moody and Martin, 2009), and reservoir storage (Rathburn et al., 2017). In fluvial systems, resilience refers to the ability to tolerate or absorb perturbations without changing to a qualitatively different state that is controlled by a different set of processes (Brierley and Fryirs, 2005; Tabacchi et al., 2009). As an example, a resilient river recovers channel geometry and sediment fluxes following a large flood and in a broader context reflects the persistence of a river ecosystem and its ability to return to pre-disturbance conditions (Webster et al., 1975; Corenblit et al., 2009). Resilience is based on how fast a system returns to its equilibrium state after a disturbance (Holling, 1996), or the *recovery time* (sometimes referred to as relaxation time).

Gaps exist in our understanding of response to disturbances because of limited temporal and spatial extent of data. As such, we often misunderstand the dominant processes of recovery. Assessing the historical range of variability (HRV) of systems (Wohl and Rathburn, 2013) expands the temporal scale of disturbance recovery analysis. Coupling HRV and contemporary process measurements of recovery trajectories

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from a variety of disturbances, along with recurrence intervals of the disturbance, gives a broad understanding of recovery. Here we focus on post-disturbance sediment fluxes following fires, floods, and debris flows to quantify the sediment component of recovery. This is defined as the time required to achieve pre-disturbance sediment magnitudes within fluvial systems, as well as understanding the complex pathways of recovery. We examine the geomorphic response and sediment recovery of three small watersheds (1.5–100 km^2) to varying disturbances (fire, flood, and anthropogenically induced debris flow) in the southern part of the Rocky Mountains in Colorado. In all cases, while we recognize response to disturbances is highly context specific and spatially and temporally contingent, our data augments existing studies on site-specific types of disturbance recovery. This has application to other catchments where comparable geomorphic conditions and process domains occur (Montgomery, 1999; Wohl, 2010). Our approach is also applicable to other systems to determine whether a set of processes and responses are part of the expected behavior of a river or whether the response is anomalous. In all three basins examined, one or more extreme events altered runoff and abruptly increased sediment supply to channels either as a single input of excess sediment (debris flow), or as a widespread sediment supply perturbation (wildfire or high magnitude rainfall event). We evaluated post-disturbance sediment flux (sediment mass per unit time or per storm) to assess recovery. Recovery time frames span 10^0–10^3 years, allowing different pathways of response and recovery to be identified. While the focus is on sediment recovery following disturbances, we also address the spatial and historical variations in sediment supply as influenced by antecedent conditions and the sequencing of events. We note that geomorphic response to various disturbances may be recovery to pre-disturbance conditions or not (disturbance pushed the system beyond the capacity to return to baseline), and recovery may manifest as response toward a suite of states, rather than one target endpoint (Phillips and Van Dyke, 2016). Finally, we provide recommendations on how to promote geomorphic resilience in a management context.

2. Background and objectives

2.1. Landscape sensitivity

To fully understand the geomorphic context of resilience, tracing the roots and usage of related terms is necessary. Ecological disturbance theory spurred inquiry into *landscape sensitivity*, and landscape sensitivity is another way to assess landscape *resilience* and *resistance* (ability to resist changes in form and process caused by external factors; Webster et al., 1975). Like resilience and resistance, landscape sensitivity to disturbance has historical use in the ecological literature (Phillips and Van Dyke, 2016; Westman, 1978). Brunsden and Thornes (1979) provided a thorough analysis of landscape sensitivity through the contrast of constant process-characteristic form and the transient behavior of a system in response to a few large events that may produce substantial, long-lived landscape change. Other work on sensitivity as summarized by Tabacchi et al. (2009) included that by Schumm (1991) who defined it as the propensity of a system to respond to a minor external change and by Brunsden (2001) as the potential that changes in the controls of a system or the forces applied to the system will produce a recognizable and persistent response. Sensitivity can thus be considered a function of the spatial and temporal distributions of the resisting properties (e.g., rock strength, resistance to weathering and erosion) and forces of the disturbance (e.g., sediment load, high shear stress). Since the original work by Brunsden and Thornes (1979), research into landscape sensitivity has addressed soil erosion (Evans, 1993), the capacity of rivers to absorb change (Downs and Gregory, 1993), hillslope and channel coupling (Harvey, 2001), tectonic uplift (Snyder et al., 2000), and climate and tectonism (D'Arcy and Whittaker, 2014), among many others. Fryirs (2017) provided a recent, thorough review of river sensitivity and advocates for using it as a guiding concept in river management. Understanding the sensitivity of earth materials to internal and external processes and the resulting landscape forms is of major research importance within the surface process community.

2.2. River resilience and connectivity

Evaluating resilience, according to Tabacchi et al. (2009), assumes that a system exists near a single equilibrium condition and that it is possible to quantify how far a system has moved from equilibrium and the time required to return. As applied to river systems, similar assumptions of equilibrium are reasonable. Furthermore, a resilient river is able to adjust to and absorb perturbations, such that disturbances do not impose a morphologic response. This ability is also referred to as the *system buffering capacity* (Brierley and Fryirs, 2005). On highly regulated systems, resilience has been indirectly addressed through environmental flows that support discharges and sediment transport to maintain the physical channel (Ryan, 1997) or riparian vegetation downstream from a dam (Rathburn et al., 2009). More commonly, resilience studies address recovery following natural disturbances that encompass the trajectory of landform response over time, with full recovery indicated by return to pre-disturbance conditions. Our emphasis is on sediment recovery following disturbance, defined as the time required to attain background sediment yields, concentrations, or rates and volumes of aggradation and degradation. We should note, however, that pre-disturbance conditions are not the only indicator of recovery and resilience, nor may it be possible to return to pre-disturbance conditions, as in the case of a complete state shift or because of long-term climate change. In such situations, ensuring that fluvial processes maintain a desired channel form or that the system maintains a functional position in the landscape is a more appropriate goal. Even systems that undergo complete state changes may be resilient, whereby resilience pertains to how the system will adjust and change or its 'coping capacity' (Walker and Salt, 2012).

Because of the considerable spatial variation in landform parameters that influence resilience, a number of metrics and indices have been developed to facilitate broader comparisons. Examples include measures of the effectiveness of disturbances to form landscape features relative to the rate of recovery (Wolman and Gerson, 1978); the persistence of stored sediment indicated by the residence time, defined as storage volume/annual transport rate (Dietrich and Dunne, 1978); the persistence of landforms or the transient form ratio (Brunsden and Thornes, 1979); or channel forms of adjustment resulting from morphologic and historical resilience to catastrophic flooding (Fryirs et al., 2015). Brierley et al. (2005) suggested the sediment delivery ratio (portion of hillslope derived-sediment that reaches the channel network) as a measure of sediment connectivity in a basin, which makes it a useful metric to assess resilience. Continued work on effectively capturing river system resilience through useful metrics will improve understanding and prediction of disturbance response on dynamic river systems (Tabacchi et al., 2009).

Recent work identifies connectivity between different portions of the landscape as an important driver of resilience (Poeppl et al., 2017). Several forms of connectivity influence resiliency to different degrees. Here, we are concerned primarily with sediment connectivity that is the potential for sediment to move through geomorphic systems (Hooke, 2003) or as the water-mediated transfer of sediment between two landscape compartments (Fryirs, 2013) that can be assessed within hillslopes, between hillslopes and channels, and along channels (Harvey, 2002). It may also be considered as the likelihood for the effects of a disturbance to be propagated through a basin (Brierley et al., 2005). Sediment connectivity may exhibit a threshold response. Certain disturbances may connect or switch on previously unconnected parts of the basin (Fryirs et al., 2007), but high connectivity results in greater fluxes of sediment downstream (Cavalli et al., 2013). Post-disturbance sediment yields cannot be assumed to be delivered to downstream targets because of lateral (hillslope-channel; channel-floodplain) and longitudinal (channel-tributary fan) storage and impediments to transport. Some argue that geomorphic systems with low connectivity are more resilient to disturbance, as the propagation of the effects of change is limited (Poeppl et al., 2017). This may apply only to systems with naturally low connectivity rather than artificial or anthropogenic constraints or barriers imparting the low connectivity. Low connectivity from nonnatural alterations may reduce resilience, particularly if the propagation of the disturbance through the basin is required to attenuate it.

2.3. Objectives

We combine new research and review of existing literature to address the questions: (i) What are the characteristics of watershed responses to disturbances? (ii) What are the dominant site-specific controls on response? (iii) With respect to case studies, what is the relative post-disturbance recovery within and between systems? and (iv) What metrics of recovery indicate channel form and process resilience? A final question is: 5) How can we foster watershed resilience through resource management activities, decisions, and policy? While all of the posed questions are timely, the last question underscores the applied importance of understanding post-disturbance recovery and resilience and of the growing interest and effort in directly manipulating restoration approaches to enhance resilience (Smith et al., 2000; Lake et al., 2007).

Although the spatial scales of disturbance differ widely in the presented examples, important patterns still emerge related to the temporal recovery of sediment fluxes from a representative suite of disturbances. We assess patterns of response such that comparisons may be broadly informative. From the examples of sediment recovery, we scale up to discuss channel form resilience and, where possible, process resilience to inform overall system resilience.

3. Post-disturbance recovery case studies

Sediment recovery was assessed in three small watersheds (1.5–100 km^2) in north-central Colorado (Fig. 1) following disturbances over different time scales of disturbance and recovery ranging from

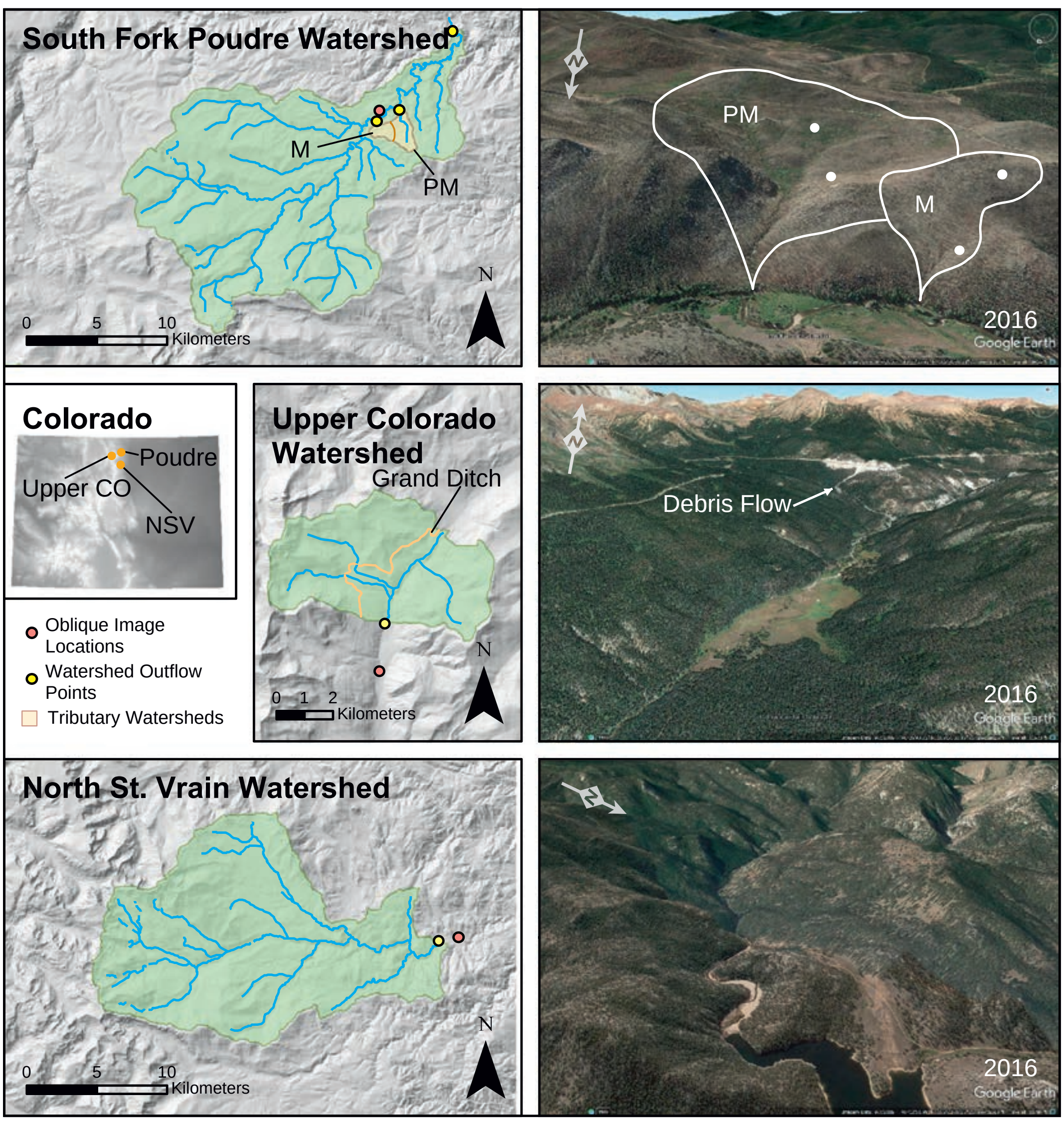


Fig. 1. Study watersheds in northern Colorado where sediment disturbances occurred between 2003 and 2013. A mulched (M) and partially mulched (PM) watershed within the South Fork Cache la Poudre basin was affected by the 2012 High Park fire and the 2013 Front Range flood. The white dots on the Google Earth image are locations of rain gages. The upper Colorado River received debris flow deposition from a breach in Grand Ditch in 2003. A 15-km study reach upstream from Ralph Price Reservoir along North St. Vrain Creek is where 2013 flood-related sediment erosion and deposition was particularly high. Evidence of that deposition (as light colored sediment) is captured in the Google Earth image at the inlet of the reservoir. Oblique Google Earth view is upstream on all images.

10^0 to 10^3 years. The disturbances include a natural wildfire at one site in 2012 (the primary case study site), extreme precipitation that triggered flooding at that site and at a second site in 2013, and an anthropogenically induced debris flow at the third site in 2003. At one site, we present new data on fire recurrence intervals to aid the evaluation of recovery relative to the return period of disturbance. Where background sediment loads, concentrations, and sediment deposition and aggradation volumes are known, we use those measures to assess recovery. In other cases, we use HRV to compare channel bedforms (step characteristics) and geometry (width:depth) from reference reaches to inform the degree of recovery.

The case study watersheds lie within montane (1830–2740 m) or subalpine forests (2740–3400 m) of the Colorado Rocky Mountains (Veblen and Donnegan, 2005) (Table 1). This region is prone to higher frequency wildfires (Veblen and Donnegan, 2005) and associated debris flows and tributary flash floods, as well as to infrequent but high-magnitude rainfall-generated flash floods. Mean annual precipitation varies from 330 to 1350 mm. The majority of precipitation falls as snow, but intense rainfall from convective storms at elevations below ~2300 m can occur (Jarrett, 1990). Fire regime in the upper montane zone is characterized by variable severity and is capable of supporting stand-replacing crown fires and surface fires, creating variable tree species and cohort ages. Within the montane zone, elevation is the primary predictor of fire regime (Veblen et al., 2012).

All of the case studies are located within either national forest lands or a national park where human influences are nominal, including minimal post-disturbance sediment mitigation, with one exception. Post-fire treatment of hillslopes occurred at one site to mitigate sediment delivery to streams. In this case, a burned but largely untreated control watershed was used to assess recovery. Two of the study sites are on national forest lands that are currently unmanaged forest with historic timber harvesting and cattle grazing. The study site in the national park was a short-lived mining camp (1879–1884) where logging also occurred. Today, flow regulation in the form of a transbasin diversion is the main anthropogenic activity. The three sites provide perspective on the different temporal responses of low order, steep gradient mountain rivers and the recovery patterns without substantial human influence. Additionally, successive disturbances at one site (2012 fire followed by 2013 flood) provide data on the inheritance mechanisms (Tabacchi et al., 2009) and preconditioning of the landscape (one disturbance influences response to the next disturbance), allowing us to assess the spatial-temporal overlap of response. Because many climate-related disturbances often occur simultaneously or in rapid succession, antecedent geomorphic and/or land use conditions may exert a strong influence on the resilience of geomorphic systems to cope with individual extreme events (Naylor et al., 2017). Even more moderate events can be amplified by antecedent geomorphic and land use conditions. We adopt the term *compound* disturbance (Buma, 2015) to describe the effects of interacting disturbances that alter the recovery time or trajectory. Ecosystems already disturbed are likely to be less resilient (Holling, 1973), although whether compound disturbances play out differently on sediment recovery is still to be addressed. Compound disturbances may serve as a positive feedback to augment recovery or as an impediment whereby a succession of disturbances accentuates sediment fluxes moving recovery further from background levels.

3.1. Primary case study: fire and flood — South Fork Cache la Poudre basin

The High Park fire burned 35,000 ha (350 km^2) of forested mountains in early summer 2012 within the semiarid Colorado Front Range (Fig. 1). Approximately 7% of the total burn area was severely burned and 40% was moderately burned (BAER, 2012), whereas in the study watersheds 75–80% of the area was severely burned (Table 1; Shahverdian, 2015). Stakeholders expressed concerns over excessive sediment entering the main stem Cache la Poudre River, the drinking water supply for approximately half a million people, as a result of erosion within the South Fork Cache la Poudre basin. Interest in applying post-fire treatments to mitigate sediment erosion and to identify post-fire mechanistic controls on sediment delivery to channels further motivated this study (Shahverdian, 2015). The aerial application of agricultural straw and wood straws was selected as the quickest way to treat the steep, severely burned hillslopes of the High Park fire burn area (Miller et al., 2017). Two adjacent watersheds with similar characteristics that drain directly to the South Fork Cache la Poudre River (SFR for South Fork River) were instrumented for this research (Table 2; Fig. 1). One was treated by aerial spreading of straw mulch over a substantial

Table 1
Summary characteristics of example watersheds and sediment recovery and resilience, northern Colorado.

Characteristic	South Fork Cache la Poudre	Upper Colorado River	North St. Vrain Creek
Drainage area (km^2)	1.5–3.3	29	100
Elevation range (m)	2340–3030	2700–2940	1950–2350
Disturbance	2012 High Park Fire, 2013 flood	2003 anthropogenic debris flow	2013 flood
Disturbance regime time frame (year)	10^3	10^2	10^2
Recovery time frame (year)	10^0	10^2–10^3	10^0
Disturbance response	Channel incision, headcutting and widening; avulsions; fan deposition; high suspended sediment concentration	Channel incision and widening; avulsions; aggradation in debris fan; logjams; subsequent remobilization and redeposition; channel avulsions at footbridges	Landslides, channel incision, widening, bank failure, aggradation; delta progradation; logjams
Sediment recovery metric[a]	Pre- and post-suspended sediment concentrations	Sediment transport/fan erosion; HRV channel geometry and wetland aggradation	New baseline — change in system state; sediment transport and valley bottom morphology
First order controls[b]	Precipitation, valley morphology (slope, confinement), particle size, vegetation, time since disturbance	Discharge, valley morphology, particle size	Discharge, valley morphology, reservoir impoundment
Second order controls	Compound disturbance	Sediment supply; earlier debris flows	Not applicable
Sediment recovery	3 years post fire	Ongoing	Ongoing
Relative sediment resilience[c]	High (3 year/600 year *RI*)	Moderate (14 year/8 year *RI*)	Low (minimal recovery/200 year *RI*)
Relative form resilience	Moderate (due to lack of vegetation recovery; incised perennial channels)	High (due to vegetation recovery and spatial complexity)[d]	Low (due to state change, confinement, short relaxation time)
References	This paper; Shahverdian (2015)	Grimsley et al., 2016 Rathburn et al., 2013; Rubin et al., 2012	Rathburn et al., 2017; Wohl et al., 2004, 2017

[a] For all sites, sediment recovery assessed through form and process, with specific metrics listed.
[b] First and second order controls on the sediment response to the disturbance, or what controls the disturbance response.
[c] Determined as *sediment recovery/disturbance recurrence interval (RI)*; <1 rapid recovery relative to disturbance *RI* thus high resilience; >1 slow recovery relative to *RI* thus low resilience.
[d] Another debris flow occurred on a tributary of the upper Colorado River after this paper was submitted. The relative form resilience should be downgraded because of the new site conditions.

Table 2
Characteristics of paired watersheds within the South Fork Cache la Poudre River (SFR) basin evaluated for post-fire sediment yields.

Watershed characteristic	Mulched watershed	Partially mulched watershed
Overall burn severity	High	Moderate
Moderate (km^2)	0.24 (15%)	0.45 (14%)
Severe[a] (km^2)	1.18 (76%)	2.64 (79%)
Drainage area (km^2)	1.55	3.30
Aspect	North	North
Lithology[b]	Precambrian granite, quartz monzonite, schist, gneiss	Precambrian granite, quartz monzonite, schist, gneiss
Elevation range (m)	2390–2860 (upper montane/subalpine)	2340–3030 (upper montane/subalpine)
Reach slope range	0.07–0.25	0.07–0.32
Precipitation[c] (mm)	450–625	450–625
Treatment	Full aerial straw mulch/wood straws	Partial application aerial straw mulch
Ground cover (%) July 2013	28	30
Ground cover (%) July 2014	47	57
Confluence connectivity	Moderate – unconfined valley with floodplain	High – confined valley no floodplain

[a] Severely burned zones are distinguished by duff and litter layers of the forest soil that were completely consumed with only standing dead trees remaining.
[b] Braddock and LaFountain (1988); Nesse and Braddock (1989).
[c] Average annual precipitation from Richer (2009).

portion of the watershed area, while the other was partially mulched in the steep head waters but not in the area of direct analysis. Ephemeral and perennial portions of the watersheds were monitored for erosion and depositional patterns (Fig. 2) along with suspended sediment delivery to the main SFR at the mouth of each tributary. Subsequently, in September 2013 (year 1 post-fire), a >200-year storm delivered up to 350 mm of rain in a 4-day period over large portions of the Colorado Front Range (Gochis et al., 2015), causing widespread flooding, damage to homes and infrastructure, and loss of life. Between 155 and 170 mm of rain fell in the study watersheds of the SFR over the duration of the storm. Fieldwork in 2014, during year 2 post-fire, incorporated the dual disturbance effects on the study watersheds. The reader is referred to Shahverdian (2015) for a detailed literature review of the effects of fire on watershed hydrology and channel network change, as well as detailed methods and analyses.

3.1.1. Ephemeral channel response

Localized, short-duration summer rainstorms were the dominant driver of post-burn sediment transport in the burned area. Some of the highest precipitation was received in July 2012 that helped to extinguish the fire, but it occurred prior to field site access in 2013. One of the largest recorded storms measured (16 mm) in a rain gage 500 m from our fully mulched watershed (E. Berryman, unpubl. data) (Fig. 3) also occurred prior to field instrumentation in 2013 (Table 1; Fig. 3). Eight storms in 2013 exceeded the 10 mm h^{-1} maximum intensity 30-minute storm (I_{30}) or 8 mm rainfall depth thresholds (Fig. 3) that have been found to be important for generating substantial overland flow and soil erosion in other watersheds burned in the same fire (Schmeer, 2014; Kampf et al., 2016). In 2014, two storms (12 July and 29 July 2014) exceeded thresholds, and both produced bed incision measured by scour chains. Precipitation was not measured in 2015 within the small paired watersheds, but it was measured on the main stem South Fork River ~2 and 4 km upstream from the mouth of the mulched and partially mulched watershed respectively. Data from that site indicates that three storms received in both watersheds were above this threshold.

Sediment transport within ephemeral channels occurred in pulses, with erosion of previously deposited sediment occurring during the rising limb and deposition on the falling limb of each rainstorm hydrograph. While erosion and subsequent deposition masked any net channel cross section changes, release of links on multiple scour chains indicated that scour and fill was occurring during the storms (Fig. 4). Sediment transport caused by excess overland flow was the dominant process of sediment entrainment and delivery to the channels, with downstream transport in the channels being a function of available transport capacity. The episodic transport during storms generated pulses of sediment that were moved downstream depending on the available storm-dependent transport capacity. Overall, I_{30} determined the direction of ephemeral channel change, whereby higher intensity rain events resulted in net aggradation and lower intensity events net

Fig. 2. Ephemeral (left on 11 Sep 2013) and perennial (right on 9 Jul 2014) channels within paired watersheds that were burned in the 2012 High Park fire in northern Colorado. The ephemeral channel is within the mulched watershed (M in Fig. 1 at downstream rain gage), and the perennial channel is within the partially mulched (PM in Fig. 1 at downstream rain gage) and served as the control watershed. Field instrumentation in both basins in 2013 included two rain gages, three monumented channel cross sections along ephemeral channels, scour chains installed in the bed of first order ephemeral cross sections, and an automatic suspended sediment sampler and turbidity meter installed at the confluence of both on the main stem South Fork River. In 2014, additional channel cross sections were established within the perennial reaches of both watersheds and outfitted with scour chains. (Left photo courtesy of M. Dixon.)

degradation. Small spatial scale ephemeral channels become transport limited during high intensity storms. Low intensity storms were supply limited.

Coarse particle (>0.6–64 mm) sediment yields within the ephemeral channels calculated from scour chain data indicate that the mulched watershed had lower sediment yields for higher I_{30} early in 2013 than the partially mulched (PM) watershed (Fig. 4), but that pattern changed by the third storm in 2013. Measured sediment yields were greatest in the mulched watershed in 2014 after the largest I_{30} during the study period was recorded; a value that exceeded the September 2013 yield (Fig. 4). There is no comparable 2014 data for the PM watershed because the scour chains were eroded out by channel erosion. Channels in the mulched and partially mulched watersheds acted to store and transport hillslope sediment on an event basis. The ephemeral channels themselves did not appear to be post-fire and flood sediment sources.

3.1.2. Perennial channel response

Our first field observations in October 2012 indicated that ~1 m of incision occurred during rainstorms immediately following the fire, so downstream perennial channels were in a state of incision prior to field instrumentation. Debris flows and hyperconcentrated flows were observed in nearby burned tributaries with private inholdings, and the channels were incised there as well. Therefore, channel incision in the study watersheds is thought to have occurred during the same post-fire storms. Normally ephemeral channels were flowing perennially in October 2012, presumably because of the increased base flow associated with increased infiltration-excess flow and reduced evapotranspiration normally shed from living vegetation. Small, localized changes in channel form were observed during rainstorms in 2013 (but not measured until 2014). The September 2013 flood, however, caused up to 0.5 m of vertical incision in addition to channel avulsions, coarsening of the channel bed, and bank collapse with tree fall. These deeply incised channels with over-steepened banks and exposed root systems were evident throughout the High Park fire burn area in the South Fork basin after the 2013 flood. In 2014, up to 10 cm of maximum incision and 4 cm of aggradation occurred in the perennial channels based on scour chain measurements as a result of two July 2014 storms that exceeded the thresholds for erosion.

3.1.3. Watershed-scale response

Suspended sediment concentrations measured at the mouth of the mulched and partially mulched watersheds on the South Fork River were used to assess contributions from tributaries with differing post-fire treatments and to evaluate response over time. Suspended sediment concentrations (SSC) immediately following the fire in 2012 were ~30,000 mg L^{-1}, based on samples collected along the main stem Cache la Poudre River. Overall, the sediment recovery in the study watersheds followed a nonlinear pattern with initial high sediment flux during single precipitation events followed by decreasing sediment fluxes over time (Fig. 5). In 2013, year 1 post-fire, slightly lower concentrations of suspended sediment emanated from the mulched watershed relative to the partially mulched watershed, although the differences are mostly not significant. In 2014, somewhat lower suspended sediment production was again measured within the mulched watershed in the two storms that exceeded the 10 mm h^{-1} threshold. By 2015, differences in SSC between the sites are difficult to assess because rain gages in the paired watersheds were dismantled and I_{30} data from the upstream site were used. One clear trend is evident however; between 2013 and 2015, SSC from both watersheds systematically declined and an increasingly higher I_{30} was required to generate SSC levels approximating those observed in 2013 (Fig. 5). While no pre-fire suspended sediment concentration data are available for the SFR at the locations sampled during this study, values of SSC from 1989 and 1997 at a site ~4 km upstream are typically <50 mg L^{-1}, with the maximum pre-disturbance concentration measured at ~100 mg L^{-1} (S. Ryan, unpublished data). A majority of the SSC values were at or below this 100 mg L^{-1} background level by summer 2015, three years after the fire.

In addition to increased suspended sediment yields after the fire, coarse deposits of fire-derived sediment formed fans at the mouth of several tributaries in the SFR. Fan sedimentation from six tributaries was assessed for post-fire response within the larger South Fork basin

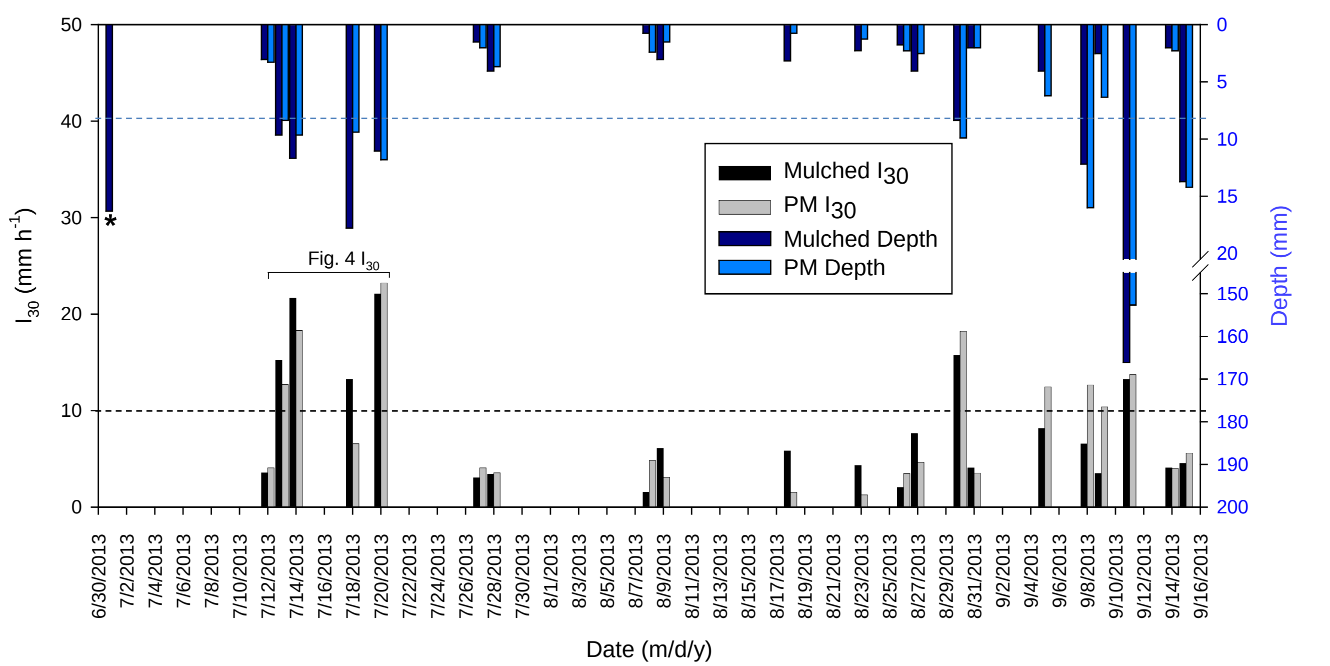


Fig. 3. Rainfall in 2013 as a maximum intensity 30-minute storm (I_{30}) and rainfall depth for mulched and partially mulched (PM) watersheds in the 2012 High Park fire burn area. Access to the field site to install instrumentation was not possible until June 2013. The 2013 September storms produced a >200-year event and widespread flooding throughout the Colorado Front Range. * indicates rainstorm totals measured prior to field instrumentation (E. Berryman unpubl. data), and the bracketed rainstorms from 13 to 20 Jul 2013 are shown in Fig. 4 with associated scour chain-derived sediment yields. Dashed lines are thresholds associated with erosion in other burned basins (Schmeer, 2014; Kampf et al., 2016). Rainfall intensity and depth in 2014 (not shown) produced just two storms (12 and 29 Jul 2014) that exceeded the 10 mm h^{-1} threshold for hillslope sediment production.

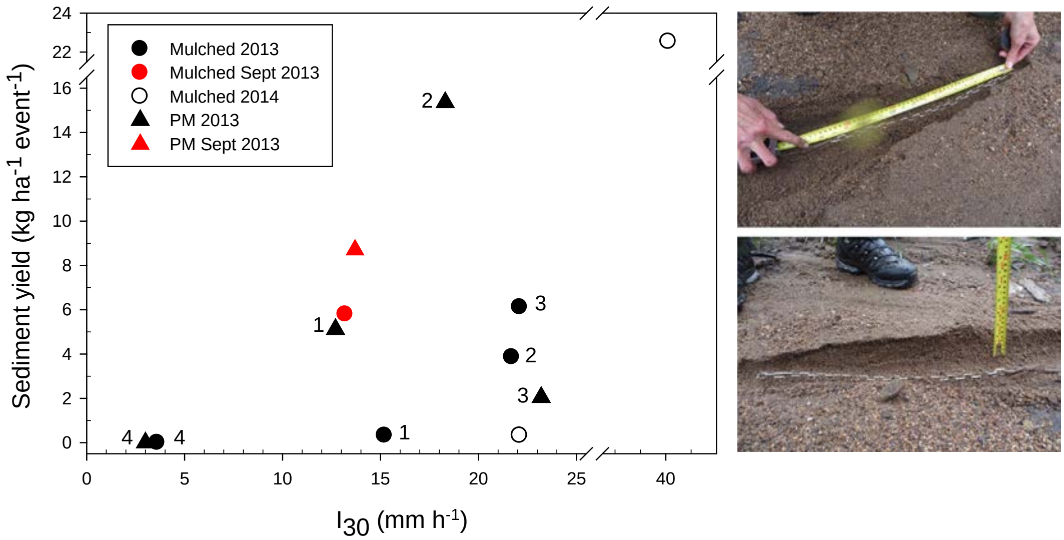


Fig. 4. Sediment yield versus maximum intensity 30-minute storm (I_{30}) for ephemeral channels within the mulched and partially mulched (PM) watersheds in the South Fork Cache la Poudre basin. Photos show scour chains installed in the bed at channel cross sections on first order streams in the mulched watershed (location shown in left photo of Fig. 2) that were used to estimate event sediment yields, assuming a 1-m reach length and unit channel width. Numbers adjacent to symbols indicate common rain storms between the mulched and partially mulched watersheds as follows: 1 = 13 Jul 2013; 2 = 14 Jul 2013; 3 = 20 Jul 2013; 4 = 28 Jul 2013. Data are missing for 2014 for the PM basin because the scour chains were eroded out and lost. (Photos courtesy of M. Dixon.)

(Fig. 6). Although the data set is small, the Spearman correlation coefficient ($\rho = 0.83$) indicates a positive monotonic correlation between contributing area and fan volume. A p-value associated with the correlation is not strictly significant (p-value = 0.06), but it is sufficient to support a relationship; larger contributing areas produced greater fan volumes, with the largest fan (3500 m^3) deposited at the confluence of Pendergrass Creek (drainage area 13 km^2) and the SFR. Moreover, presence of a fan and the degree of valley confinement also influences sediment delivery downstream through connectivity. In some locations, fan deposition decreased channel width of the SFR, forcing the creation of upstream pools and altering sediment connectivity.

3.1.4. Fire history, Cache la Poudre watershed

New data on fire history within the large Cache la Poudre basin provides important insight into disturbance recurrence intervals. Whereas infrequent, extensive, high-severity fires are natural in subalpine forests (Sibold et al., 2006), the occurrence and extent of high-severity fires in the montane zone prior to EuroAmerican settlement of the region (~1850) is uncertain. Consequently, it is not clear if extensive, high-severity burn patches from recent fires (e.g., Hayman, 2002, High Park 2012) are within the natural dynamics of fire in the montane zone or a result of the impacts of fire suppression, climate change, or a combination of the two.

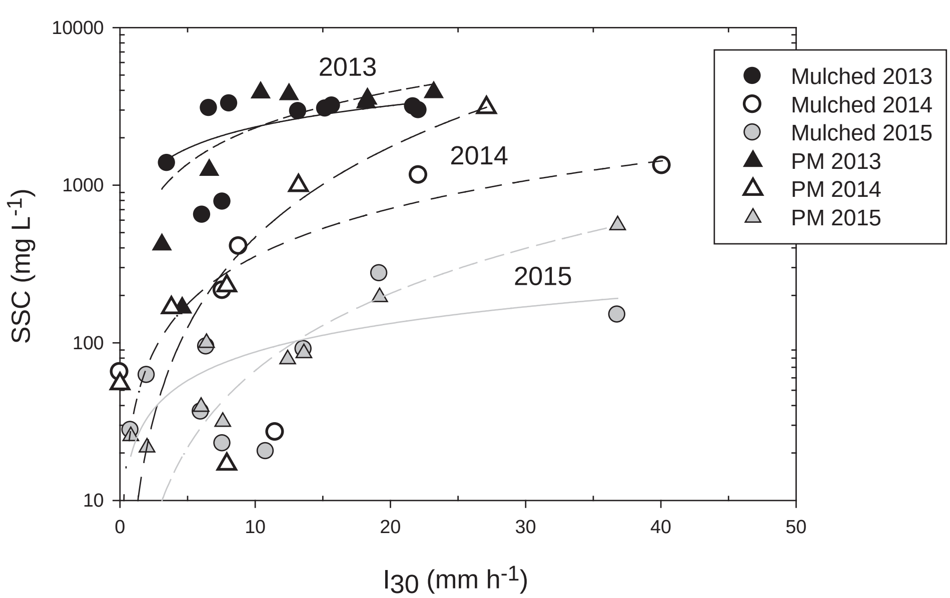
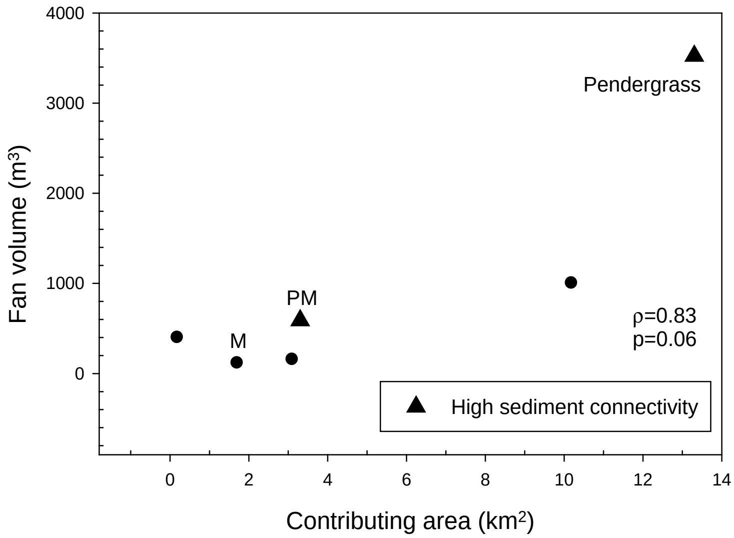


Fig. 5. Peak suspended sediment concentration (SSC) associated with maximum intensity 30-minute storm (I_{30}) measured at the outlets of the mulched and partially mulched (PM) watersheds tributary to the South Fork River. Maximum SSC in 1989 and 1997 (pre-fire background levels) from a site 4 km upstream is 100 mg L^{-1}. SSC had largely recovered to background levels by 3 years post-fire in the mulched and in the partially mulched watersheds. The 2014 data includes residual impacts of the September 2013 flood as well as rain storms during that year.



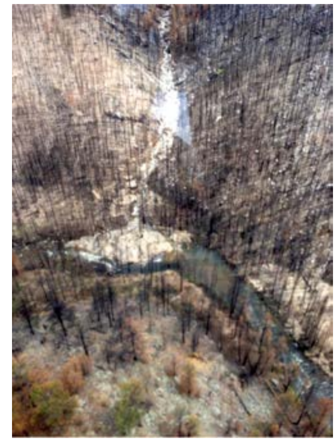


Fig. 6. Debris fan volume versus contributing area for six small watersheds within the South Fork Cache la Poudre basin. M indicates the mulched watershed and PM indicates the partially mulched watershed with all others not mulched. The Spearman correlation coefficient ($\rho = 0.83$; p-value $= 0.06$) indicates a positive correlation between contributing area and fan volume with high connectivity influencing fan volume at two sites. Photo is of the fan at the confluence of Pendergrass Creek with the South Fork, 13 May 2013 (courtesy of B. Piehl). Flow is from right to left on the South Fork River.

Vertical incision of perennial channels in the SFR study watersheds (upper montane) during the September 2013 storms exposed two charcoal layers separated by coarse sediment, indicating at least two fire-flood sequences. Post-fire floods (fire-flood cycles) get preserved in channel banks or within debris fan stratigraphy. Radiocarbon analysis of the charcoal layers returned ages of ~1200 and 1900 YBP, with overlap of the 1200-year charcoal with that from a basin 45 km downstream (Cotrufo et al., 2016). These data indicate that fires of comparable severity and potential extent to the High Park fire occurred 1200 and 1900 YBP. When these earlier fire dates are combined with the 2012 High Park fire (three events in 1900 years), it suggests that extensive, high-severity wildfires with the potential to create significant charcoal layers have occurred approximately every 600 years (using the equation $T = N / n$, where T is the recurrence interval, N is the number of years of record, and n is the number of events). Hillslope processes of weathering, soil development, and vegetation reestablishment would thus occur on shorter time scales in these watersheds. Although this evidence cannot rule out the potential influences of fire suppression or climate change in shaping patterns of fire severity in the High Park burn area, it does suggest that extensive, high-severity wildfires can occur in this system and that the system does recover from such events.

3.2. Debris flows — upper Colorado River

In May 2003, a breach in an earthen water conveyance ditch in Rocky Mountain National Park (Fig. 1) initiated a debris flow that caused 36,000 m^3 of aggradation in a fan at the mouth of a tributary of the upper Colorado River (Rubin et al., 2012; Rathburn et al., 2013) and up to 1 m of sand deposition in a wetland farther downstream. Details are provided in these earlier publications, with the overall impacts summarized here. Channel changes as a result of the debris flow include a ten-fold increase in width along the main debris flow path down a step-pool tributary, deposition of up to 2 m high unconsolidated debris flow berms, mortality of ~20,000 trees along the debris flow path, and transformation of single-thread to multithread channel reaches on the upper Colorado main stem (Fig. 7). Nearly a decade of monitoring the effects of the debris flow and the recovery of channel form and sediment transport processes along the Colorado River indicate differential rates of recovery between the tributaries and main channel (Rathburn et al., 2013). No pre-disturbance sediment transport data were available, so contemporary mean and maximum bedload transport rates were applied to the depositional fan volume to determine fan persistence. The estimates range from 30 to 190 years for full fan evacuation under the current regulated flow regime. The historical range of variability (HRV) of bedforms based on comparisons to appropriate reference reaches indicate partial recovery of step-pool geometry in the debris-flow-sluiced tributary (Rathburn et al., 2013). Bankfull channel geometry on the Colorado River, however, remains outside the HRV expected for mountain pool-riffle channels. Downstream sediment flux, based on bedload and suspended sediment sampling, was nonlinear over time with increased bedload occurring during higher discharges but also as other controls influenced sediment supply (e.g., blocking of footbridges causing avulsion). The episodic nature of sediment transport influenced by flow regulation and transport-limited conditions with respect to coarse sediment means that the form of the Colorado River is not being maintained by processes within HRV (Rathburn et al., 2013). Furthermore, over the last century, at least 19 debris flows have occurred in the valley (11 originating on the west side, 8 on the east), with four of the five largest in association with Grand Ditch (Grimsley et al., 2016). The recurrence interval between debris flow disturbances is too short (~8 years, based on a 93-year record with 11 anthropogenic debris flows) to allow channel geometry adjustments.

Over time the downstream reaches of the Colorado River continue to undergo changes as a result of the dispersion and translation of sediment delivered from the debris flow fan. Flows with higher Froude numbers and low sediment concentrations show dispersive transport, whereas at lower Froude numbers finer bedload sediment transport over a coarser bed facilitated translation (Rathburn et al., 2013), findings similar to Lisle (2008). This continued downstream transport of sediment is supported by differencing airborne LiDAR-derived DEMs in 2004 and 2012 (Mangano, 2014). Growth of gravel bars at the head of the wetland in an unconfined reach has continued, as has the ongoing nature of sediment recovery (Table 1).

3.3. Flood — North St. Vrain Creek

The same long-duration storm in September 2013 that caused avulsion and incision in the SFR tributaries also generated widespread flooding, erosion, and sedimentation in other Front Range watersheds. The storm produced peak flows of over 280 m^3/s, hundreds of landslides, and streamside erosion of >500,000 m^3 of sediment along a 15-km reach of North St. Vrain (NSV) Creek where total rainfall depths

Fig. 7. Upper Colorado River study site in Rocky Mountain National Park (top left photo; from Rathburn et al., 2013) looking upstream on 7 Sep 2003. Deposition of light colored sediment resulted from the May 2003 debris flow. The unvegetated area on the hillslope is Grand Ditch at the site of the ditch failure and the debris flow initiation. North St. Vrain Creek as it enters Ralph Price Reservoir (top right) showing September 2013 flood deposition on 21 Mar 2014. Prior to the flood the entire inlet was reservoir backwater. View is downstream. The South Fork mulched watershed on 2 Jul 2013 (lower left) and 17 Sep 2013 (lower right) that was burned in the 2012 High Park fire. Coarsening of the hillslopes occurred increasing hydraulic roughness. View is downstream.

were on the order of 350 mm (Rathburn et al., 2017). A detailed sediment budget based on pre- and post-flood LiDAR was developed to track sediment from source to anthropogenic sink (water supply reservoir). The results indicate that initial flood-induced channel widening within confined reaches of the NSV created storage for over 40% of the total eroded sediment volumes. Ongoing sediment flux is controlled by threshold water discharges sufficient to entrain and transport that sediment downstream, with post-flood spring runoff in 2014 delivering a flood-equivalent volume of sediment to the reservoir. No flow regulation exists upstream from the reservoir, so all flows to the reach are largely natural. In total, flood sediment deposition resulted in 2% loss in reservoir storage capacity, with another 1% potential loss attributed to remobilization of stored sediment within the catchment (Rathburn et al., 2017). We anticipate a nonlinear sediment response during subsequent years as stored sediment is evacuated by high snowmelt discharges and transported downstream to the reservoir. Additional research indicates that failure of flood-induced debris dams associated with landslides and tributaries within the upstream reach likely increased the erosion and channel widening and enhanced post-flood sediment storage (Bennett et al., 2017). Episodic, transport-limited release of this sediment from mid- and lateral-channel gravel bars, from behind large logjams, and from overbank areas in the few moderately unconfined reaches within the study site is anticipated.

Sediment recovery of North St. Vrain Creek to the September 2013 floods is ongoing (Table 1). The ~300,000 m^3 of sediment deposited in the reservoir inlet that created an approach channel (Fig. 7) is an example of a fundamental state change (Phillips and Van Dyke, 2016) imposed by the flood disturbance. A *state space expansion event* occurred because the new state is something never experienced within the timespan over which the reservoir has existed (Phillips and Van Dyke, 2016); a backwater inlet to the reservoir was transformed into an approach channel (Rathburn et al., 2017) because of the existence of the reservoir. That implies no return to initial conditions, but recovery of sediment loads to a new state is possible. Human activities may prevent systems from ever recovering resilience; sediment will continue to be transported downstream, ending up in the reservoir for long-term deposition over the life of the dam.

4. Discussion and management implications

Sediment disturbances within watersheds range from single point source inputs to spatially extensive perturbations that increase the volume of sediment supplied to a stream network from colluvial and near-channel sources. Evaluating recovery following disturbances through sediment fluxes and the time required to return to background is an approach that integrates sediment delivery and transport throughout a watershed. Brierley et al. (2005) posit that the capacity of a river system to recover following disturbance may be enhanced in transport-limited landscapes where sediments are readily available to be reworked. Supply-limited landscapes, in contrast, may experience prolonged recovery because of the lack of geomorphic tools to carry out geomorphic recovery. In the three study cases compared here, transport-limited conditions prevailed, suggesting that recovery periods generally may be more rapid. Modifying the transient form ratio (Brunsden and Thornes, 1979) is a way to assess dimensionless relative sediment resilience (Table 1) as the ratio of *sediment recovery/disturbance recurrence interval* where sediment recovery is time required to attain background fluxes, and disturbance recurrence interval is the number of years in the record divided by the number of events (Table 1). Ratios < 1 indicate rapid recovery relative to the recurrence interval of disturbance and therefore high resilience. Ratios > 1 imply long recovery times relative to disturbance recurrence intervals and thus low resilience because the system is in a state of ongoing recovery.

The system response to sediment influxes within the three study sites can be summarized in conceptual models as response curves that depict the time and potential for full recovery (Fig. 8). Additionally,

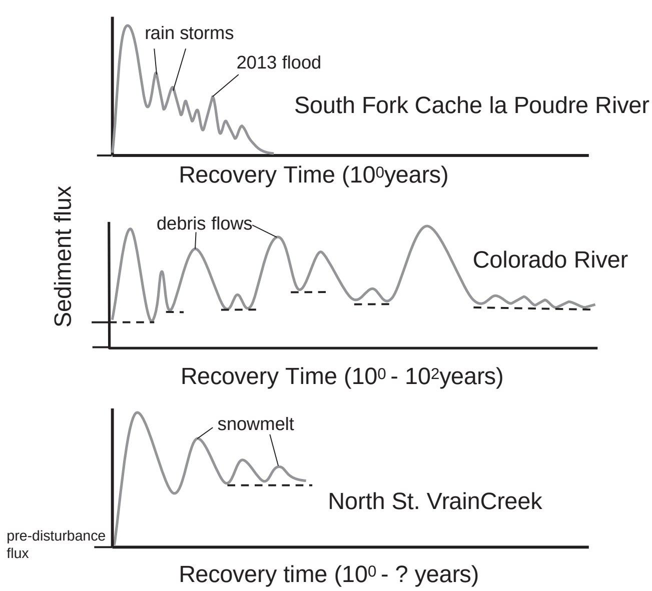


Fig. 8. Conceptual sediment recovery curves for the South Fork Cache la Poudre River, upper Colorado River (modified from Rathburn et al., 2013), and North St. Vrain Creek, northern Colorado. Relative sediment flux refers to discharge (mass per unit time) of sediment transported downstream following a disturbance. Sediment flux begins at conditions that existed prior to the disturbance. For the Colorado River, the short horizontal bar on the *y*-axis demarcates elevated starting sediment loads from anthropogenic influences of Grand Ditch, and logging and mining activities in the valley (Rubin et al., 2012; Rathburn et al., 2013; Grimsley et al., 2016). Likewise, the horizontal dashed lines within each plot indicate a shifting baseline of sediment recovery as a result of the increased frequency of disturbances or because of a new system state associated with the presence of an impounding reservoir, such as on North St. Vrain Creek.

the mechanisms that control these responses, on a spectrum of natural to human-influenced systems, and the role of physical complexity in enhancing form resilience has implications for the overall resilience within these small, mountainous watersheds (Fig. 9).

4.1. South Fork Cache la Poudre River

In the case of the SFR, a full recovery to pre-disturbance conditions was expected over relatively short time scales based on previous research in similar settings. Moody and Martin (2001), Benavides-Solorio and MacDonald (2005), Wagenbrenner et al. (2006), and Robichaud et al. (2013) found that suspended loads attained background levels in 3–5 years and in 3–10 years for more coarse materials. Sediment recovery in the High Park fire paired watersheds varied over time and space, and was influenced by first and secondary controls to different degrees (Table 1). The initial high sediment flux on the South Fork River is associated with storms immediately following the 2012 High Park Fire (initial peak, Fig. 8), storms that helped to extinguish the fire in summer 2012, initiating channel change that occurred prior to any data collection at the site. The combination of the 2012 High Park fire and 2013 flood evacuated sediment from the SFR basin; but valley morphology, particle size, vegetation reestablishment, and year post-fire were also primary controls. By 3 years post-fire, after eight threshold-exceeding storms had occurred, suspended sediment concentrations were comparable to pre-disturbance values. Bedload was not quantified in the same manner, but speculatively, ongoing higher rates of bedload transport may occur as fire- and flood-derived sediment is translated downstream, suggesting lower resilience for coarser sediment. The extensive watershed-scale erosion from the 2013 storms evacuated ash stored on hillslopes and post-fire sediment from the main stem channel bed during the storm, effectively improving water quality through a decrease in measured suspended sediment in the basin (Miller et al., 2017). In some areas, 2013 flood waters were sufficient to transport coarse, fire-related debris flow sediment delivered from burned tributaries and deposited it in small fans (Fig. 6).

Removal of vegetation during the High Park fire lowered the threshold of response to rainstorm-induced sediment transport in ephemeral and in perennial channels. Rainstorms eroded finer sediment immediately after the fire, resulting in coarse particles mantling the hillslopes and exposing vegetation roots (Fig. 7). This imparted high surface roughness and rendered the study watersheds moderately resilient to the effects of the fire and flood (Fig. 9). Greater surface roughness limits concentration of surface flow and the detachment of particles necessary to initiate rills and then gullies (Moody and Kinner, 2006; Wohl, 2013b).

Our analysis shows that while sediment recovery may be high, it does not necessarily equate to high resilience because of other factors that facilitate channel form complexity and hence resilience. The incised perennial channels within the burn area have moderate form resistance (Table 1, Fig. 9; middle photo) owing to undercut vertical banks and lack of high spatial complexity. Bank collapse, channel avulsions, and evidence of sediment transport have been observed since the end of data collection in 2014, indicating ongoing coarse sediment transport in spite of the fact that suspended sediment concentrations are comparable to background levels. Hence, we find that sediment recovery does not necessarily track with form resilience.

The lack of ephemeral channel response to the fire and flood indicates high channel form resilience in the ephemeral channels and contributing areas based on the metrics measured (channel geometry changes, sediment aggradation and degradation) to evaluate sediment flux recovery. Our data are corroborated by Wohl (2013b) and Wohl and Scott (2017) on channel heads within small watersheds (one of which is our mulched site) feeding ephemeral channels. After 4 years, the up-gradient migration of channel heads had ceased, with sediment infilling decreasing the contributing area in the mulched watershed.

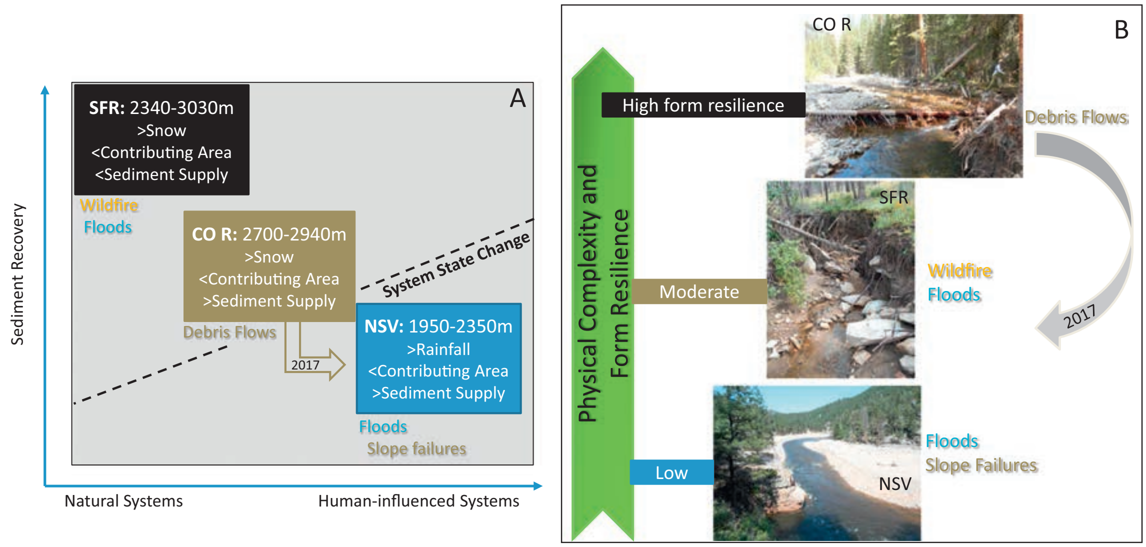


Fig. 9. (A) Sediment recovery for case studies along a natural to human-influenced gradient. Sediment recovery may not reflect channel form resilience because of a lack of physical complexity (B). While the upper Colorado River (CO R) shows moderate sediment recovery (A), high form resilience caused by channel-spanning log steps creates bedforms and habitat. The form complexity and resilience is downgraded because of another debris flow in summer 2017 (downward arrows in A and B). The South Fork River (SRF) and North St. Vrain (NSV) have lower form resilience owing to incised channels without the physical channel complexity (B).

4.2. Upper Colorado River

In the case of the upper Colorado River, long-term recovery is interrupted by a cascading series of disturbances that introduce different starting points. To a large extent, these are driven by current and historical land uses. Sediment recovery following input from a single debris flow is largely controlled by available discharge, valley geometry, and the size of materials in transport. The history of debris flows provides a second-order control (Table 1) that influences the supply of sediment and state of condition in the main stem. Furthermore, an increased frequency of debris flows over the last two centuries caused by logging and mining activities in the Colorado River valley (Rubin et al., 2012) results in a shorter recovery from events such that overlapping influences occur, amplifying the effects of debris flows and increasing the threshold of response (Fig. 8). Hence, the starting condition in a debris-flow-impacted system is highly influenced by events occurring at differing time scales and under varying management influences.

Channel form resilience on the upper Colorado River is high relative to the other two sites, as evidenced by increasing physical channel complexity that has developed since the 2003 debris flow (Fig. 9). Channel-spanning logs create steps that pond flow and allow sediment and nutrients to settle out upstream from the step. Pools that develop downstream from the steps are deeper and cooler, and the step itself creates complex habitat. Other features like bank undercutting and increased riparian vegetation contribute to higher complexity and hence high form resilience relative to other case studies.

4.3. North St. Vrain Creek

In the case of the North St. Vrain, sediment recovery is unlikely to be fully achieved as a state change has occurred. Along the North St. Vrain, we were able to quantify sediment fluxes associated with the flood through pre- and post-LiDAR coverage. Flood disturbances on NSV are also ongoing as 2013 flood-eroded sediment in storage continues to be transported downstream into the water supply reservoir. A new system state results in a shifting baseline of recovery (Fig. 8). Resilience of the NSV watershed to the September 2013 storms was low (Fig. 9) because of the existence of the reservoir and dam that caused the extensive deposition. In contrast, lateral connectivity with the upper NSV allowed flood waters to expand throughout the wide valley bottom, limiting the effects of the 2013 flood to just centimeters of aggradation (Wohl et al., 2017). We speculate that prior to closure of the dam in 1969, the NSV was likely more resilient and has become less so over time. Flood sediments would have been readily transported downstream through the bedrock-confined reaches, with flood attenuation in the lower gradient, formerly unconfined reaches that were beaver meadows but are now occupied by the current reservoir. Pre-dam aerial photos in 1969 indicate a beaver meadow occupied the valley where the reservoir is now located.

4.4. Management approaches to enhance recovery and resilience

As climate change modifies storm frequency, magnitude, and duration, we expect resilience to disturbance to change also. Greater variability in temperature, moisture, and wind patterns will affect soils, vegetation, and the hydrologic regime that drives storms and droughts and hence disturbances including floods, fires, and mass movements (Phillips and Van Dyke, 2016). With projections of increased fire intensity, frequency, and extent in western USA, as well as longer fire seasons and greater temperature extremes (Westerling et al., 2006; Abatzoglou and Williams, 2016), sediment yields are also expected to increase (Goode et al., 2012). With these changes come questions about how to promote resilience under increasingly more frequent disturbances or in heavily human-influenced systems. In a broad sense, we would argue for (i) managing geomorphic systems for open energy transfer; (ii) allowing space for rivers to adjust and respond (e.g., freedom space for rivers; Biron et al., 2014); and (iii) maintaining enhanced structural and functional landscape complexity (e.g., let wood be; beaver meadows). All three approaches promote physical complexity in rivers, which increases the sediment resilience to disturbances. Even under conditions of high sediment load, active lateral migration and high complexity will naturally attenuate downstream sediment fluxes (Hooke, 2007). Or a high sediment load that may arise or continue under a changing climate and increased frequency/intensity of disturbances may lead to a meandering to braided transition. Although a state change would occur in this situation, the system may still be considered resilient as it is slowly responding to the higher sediment load. Depending on the time and space scales of highest priority along dynamic river systems, resilience understanding can be incorporated into river and water resource management. This is exemplified by an increasing number of municipalities proactively addressing resilience issues in their communities and developing resilience plans to protect water supplies in mountainous watersheds.

While the ideas of open energy, space, and complexity are not new, especially within the restoration community where they have been widely circulated as management principles that preserve natural process and form (e.g., Downs et al., 2002; Downs and Gregory, 2004), reiterating fundamental thinking about resilience as it enhances restoration is critical. Understanding the sensitivity of a channel to change is a direct tie to thinking about and managing a river as an ecosystem and to its recovery potential during restoration. Understanding the dynamics of sediment supply, storage, and transport within a watershed, or the sediment recovery potential, helps to illuminate the spatial controls on channel adjustment in order to gauge the level of energy available for recovery and the type of recovery to be expected (Fryirs and Brierley, 2000).

4.4.1. Restoration decisions

Application of mulch within the South Fork watershed was intended to limit post-fire hillslope erosion and sediment delivery to the main stem. The mulch was applied in late 2012 and early 2013 to portions of the two watersheds, particularly in the steep upper portions. Spring precipitation in 2013 mobilized much of the freshly applied mulch along channels as discharge was rapidly conveyed downstream (Fig. 10). Where the mulch stayed in place, it was effective in facilitating rapid vegetation growth of the seeds within the straw. The effectiveness of the mulch at limiting erosion on a watershed scale is uncertain given the somewhat contradictory results of in-channel scour chain data on sediment yields and suspended sediment concentrations measured at the outlets of both watersheds.

The decision on where to apply mulch is typically based on measures of fire severity, slope steepness, geologic characteristics, as well as downstream values at risk (Cannon et al., 2001). Additionally, the degree to which a tributary watershed is connected to the main channel could also be a useful factor in deciding where to expend scarce post-fire restoration resources, as indicated by treatment priorities (Fig. 11) such that highly connected tributaries are the highest priority. The partially mulched watershed contributed somewhat higher (or comparable) levels of suspended sediment to the SFR, an expected result under conditions of lower mulch application. Moreover, the partially mulched watershed has a higher level of connectivity as controlled by valley confinement at the confluence (Fig. 11). Understanding differences in sediment connectivity to the SFR may be equally as important as the post-fire treatments in controlling fine sediment delivery. Hence, an assessment of sediment connectivity potential at the confluence of watersheds of concern could further inform estimation of the likelihood of sediment reduction from burned watersheds and guide treatment decisions.

Moody and Martin (2009) suggested that 75% of post-fire sediment yield comes from channels, though they consider rills and gullies as channels, unlike our classification. Field observations throughout the SFR basin indicated substantial channel incision in perennial channels. However, ephemeral channels did not function as source areas for sediment, rather transporting it or providing temporary storage between storms. As such, mulching hillslopes may not affect in-channel processes. Mulching does appear to be effective at reducing runoff and erosion on hillslopes lower in the Cache la Poudre River basin (Schmeer, 2014; Kampf et al., 2016), where more frequent, higher intensity rainstorms occurred.

In the case of the upper Colorado River, knowledge of recovery patterns could be incorporated into resource management decisions and policy, especially pending restoration of the affected wetland. Restoration efforts that restabilize the failed hillslope below Grand Ditch and target restoration in areas prone to failure elsewhere along the Ditch would likely impart the greatest sediment resilience. Restoration efforts that do not address the ongoing, episodic sourcing of sediment via slope failures, continued entrainment and transport of existing unconsolidated debris flow sediment, and transport of large wood that block footbridges and create channel avulsions miss the dominant process drivers within the river valley. Restoration efforts that do not consider the sediment transport processes from hillslope source to wetland sink may enhance dynamically unstable conditions that cause the effects of the 2003 perturbation to not only persist but grow over time. Field observations indicate width-spanning log steps within the channel (Fig. 9B photo) create hydraulic and physical complexity. The Colorado River site was likely more resilient before mining and logging >200 years ago, when wood recruitment and abundance within geomorphically effective steps and jams was probably more common. An overall loss in resilience has resulted because of human alterations to the landscape.

4.4.2. Incorporating beavers to enhance resilience

Beavers were once abundant along the upper Colorado River in Rocky Mountain National Park (Andrews, 2015). Within the study site specifically, beaver ponds appear in the earliest aerial photos in 1937. A radiocarbon age of CE 1634–1662 from a log within a buried beaver

Fig. 10. Repeat photos of an ephemeral channel showing mulch effectiveness where it was retained after a storm on 1 Jul 2013 in the fully mulched watershed of the South Fork Cache la Poudre basin (left photo) and on 17 Sep 13 (right photo).View is downstream.

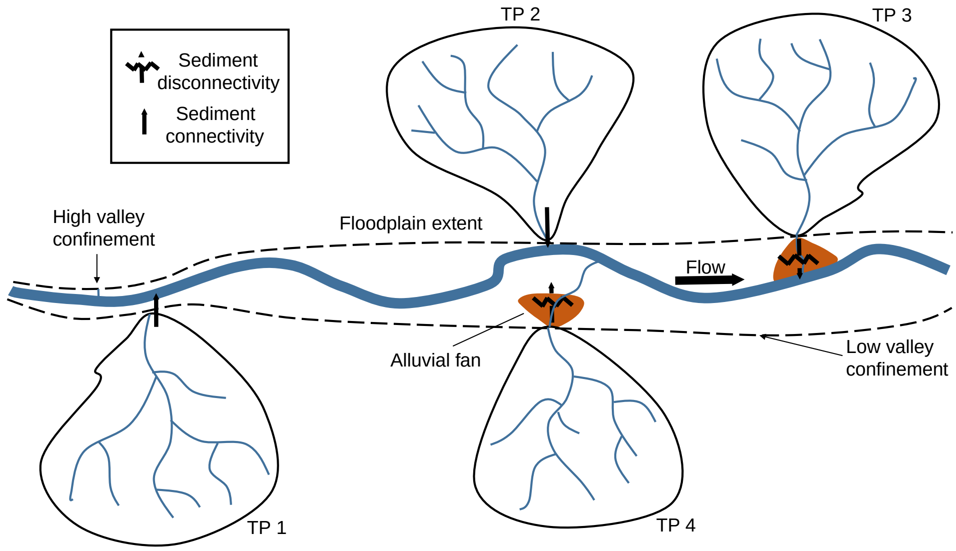


Fig. 11. Sediment connectivity and disconnectivity influences on post-fire treatment priorities. TP1–TP4 represents watersheds with highest (TP1) to lowest (TP4) treatment priority based on sediment connectivity. In the South Fork River paired watersheds, the mulched watershed represents TP4 because of the wider floodplain and development of a sediment fan, whereas the partially mulched watershed represents TP1 with high valley confinement and high sediment connectivity.

dam supports the presence of beavers well before the aerial imagery record (Rathburn et al., 2013). Elsewhere in the Park, beaver meadows create high geomorphic resilience (Polvi and Wohl, 2012) as illustrated by the beaver meadow along the upper North St. Vrain Creek (upstream from our 15-km study site) that largely resisted September 2013 flood erosion (Wohl et al., 2017). This is in stark contrast to the downstream, confined reach of NSV that underwent extensive erosion and channel alteration (Rathburn et al., 2017). While valley confinement may be a key factor controlling flood effects, introducing beavers is one management practice that would foster greater resilience to extreme events. Beavers create obstructions to flow through the dams they build, increasing depth, extent, and duration of overbank flows that sustain high riparian water tables within beaver meadows (Westbrook et al., 2006; Wohl, 2013a). Furthermore, beaver meadows can increase open water area and base flow during dry periods (Hood and Bailey, 2008), thereby increasing resistance and resilience to drought. An indication of the growing interest in using beaver as a restoration and climate adaptation tool is, for example, the development of quick methods to estimate the increase in surface water storage from surface area and beaver dam height (Karran et al., 2017).

4.4.3. Future decisions concerning geomorphic resilience

For the broader surface process community, where we go from here in terms of resilience requires the continued efforts of a devoted cadre of scientists working in a range of landforms using multifaceted approaches. To foster resilience to increasingly extreme events, scenarios and models of how geomorphic systems have responded in the past and may respond to future disturbances are required (Van de Wiel et al., 2011; Lane, 2013). Models that track fluxes of sediment to identify geomorphic hotspots (Czuba and Foufoula-Georgiou, 2015), or sediment pulse evolution (Gran and Czuba, 2017) are useful for management decisions. Careful field studies with longer time frames will help quantify model boundary conditions and assist validation of the models, as well as refine response trajectories that show expected behavior of how geomorphic systems have responded to past and recent extreme storms and floods (Naylor et al., 2017 Grand Challenge #1). Stream evolution models that explicitly assess resilience (Cluer and Thorne, 2013) may gain traction as river scientists integrate habitat and ecosystem benefits into management and restoration efforts at increasingly larger spatial scales.

Our analysis of sediment recovery is limited to relatively small watersheds with little change in human influences over the recovery period. Evaluating sediment recovery as the time to attain background sediment yields, concentrations, or rates and volumes of aggradation and degradation is only feasible when comparable land use and human development exist during the recovery period. Should development occur following a disturbance that alters the runoff processes for example, our approach to determining recovery would be less valid. As more people move into the urban-wildland interface, watersheds undergoing rapid development may be especially in need of resilience assessments because disturbance-driven damages to land and water resources are amplified through continued construction of river corridor infrastructure. Our work ahead is to improve understanding of what controls resilience and how to implement management strategies that enhance the ability of watersheds to withstand future disturbances.

5. Conclusions

Sediment recovery within three small mountainous watersheds in the Rocky Mountains of Colorado was evaluated following single or compound disturbances. The dominant site-specific controls on the response to disturbances for the South Fork Cache la Poudre, upper Colorado River, and North St. Vrain basins include precipitation intensity and duration, discharge, valley morphology that influences connectivity, sediment characteristics, and anthropogenic activities. The South Fork study site shows high sediment recovery because measured suspended sediment concentrations were at background levels 3 years after the 2012 High Park fire. The compound disturbance of the September 2013 flood hastened that sediment recovery. Debris flows along the upper Colorado River over the last two centuries has shifted the baseline of sediment recovery caused by anthropogenic activities that increased debris flow frequency. The flood in September 2013 on North St. Vrain Creek resulted in extreme sedimentation within a downstream reservoir that led to a physical state change. An index of relative sediment resilience as *sediment recovery/disturbance recurrence interval* allows comparison between sites. Sediment recovery may or may not imply watershed resilience, however, because of a lack of physical complexity that enhances channel form resilience. Under increasingly more frequent disturbances and human-influenced systems, we propose (i) managing geomorphic systems for open energy transfer; (ii) allowing space for rivers to adjust and respond; and (iii) maintaining landscape complexity. All three approaches promote physical complexity in rivers that increases the sediment resilience to disturbances. Assessing sediment connectivity within small watersheds provides land managers a valuable tool when developing restoration treatment priorities.

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