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Impacts of wildfire on runoff and sediment loads at Little Granite Creek, western Wyoming

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ABSTRACT

Baseline data on rates of sediment transport provide useful information on the inherent variability of stream processes and may be used to assess departure in channel form or process from disturbances. In August 2000, wildfire burned portions of the Little Granite Creek watershed near Bondurant, WY where bedload and suspended sediment measurements had been collected during 13 previous runoff seasons. This presented an opportunity to quantify increases in sediment loads associated with a large-scale natural disturbance. The first three years post-fire were warm and dry, with low snowpacks and few significant summer storms. Despite relatively low flows during the first runoff season, the estimated sediment load was about five times that predicted from regression of data from the pre-burn record. Increased sediment loading occurred during the rising limb and peak of snowmelt (54%) and during the few summer storms (44%). While high during the first post-fire year, total annual sediment yield decreased during the next two years, indicating an eventual return to baseline levels. The results from this sediment monitoring lacked some of the more dramatic responses that have been observed in other watersheds following fire. In other environments, moderate-to-high intensity rainstorms caused significant flooding, widespread debris flows and channel incision and aggradation. A few moderate intensity storms (<2 year recurrence interval) occurred in the Little Granite Creek watershed, but they did not trigger this type of response. Instead, ash and charcoal rich discharges (herein described as "blackwater flows") and heavily sediment laden flows were observed without physical evidence of debris flows, as defined by channel incision into previously unchanneled areas. Speculatively, the sedimentation pattern and geomorphic response in Little Granite Creek may be fairly typical of stream responses to wildfire during times of continued drought and in the absence of widespread, significant rainfall, representing one type of response on a continuum of effects following wildfire.

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1. Introduction

The effects of wildfire on watersheds include first-order impacts, such as burned vegetation and reduced soil infiltration, and second-order impacts, such as increased runoff, hillslope erosion, stream sedimentation, and significant alteration of terrestrial and aquatic habitat. Post-fire erodability is related to a multitude of factors, including burn severity, topography, underlying geology, and nature of the soils, making potential sedimentation impacts difficult to predict (Ryan and Noste, 1983; Meyer et al., 1995; Cannon et al., 2001a,b; Wondzell and King, 2003; Moody et al., 2008). Perhaps the most critical component in determining the degree and type of erosion response is the timing, magnitude, and duration of storms immediately following the fire (Hassan et al., 2005). While stream flow responses to wildfire can be quite varied (Lane et al., 2006), significant increases in flow following rainstorms have been reported during the early post-fire period (Benavides-Solorio and MacDonald, 2001; Elliott and Parker, 2001; Moody and Martin, 2001a; Wondzell and King, 2003). In snow-dominated regimes, there is often a tendency for flows from spring snowmelt to be higher following fire (Minshall and Brock, 1991) and arrive earlier in the season (Troendle and Bevenger, 1996). The greatest erosion threat occurs when severe fire is followed by rainfall (2–10 year recurrence frequency) (Cannon et al., 2010) and peak flows arrive faster and higher because of water repellency and exposure of denuded soils to rainfall following vegetative loss (Gresswell, 1999; Neary et al., 2003) and prior to vegetation recovery (Robichaud et al., 2000).

Increased erosion and flooding emanating from burned areas not only impacts rates of sediment delivery and transport but also the structure and function of streams downslope and downstream. Greater flow and increased sediment loading can produce episodes of exceptionally high rates of sediment transport (Minshall et al., 1990; Troendle and Bevenger, 1996). Because sediment loadings are

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highly dependent on sporadic inputs from burned areas, they tend to be transient and irregular (Helvey, 1980; Moody and Martin, 2001b). While the effects of these events may be fleeting, the aftermath is often significant since they can clog the streambed with fine sediment, increase channel instability, and alter temperature regimes, thereby affecting aquatic biotia (LaPointe et al., 1983; Gresswell, 1999; Minshall et al., 2001a,b; Benda et al., 2003). Rates of hillslope erosion typically return to pre-burn levels within a few years to one decade (Morris and Moses, 1987; White, 1996; Robichaud et al., 2000), although sediment delivered to and stored in channels and depositional areas can take many more years to move through the system (Moody and Martin, 2001b; Reneau et al., 2007). In general, the effects of fire on aquatic ecosystems are diverse and often related to pre-fire habitat conditions and the characteristics of the species (Bisson et al., 2003); timeframes for species recovery are likewise variable (Dunham et al., 2003).

Predicting changes in the transport of coarse sediment (bedload) and channel form following wildfire present a challenge because of the irregularity of processes by which bedload is moved (e.g., Reid and Frostick, 1984). Increased runoff and higher, faster, and more erosive discharges may cause parts of the channel to degrade, particularly in higher elevations where streams tend to be steeper with greater connectivity to hillslopes (Minshall et al., 1997). In flatter reaches, the channel may aggrade as coarse materials scoured from upstream are deposited in response to reduced slope and widening of the channel (Moody and Martin, 2001b). Depending on the nature of the coarse sediment load and geomorphic sensitivity of the watershed, the impacts of wildfire on channels downstream of burned areas can last for decades (Swanson, 1981).

Hydrologic and geomorphic impacts of wildfire are often evaluated by comparing physical processes or transport rates between burned and unburned areas because adequate data on sedimentation rates and patterns prior to burning are rare (Moody and Martin, 2001b; Lane et al., 2006). Changes in discharge, hillslope and channel erosion, rates of sediment transport, and instream deposition have been evaluated using these paired watershed comparisons (e.g., Albin, 1979; Troendle and Bevenger, 1996; reviews in Robichaud et al., 2000; Petticrew et al., 2006; Silins et al., 2009). This approach assumes, however, that the systems were similar enough prior to burning so that general comparisons can be made. Where predisturbance data do exist (e.g., Helvey, 1980; Woodsmith et al., 2004), the magnitude of the hydrologic and sediment response can be better quantified, placing changes in rates of runoff and sedimentation into a broader comparison with the background rate (Shakesby and Doerr, 2006).

In this study, we build upon a series of serendipitous events and preexisting measures of sediment transport rates that permit an in-depth evaluation of flow and sedimentation responses following wildfire. In August 2000, a 1400-ha (3500 acre) wildfire in the Gros Ventre Wilderness area near Bondurant, WY, burned substantial portions of the Boulder Creek watershed (Fig. 1). Roughly 75% of the forested area in this watershed was burned, 67% of which burned at moderate to high severity. These estimates of burn severity were derived from a Burned Area Reflectance Classification (BARC) map processed in 2008 at the Remote Sensing Applications Center (RSAC) (procedure as described in Bobbe et al., 2004). The Boulder Creek watershed comprises 40% of the area within Little Granite Creek where researchers from the U.S. Geological Survey (USGS) and U.S. Forest Service (USFS) had previously collected data on bedload and suspended sediment loads (Ryan and Emmett, 2002; Ryan and Dixon, 2008) during 13 snowmelt runoff seasons between 1982 and 1997. The disturbance caused by wildfire presented an opportunity to quantify increases in sediment loads associated with a wildland fire relative to established baselines at the Little Granite study site (Fig. 1, site 3). Additionally, a second subwatershed (Upper Little Granite Creek) – comparable in size, aspect, and geology to the Boulder Creek subwatershed – remained largely unburned (<5% of the watershed area burned at moderate to high severity). This presented an additional opportunity to compare disturbance and recovery processes within burned and unburned areas that are nested within a larger watershed for which pre-burn data exist.

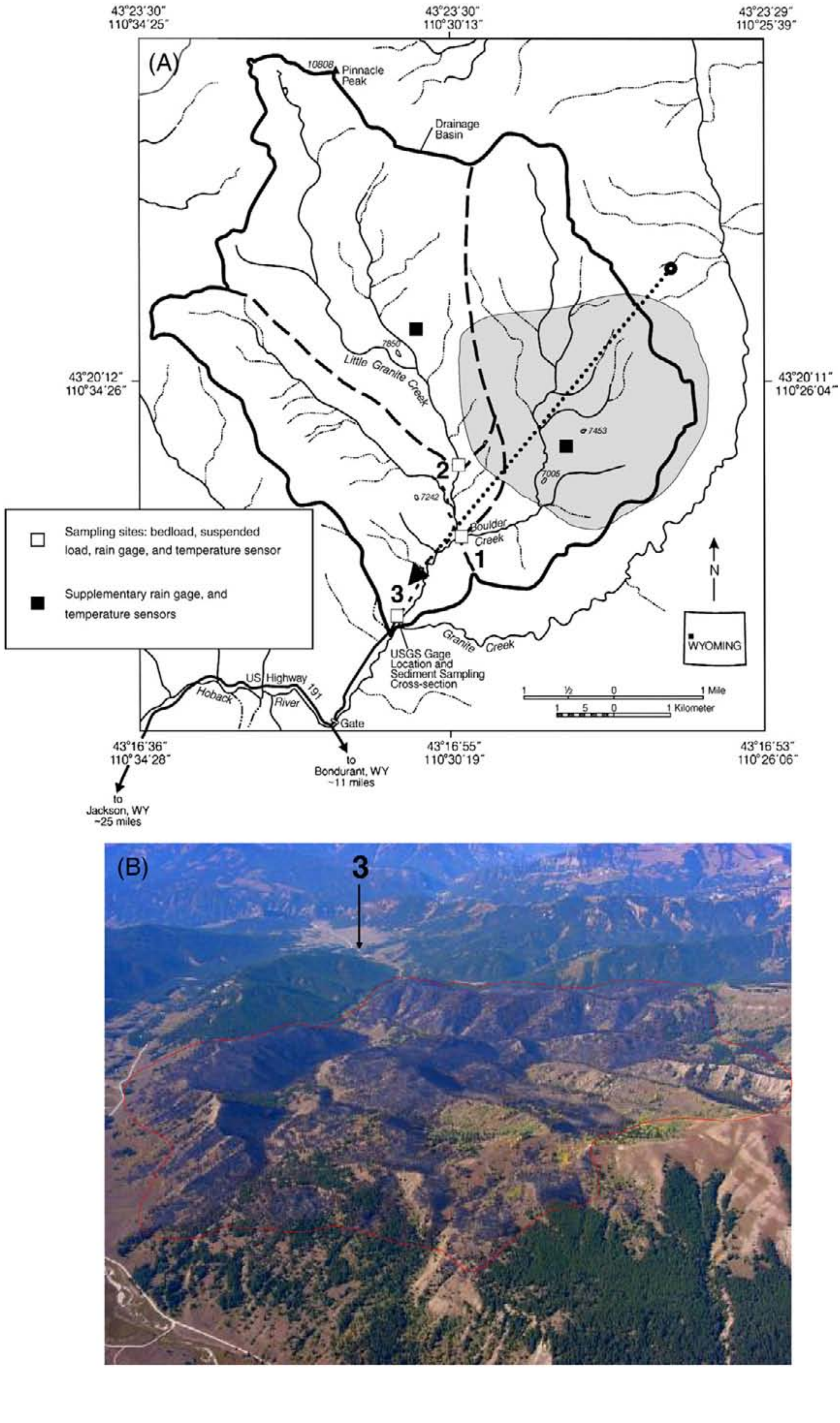
The primary research objectives were to (i) evaluate the influence of snowmelt runoff and rainstorms on sediment dynamics for the first three years following wildfire; (ii) quantify differences in suspended sediment concentrations relative to the pre-burn period and between burned and unburned watersheds; and (iii) compare pre- and post-fire sediment yields. In support of these objectives, we also examined precipitation and runoff patterns and evaluated grain size and organic matter composition of post-fire suspended sediment samples.

2. Watershed description

Little Granite Creek, an upland contributor to the Snake River system, drains 21.1 mi^2 (54.6 km^2) of the Gros Ventre range south of Jackson, WY. The area is administered by the USFS, Bridger-Teton National Forest, Jackson Ranger District. Over half of the basin is in the Gros Ventre Wilderness Area. The two main tributaries to Little Granite Creek are Boulder Creek (8.0 mi^2/20.7 km^2) and the upper basin of Little Granite Creek (Upper LGC) (7.6 mi^2/19.7 km^2) (Fig. 1). The basins have similar lithologies (see description below) and face south, making them largely suitable for a paired watershed comparison. The primary differences between the watersheds are higher elevations and greater expanse of Pleistocene glaciation and moraines in Upper LGC. Prior to burning, forest cover in the two subwatersheds was dominated by lodgepole pine, classified as the persistent lodgepole pine (*Pinus contorta*) community type, with different understory shrubs and graminoids (Steele et al., 1983; Bradley et al., 1992). In the broader valley bottoms, riparian vegetation is dominated by willow species (*Salix* spp.), with an extensive herbaceous understory (Youngblood et al., 1985). In more confined portions, the floodplain overstory is composed of a mixture of lodgepole pine, Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), with riparian shrubs occurring along the streambanks (Youngblood et al., 1985).

Runoff in the Little Granite Creek watershed is generated primarily by melting of the annual snowpack, with peak flow occurring typically between mid-May and mid-June and high, out of bank flows lasting 1–2 weeks (Ryan and Emmett, 2002; USGS, 2007a,b). Thunderstorms are common in summer but are generally short in duration and of low magnitude. The 2 year, 6 h storm estimated for the region is 21 mm (0.82 in.) while the 2 year, 1 h storm is 17 mm (0.69 in.) (derived from Miller et al., 1973). The estimate for the 5 year, 6 h storm is 25 mm (1.0 in.) and the 5 year, 1 h storm is 19 mm (0.74 in.). Storms of this duration and magnitude produce only minimal rises in the hydrograph (<25 cfs or 0.7 m^3 s^{-1}) (unpublished USGS 15-min stage records). Mean annual temperature is 33.3 °F (1.0 °C) and mean annual precipitation is 52.15 cm (20.53 in.) at a climate station in the vicinity of Bondurant, WY (elevation 6504 ft/1982 m) [Western Regional Climate Center (WRCC, 2005b); National Climate Data Center

Fig. 1. Map A) of study sites within the Little Granite Creek watershed (thick solid line). Gray area approximates the boundary of the burned area. Bold numbers indicate the location of the three sediment/flow/ rainfall measurement sites: (1) Boulder Creek, (2) Upper Little Granite Creek, and (3) Lower Little Granite Creek. Dashed lines delineate the boundaries between the Boulder Creek and Upper Little Granite watersheds above the sampling locations. Pre-burn data was collected only from the Lower Little Granite Creek site (3) between 1982 and 1997. Black squares indicate the location of supplemental rain gages in the upper portion of the watershed. Oblique aerial photograph B) taken in September 2000 depicts area of burn within Boulder Creek watershed (red line). View is from the NE section of the burned area looking toward Lower Little Granite to the SW [direction noted by dotted line with arrow on map A)]. Photograph courtesy of Remote Sensing Applications Center (RSAC).



43°23′30″
110°34′25″
43°23′30″
110°30′13″
43°23′29″
110°25′39″
(A)
10808
Pinnacle Peak
Drainage Basin
7850
Little Granite Creek
43°20′12″
110°34′26″
43°20′11″
110°26′04″
7453
7005
7242
2
Boulder Creek
1
3
Sampling sites: bedload, suspended load, rain gage, and temperature sensor
Supplementary rain gage, and temperature sensors
N
Granite Creek
WYOMING
USGS Gage Location and Sediment Sampling Cross-section
US Highway 191
Hoback River
Gate
1 ½ 0 1 Mile
1 .5 0 1 Kilometer
43°16′36″
110°34′28″
43°16′55″
110°30′19″
43°16′53″
110°26′06″
to Bondurant, WY ~11 miles
to Jackson, WY ~25 miles
(B)
3

(NCDC) Normals, 1961–90]. Most of the precipitation falls as snow from November through March. Average annual snowfall measured at Bondurant between 1948 and 1999 was 340 cm or 134 in. (standard deviation ± 124 cm or 48.9 in.) (WRCC, 2005a).

The basin is underlain primarily by deformed sedimentary formations (sandstone and claystone) of marine origin (Love and Christiansen, 1985). Areas are prone to mass wasting and over 100 landslides have been mapped previously (Table 1), impacting about 20% of the watershed area (WSGS and WRDS, 2001; refined by S. Ryan using field reconnaissance and aerial photographs). Types of landslides include large, slow-moving earthflows and smaller scale slumping (23% of mapped landslide area), debris flows (18%), and rock/debris slides (18%). The remaining forms include complex combinations of large earthflows and multiple debris slides/flows (27%), Quaternary aged landslides (8%), and rock glaciers and avalanches (6%). Within the Boulder Fire burned area, 60% of the mapped landslide area was classified as earthflow or slump, 19% as debris flow, 16% as rock/debris slide, and 5% complex. The relative differences in percentages between the burned area and the rest of the watershed are because the fire occurred primarily in mid-basin were earthflows and slumps are more common. The larger failures become particularly problematic during years with heavy snowfall followed by periods of rapidly warming temperatures when saturated conditions prevail and cause destabilization along deep-seated failure planes (Chleborad, 1997). Where impinging on stream channels, these slow-moving features are a source of fine-grained sediment. Additionally, active rock/debris slides and exposed and eroding deposits of glacial origin in the headwall and upper portion of the watershed contribute a considerable supply of fine sediment to the system, particularly during snowmelt runoff. As a result, baseline values of suspended sediment concentrations (SSC) in the watershed are relatively high (between 100 and 1000 mg L^{-1}) during peak runoff. By comparison, SSC from streams in undisturbed forested areas draining granitic and/or metamorphic terrain under similar climatic and vegetative cover are typically no greater than about 100 mg L^{-1} (Andrews, 1984; King et al., 2004; USFS unpublished data).

The channel of Little Granite Creek ranges from step-pool and rapids in confined valley bottoms to plane bed and pools/riffles in wider floodplains. Bed material ranges from gravel to small boulders, with <10% sand-sized grains located primarily at the channel margins and in small patches in the lee of larger particles. The primary in-channel sources of sediment are scour and resuspension of fines from the channel bed and banks. Peripheral sources of sediment come from mass wasting (described previously) and slumping from undercut terraces and road cuts. Upland resource uses include grazing and dispersed recreation. A USFS road parallels the stream for about 1.5 mi (2.4 km) in the lower portion of the watershed. Former land uses include coal extraction and a mining camp near the main stem just above the confluence with Boulder Creek (Fig. 1). These former and present uses are small in scale and their influence on sediment delivered to the channel is considered to be nominal.

2.1. Preexisting sediment and flow data

Sediment and flow measurements were made during the course of 13 runoff seasons between 1982 and 1997 near the confluence of Little Granite Creek with Granite Creek (Fig. 1, site 3). Flows were measured at a USGS gaging station (USGS, 2007a) that was active between 1982 and 1993. A sediment sampling program was initiated at this site in 1982 as part of an environmental monitoring project conducted in conjunction with an exploratory effort in the upper basin. Though the exploration for fossil fuels was abandoned, routine sediment monitoring continued through 1993. The database was expanded when additional bedload samples were collected by USFS personnel during high flow in 1997 (Ryan and Emmett, 2002). Bedload, moved by flows ranging from 0.05 times to nearly twice the bankfull discharge (11.3 $m^3 s^{-1}$ or 400 $ft^3 s^{-1}$), was measured using a Helley-Smith bedload sampler (Helley and Smith, 1971). Samples of suspended load were collected using depth-integrating samplers. Laboratory analyses were conducted in accordance with standard USGS methods (e.g., Guy, 1969). Data on rates of bedload transport, particle size distribution of individual samples, suspended sediment load, measurements of hydraulic geometry, and channel surveys are published (Ryan and Emmett, 2002); the sediment data are available electronically at the USFS, Rocky Mountain Research Station data achieve site (http://www.fs.fed.us/rm/data_archive/dataaccess/LTLGRAN_HAYDEN_Brkpt_Tutorial.shtml). Other types of data collected during previous efforts include several years of flow record, channel surveys, and data on dissolved loads (Ryan and Dixon, 2008).

Table 1
Landslide inventory for Little Granite Creek watershed and burned area.

Landslide type	Number of landslides in basin	Number of (pre-burn) landslides in burned area	Total area of landslides in basin (km^2)	Total area of landslides in burned area (km^2)	Percentage of landslide area within basin (%)	Percentage of landslide area within burned area (%)	Percentage of landslide area by type in basin (%)	Percentage of landslide area by type in burned area (%)
Complex (multiple landslide types)	12	2	3.0	0.08	5.4	0.8	27	5.6
Slump/ Earthflow	23	13	2.5	0.89	4.6	8.6	23	60
Debris flow (debris slide with flow)	54	11	1.9	0.28	3.5	2.7	18	19
Rock slide (steeper, in rock)	19	1	1.2	0.02	2.2	0.17	11	1.2
Quaternary landslide	3	0	0.86	n/a	1.6	n/a	7.9	n/a
Debris slide (finer grained, in vegetated area)	19	4	0.71	0.22	1.3	2.1	6.5	15
Avalanche	2	0	0.42	n/a	0.77	n/a	3.9	n/a
Rock glacier (likely ice core)	3	0	0.31	n/a	0.57	n/a	2.9	n/a
Total	135	31	11	1.5	20	14	100	100

2.2. Wildfire in Little Granite Creek Watershed

The Boulder Creek fire was ignited by lightning on 30 July 2000 in the Upper LGC watershed near the divide with Boulder Creek (Fig. 1). The fire moved eastward into the Boulder Creek watershed within 2 days of ignition and, over the next month, burned the upper and middle portions of the watershed primarily within the Gros Ventre wilderness area. The fire eventually crossed a second divide into the Granite Creek watershed where a concerted effort was made to halt its progression to protect private in-holdings. Reduced fuel loads, cooler weather, and easier access assisted fire fighters in extinguishing the fire, which was nearly contained by 4 September. In mid to late October (immediately post-fire), rainfall and rainfall/snowfall mixtures were measured at a nearby snow telemetry site (Granite Creek, Station ID: 10f29s, NRCS). Though flow response to these storms prior to our re-instrumentation of the sites is unknown, we suspect that sedimentation impacts were minimal because the storms were small or consisted of rain mixed with snow. By early November, measured precipitation was mostly accumulated snowfall and therefore unlikely to cause changes in streamflow or trigger significant sediment input into the network.

3. Post-fire monitoring methods

3.1. Flow, precipitation, and temperature

Post-fire flows and sediment transport were monitored at (i) the mouth of Boulder Creek (burned), (ii) upper Little Granite Creek (unburned), and (iii) Little Granite Creek above the confluence with Granite Creek (site of previous work) (Fig. 1). Site 3 is ~2.5 river miles (4 km) downstream of the burned area. The elevations of the monitoring sites are about 1980 m (6500 ft). Flow stage was measured at each site from about mid-April to November (or until the sites were no longer accessible) using automated stage recorders or pressure transducers. Frequent discharge measurements (>30 per season) were made using Price AA and mini-current meters at each location so that well-defined stage-discharge relationships could be established (Nolan and Shields, 2000) and shifts in the rating curves detected. Precipitation was monitored using tipping bucket rain gages (resolution 2 mm tips) between late spring and early fall at five locations in the watershed. Three buckets were located in the vicinity of the sediment sampling sites and two were located at higher elevations in Boulder Creek and Upper LGC (Fig. 1). Total rainfall accumulation and storm duration were derived from these records. Peak 30-min rainfall intensities (I_{30}) were calculated using the maximum amount of precipitation (i.e., steepest portion of the curve on a rainfall/time plot) falling over a 30-min period during individual storms.

3.2. Sediment

Samples of transported bedload were collected at the three sites using a thick-walled Helley-Smith bedload sampler with a 3×3 in. (0.076×0.076 m) opening (Helley and Smith, 1971). The sampler and sampling protocols are identical to those used for the pre-burn data, details of which are provided in Ryan and Emmett (2002). Rates of bedload transport were typically measured at each site once per day during snowmelt runoff. Samples of stream water were collected for suspended sediment concentration (SSC) using both ISCO™ automated amplers and DH-48 integrated depth samplers (FISP, 2000). The ISCO™ samplers were programmed to collect water once every 4 h between May and October in the first 2 years of study, yielding about 800 samples per site per year. Correlation between the ISCO™ samples and those obtained using the DH-48 samplers showed that the sample masses collected under concurrent conditions were comparable, indicating that the samples obtained from a single point (ISCO™) were representative of those measured using depth/width integrated methods (DH-48). SSC was determined from the entire sample volume which was usually 300 mL (Glysson and Gray, 2002).

Laboratory analyses for suspended sediment concentration were conducted in accordance with standard methods (NCASI, 1977). A portion of the samples collected in 2002 and 2003 were fractionated into coarse and fine portions using a wet sieving procedure, dividing at the sand-silt split (63 μm) (Guy, 1969). In 2002, about 375 samples (15% of total) were fractioned and in 2003, 210 samples (90% of total) were fractionated. Nearly all of the whole and fractioned samples collected in 2002 and 2003 were analyzed for organic matter content. This was determined by burning off the volatile carbon portion of the sample in a muffle furnace (1 h at 550 °C) and determining the change in weight after incineration. Though the divisions of suspended organic matter differ from that used in the ecological literature (Wallace et al., 1996), the method essentially separates small-to-large particles from the finer components. Suspended sediment concentrations and their subcomponents are expressed in mg L^{-1}.

While the monitoring program used in 2001 and 2002 provided a detailed record of suspended sediment concentrations and the use of automated samplers reduced the risk of missing critical events, the financial and logistical effort was difficult to sustain over time. In 2003, turbidity sensors [Optical Backscatter Sensors (OBS-3)] were deployed and periodic (approximately daily during peak runoff and weekly thereafter) grab samples were obtained to calibrate the signal from the sensors. Because turbidity values can be quite irregular over short timeframes, the median value of 25 instantaneous measurements was calculated and recorded every 5 min using Campbell CR-10x dataloggers (http://www.campbellsci.com/cr10x). Later, a 5-period moving average was used to further reduce noise in the turbidity signal, and regression relationships were developed using these smoothed turbidity values and measured SSC (Ryan et al., 2006). These relationship were typically quite strong (R^2>0.95) but varied over time from changing physical characteristics of the sediment (e.g., color, composition, size, and organic matter) that affect the optical qualities of the flow, requiring the continued collection of samples over time for recalibration purposes. Later in the season, turbidity threshold sampling (TTS) was used to reduce the number of samples and to overcome some of the calibration difficulties. TTS uses an interface with the turbidity sensor and programming of the automated samplers to collect samples once a preset turbidity threshold is exceeded (Eads and Lewis, 2002; Ryan et al., 2006).

Turbidity sensors and threshold sampling procedures permit more observations and improved inference of sediment patterns than traditional discrete sampling. However, greater uncertainty exists with values derived from a surrogate of suspended sediment concentration compared to measured values. For example, turbidity readings are sensitive to factors that may not be directly related to changes in SSC (Eads and Lewis, 2002). Moreover, biological growth can cloud the sensor and cause erratic turbidity readings and false triggering of the samplers. Although a concerted effort was made to clean the sensors regularly, regrowth often began within a day after cleaning. This was particularly problematic on the sensor deployed in Boulder Creek where only part of the turbidity record could be retained and substantial gaps in the data exist for the falling limb and baseflow due to unreliable readings (Ryan et al., 2006). More specifics on how the data limitations associated with the turbidity measurements were addressed for Boulder Creek are described in the analysis section.

4. Data analysis

4.1. Mean daily and annual flow

Mean daily discharge was determined by averaging 15-min flow estimates for each 24-h period. Stage recorders were operational only part of the year during post-fire years, requiring the estimation of flows for ungaged periods at Lower Little Granite in order to calculate annual flow for comparison with the pre-burn data. A regression model was developed using the available partial year record and data from a nearby gage (Greys River above reservoir near Alpine, WY) (USGS, 2007b). The model used to estimate flow for 2001 and 2002 is as follows:

$$Q_{lgc} = -10.82 + Q_{gr}0.075 \quad (1)$$

where Q_{lgc} is the mean daily discharge estimate for Little Granite Creek (in cfs) and Q_{gr} is the mean daily discharge (in cfs) from Greys River. The model was developed from 93 observations of mean daily discharge for both sites, $R^2 = 0.98$, and the standard error of the estimate is 0.953. A slightly different model was used for the 2003 data:

$$Q_{lgc} = -7.292 + Q_{gr}0.056 \quad (2)$$

This regression was developed from 52 observations, the $R^2 = 0.99$, and the standard error of the estimate is 1.60. Flow estimates derived from the regression equations were then used to calculate mean daily discharge for the data gaps, primarily during low flows in fall and winter.

4.2. Defining “hydrograph periods”

As is common in many small watersheds (Gomi et al., 2005; Reneau et al., 2007), suspended sediment records from Little Granite Creek show a seasonal hysteresis (Ryan and Dixon, 2008) whereby more sediment is carried on the rising limb of the hydrograph than on the falling limb even under comparable levels of flow. This necessitated comparison of pre- and post-fire values where SSCs were categorized by the hydrograph period during which they occurred. Hydrograph periods were defined by visual breaks in the annual hydrograph signifying changes in runoff patterns dominated by a set of hydrologic conditions. Typically, five flow hydrograph periods were identified each year. The *rising limb* begins at the first substantial increase following the winter/early spring season and continues to the onset of the annual snowmelt runoff. *Peak flow* is defined by a continuous period of high discharge associated with snowmelt, typically occurring over several days. The onset of the *falling limb* occurs with the first substantial drop in flow following the peak. *Baseflow* is defined at a break in the slope between steeper falling limb and flatter discharge occurring later in the season. *Storms* were delineated by “spikes” in discharge associated with rainfall during the falling limb and baseflow portions of the hydrograph. Storm spikes were determined only for the post-fire years.

Because the timing of runoff often differed between sites, the early portions of some hydrograph periods were missed. For example, runoff in Boulder Creek typically initiated before instrumentation was installed, so portions of the rising limb and sometimes the early peak flows were not included in the estimates of yield. For this reason, the seasonal yield for Boulder Creek is likely underestimated.

4.3. Mean daily, hydrograph period, and total sediment yields

Mean daily SSCs for the pre-burn period were estimated using regression models based on flow and periodic suspended sediment samples collected at the Lower LGC gage site between 1982 and 1993. The equation is the same as described in Ryan and Emmett (2002):

$$G_s = 0.0127Q^{1.59} \quad (3)$$

where G_s is the suspended sediment load (in tons day^{-1}) and Q is mean daily discharge (in cfs); this relationship was derived from 169 observations and the R^2 is 0.82. Mean daily SSCs for the post-fire period were estimated for Lower LGC from averages of the six daily samples or, where sediment data were missing, were estimated using regression equations based on discharge. These regression analyses used measured discharge and sediment concentrations for the hydrograph period from which the data were missing. Daily loads for both pre- and post-fire periods were calculated as the product of the estimated daily SSCs and mean daily flows. Annual and/or hydrograph period sediment yields were then determined from the sum of the daily estimates. Similar computations were made on post-fire data for Boulder Creek and Upper LGC using flow and sediment loads measured at the two sites, but only for the seasonal period of monitoring. No extrapolations of flow (as described in Section 4.1) were performed to obtain estimates of annual yield at these two sites.

4.4. Analysis of similarity in sediment concentrations (between years and hydrograph periods)

A series of Multi-Response Permutation Procedure (MRPP) statistical tests were run to determine similarity in sediment measurements both between years and between hydrograph periods. An MRPP is a nonparametric approach for testing for similarity between two or more groups (Mielke and Berry, 2001). The test statistics were computed from Euclidean distances among observations within each group and compared against cross group distances (or permutations). The null hypothesis is that observations among the designated groups are similar and this is assessed based on the proportion of permutations that produce a test statistic more extreme than the observed test statistic. Three statistical parameters are reported for each comparison. The first is the observed and expected deltas (δ), which are weighted means for the within-group distances (observed) and for the cross group distances (expected) and describes data dispersion in the respective groups. Smaller values of δ indicate tighter clustering within groups. The second statistic is an MRPP standardized test statistic (T) that describes the separation between groups. The more negative the T (the greater the magnitude), the greater the separation. The third statistic is a p-value. A sufficiently small p-value indicates when the null hypothesis of group similarity should be rejected (when $p < 0.05$).

5. Results

5.1. Precipitation and runoff patterns 3 years post-fire

Similar to areas throughout the western United States impacted by drought, precipitation and runoff at Little Granite Creek were relatively low in water years 2001–2003. Total annual flow from Little Granite is on average about 26 million m^3, (±10.3 million m^3 s.d.) (USGS National Water Information System, 2007a,b). Total annual flows estimated for the post-fire period were considerably lower, ranging from 15.0 million m^3 in 2001 to 17.8 million m^3 in 2003. Maximum snow water equivalent (SWE) from the nearby Granite Creek snow telemetry (snotel) site in 2001 was 29.0 cm (11.4 in.), the second lowest recorded at this station (Fig. 2) (Station ID: 10f29s, NRCS, 2008). In 2002, maximum SWE was 33.0 cm (13.0 in.), which is lower than both the overall mean (41.4 cm/16.3 in.) and median (38.4 cm/15.1 in.) maximum SWE. Snowpack in 2003 was the highest of the 3 years and the maximum SWE (38.6 cm/15.2 in.) was comparable to the median maximum SWE for the period of record.

In addition to low snowpack, temperatures were warmer than those from earlier records and rainfall was lower. Typically, rainfall measured at the Granite Creek snotel is relatively low during summer [202 mm ± 69 s.d. between May and September (8 in. ± 2.7 s.d.)]. Total summer rainfall in 2001–2003 was less than average, ranging from 137 mm (5.4 in.) in 2003 to 152 mm (6 in.) in 2001 (data not shown). Overall trends based on data from a long-term climate station in Jackson, WY (WRCC, 2007) and the Granite Creek snotel suggest that mean annual temperatures in the area have been warming since about 1995 (Fig. 3).

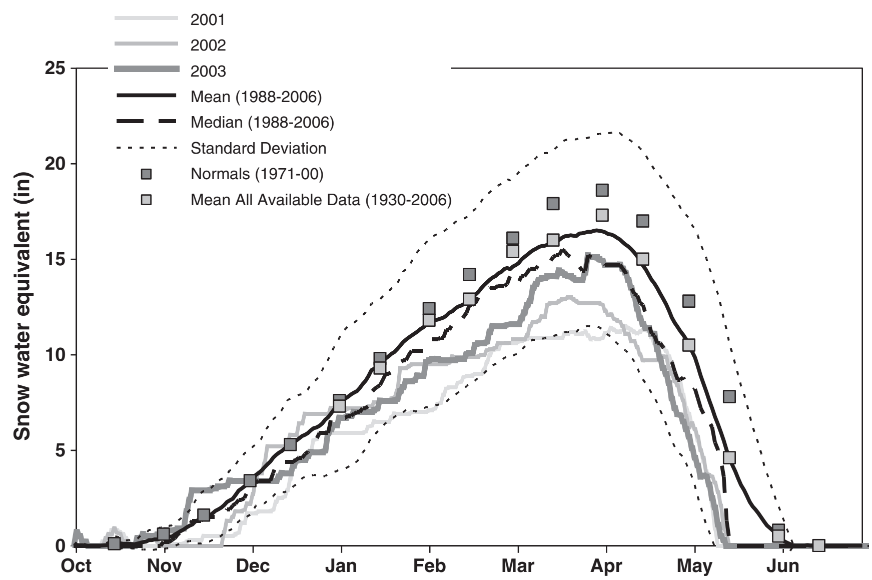


Fig. 2. Snow water equivalents measured at Granite Creek snotel site near Little Granite Creek watershed [snotel elevation 6770 ft (2063 m)]. Data source: NRCS, National Water and Climate Center (2008). Mean, median, and standard deviation calculated using daily observations for the period 1988 to 2006. Normals determined for the 1st and 15th of the month for the period 1971–2000 and "all available data" include additional measurements made intermittently on those dates between 1930 and 2000 (source: ftp://ftp.wcc.nrcs.usda.gov/data/snow/snow_course/wysnow.txt).

Bankfull (5.95 $m^3 s^{-1}$ or 210 cfs) and greater flows typically occur for one to two weeks during spring snowmelt at Little Granite Creek (Ryan and Emmett, 2002). However, out-of-bank flows were rare during the post-fire period and occurred on only 2 days during the entire 3-year period (see flows on Fig. 6, discussed in Section 5.2). In 2001, the highest flows were associated with a prolonged rainstorm during snowmelt in mid-May [between 33 and 39 mm (1.3 and 1.5 in.) of rainfall over a 31-h period]. In 2002, flows reached or exceeded bankfull at Lower LGC during the second of two small peaks in late May, but only for a few hours following a period of rapid warming. Flows on Boulder Creek peaked on 21 May, 10 days earlier than at either the Upper or Lower LGC (on 31 May) (data not shown). While the snowpack in 2003 was the highest of the 3 years, peak discharge at Lower LGC reached only 90% of bankfull. Rather than having one or two peaks, runoff exhibited a longer, more even day-to-day pattern, ranging from 70-90% of bankfull for 6 days. Flow peaked over a month earlier in Boulder Creek (24 April) than at either the Upper or Lower LGC (29 May) in 2003 (data not shown). Whether the earlier arrival of peak flow in 2002 and 2003 at Boulder Creek is from the influence of vegetation loss from burning is unknown. The snow pack in Boulder Creek may normally melt earlier because of its overall lower elevation relative to Upper LGC. The presence of two runoff peaks in the pre-fire gage record (Ryan and Emmett, 2002; Ryan and Dixon, 2008) suggests that an earlier melt in some portions of the watershed is not uncommon.

The number of summer rainfall events and amount of precipitation recorded often varied between gages, reflecting high spatial and temporal variability of rainfall characteristic of mountain watersheds. In 2001 there was an average of 48 discrete rainfall events for the five gages (between 1 June and 30 September), with an average of 28 storms lasting longer than 30 min (Fig. 4). Maximum rainfall intensities for durations of 30 min (I_{30}) ranged from <2 to 18.5 mm h^{-1}. The highest intensity was measured at the low elevation gage in Boulder Creek on 30 August while the basin average I_{30} for the five gages during this particular storm was 12.5 mm h^{-1}. Based on recurrence interval estimates for a 30-min rainfall (Miller et al., 1973; Arkell and Richards, 1986), this represents a relatively frequent storm that can be expected to occur annually (the 2-year, 30-min total rainfall was estimated to be roughly 20 mm). In 2002 an average of 44 discrete events occurred with 30 lasting longer than 30 min. The highest I_{30} was 13.7 mm h^{-1} measured at the low elevation site near the Upper LGC gage; the basin average I_{30} for this storm was 9.2 mm h^{-1}. In 2003 an average of 31 discrete events occurred with 22 lasting longer than 30 min. The maximum I_{30}, recorded at the high elevation gage in Upper LGC, was

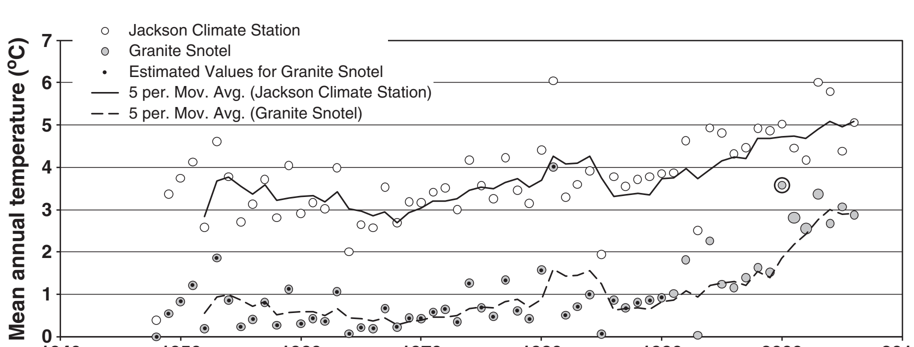


Fig. 3. Mean annual temperature recorded at Granite Creek snotel (1991–2006) and at a longer-term climate station in nearby Jackson, WY (1948–2006). Data shown for the snotel site between 1948 and 1990 are estimates based on a regression relationship between the two sites (R^2 = 0.40) and are shown to demonstrate *probable* trend in annual temperatures. The encircled point is the value for the year the wildfire burned in Boulder Creek watershed. Larger light gray circles are the years during which post-fire data were collected in this study.

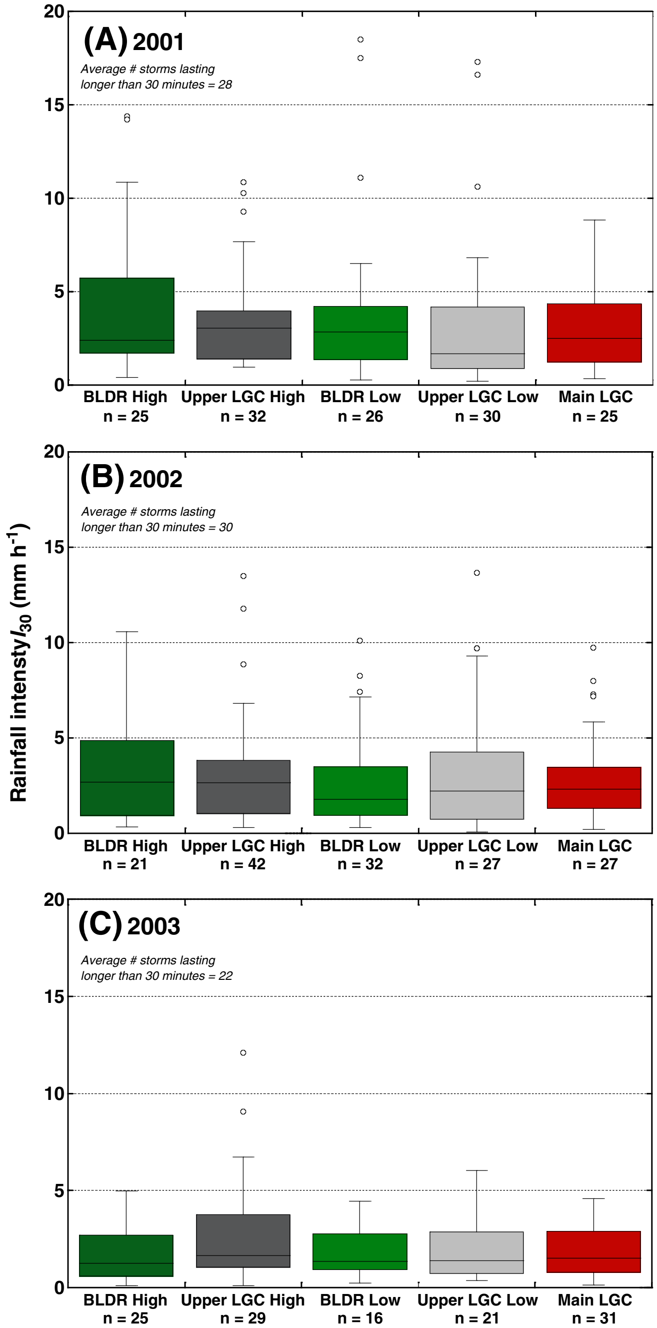


Fig. 4. Box plot distributions of 30-min maximum rainfall intensities (I_{30}) measured at five tipping bucket rain gages during spring and summer 2001–03 in Little Granite Creek watershed. The bars represent 25th and 75th percentiles and the median value. Lines represent the 10th and 90th percentiles. Circles represent outliers and the more substantial storms.

12.1 mm h^{-1} and was the only gage to register an I_{30}>10 mm h^{-1} during this year.

Recent studies have indicated that different rainfall intensities and durations may be associated with the onset of flooding and increased sediment from burned sites. For instance, storms generating maximum 30-min rainfall intensities >~10 mm h^{-1} resulted in significant increases in discharges from areas burned by wildfire in Colorado, South Dakota, and New Mexico (Moody and Martin, 2001b). In similar work, maximum 30-min rainfall intensities >~20 mm h^{-1} were associated with the onset of significant instream sedimentation (Cannon et al., 2001a, b). However, thresholds of rainfall intensities and durations associated with increased flows and postfire sedimentation are likely to vary with local conditions and include factors such as burn severity, soil type and conditions, hillslope and channel gradients, and the availability of material for entrainment (Cannon et al., 2008). It is therefore important to define specifically the intensity thresholds that may be operating in a specific area burned by wildfire.

In this study, a few storms had basin-averaged I_{30} values > 10 mm h^{-1} in 2001 and 2002, but most failed to produce substantial increases in the flow hydrograph (Fig. 5). Though no comparable measurements of site specific rainfall intensity are available for the pre-burn period, an evaluation of the available 15-min flow records from the former USGS stream gage showed no increases in flow > 0.70 m^3 s^{-1} (25 cfs) associated with rainfall runoff prior to burning (Fig. 5 inset). Hence, we use this value as a baseline for comparing post-fire increases in flow following summer storms. With the exception of one noteworthy rise in discharge, post-fire changes in summer flows did not exceed this pre-burn baseline. The one substantial change in discharge followed a series of storms on 13 September 2001 (basin average I_{30} of 4, 14, and 3 mm h^{-1}). Flow increased by 2 m^3 s^{-1} (70 cfs) at Lower LGC, which was 10 times the pre-storm baseflow level. The rapid rise took place over a 30-min period and subsided more gradually thereafter, returning to the pre-storm stage within 14 h (Fig. 6A, asterisk). The change in flow was more pronounced in Boulder Creek where discharge increased from 0.054 (2 cfs) to 3.3 m^3 s^{-1} (116 cfs), an almost sixtyfold increase within a period of 15 min (flow data not shown) and returned to pre-storm stage within 7 h. For comparison, flow increased by 0.14 m^3 s^{-1} (3.7 cfs) at the Upper LGC gage.

5.2. Changes in suspended sediment concentrations following wildfire

In contrast to post-fire flow responses, several substantial though short-lived increases in SSCs were observed relative to (i) concurrent observations with the control site (Fig. 6 and Table 2) and (ii) pre-burn measurements from Lower LGC (Fig. 7 and Table 3). The most pronounced increases occurred the first year post-fire during the rising limb and snowmelt runoff and during the more substantial storms (Figs. 6A and 7). On the rising limb, SSCs were about two to three times greater than that of the composite pre-burn period (Table 3, median post-burn/median pre-burn = 2.7, p < 0.001). During snowmelt, SSCs ranged from 300 to 5000 mg L^{-1}, which were about nine times greater than for a comparable level of flow for the pre-burn period (Table 3, p < 0.001). No significant differences were identified between pre- and post-burn SSCs on the falling limb of the seasonal hydrographs (Table 3, p = 0.296).

No comparable analysis was made for storm flows because data were lacking for the pre-burn period. However, the higher concentrations (outliers in Fig. 7) were several orders of magnitude greater than previously observed at relatively low discharges (between 5–20% bankfull) and are likely due to increases in sediment supply following fire. Yet, outside of these extreme values, SSCs during storms were not dissimilar between sites (Table 2, all 2001 storm p-values > 0.15) and most of the post-fire storm measurements were within the range of those measured on the falling limb/baseflow of the pre-burn period (Fig. 7).

While relatively short-lived, the larger sedimentation events in 2001 present the most substantial post-fire impact observed at Little Granite Creek. Sedimentation patterns exhibited during individual storms varied, with highest concentrations occurring later in the season. In mid-summer, during low to moderate intensity thunderstorms (<10 mm h^{-1}) when discharge increased by a negligible amount, SSC increased between one and two orders of magnitude (e.g., 24 June, Fig. 6A). Concentrations typically returned to pre-storm values within a few hours following these smaller events, characterized by higher concentrations of burned organic matter carried during low flows (herein referred to as "blackwater flows") (Fig. 8). In mid-to-late summer 2001, higher intensity rainstorms produced the largest SSCs measured post-fire. The first occurred on 8 July when a storm with a basin average I_{30} of 15 mm h^{-1} (at three

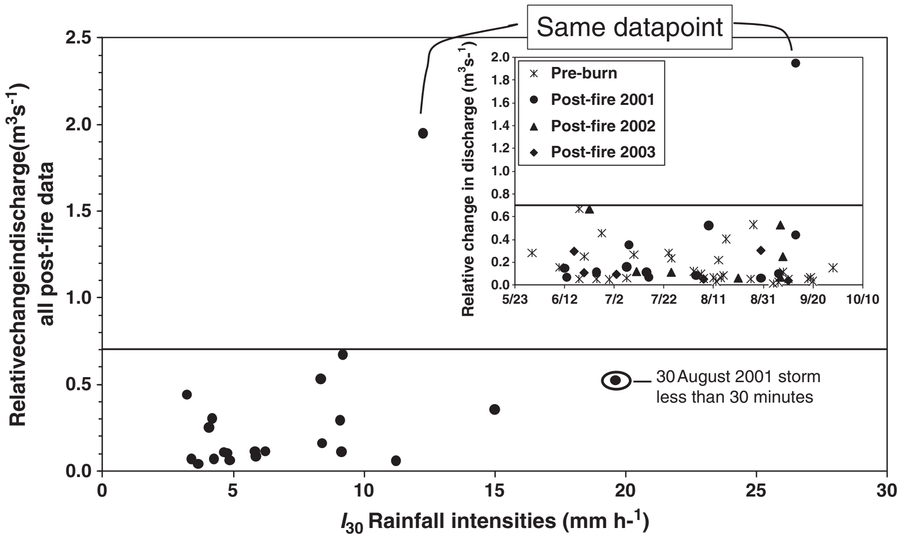


Fig. 5. Relationship between basin average I_{30} rainfall intensity and relative changes in streamflow measured at Lower Little Granite Creek gage. Inset graph shows relative changes in streamflow from summer precipitation available for pre- and post-fire years. In this system, summer storms rarely produce changes in streamflow > 0.7 $m^3\ s^{-1}$ (25 cfs), the level of which is indicated by the horizontal line.

gages) produced peak concentrations on the order of 17,000 mg L^{-1} at Lower LGC, 1600 mg L^{-1} at Boulder, and 50 mg L^{-1} at Upper LGC. Values returned to pre-storm concentrations after 2 weeks. The second spike occurred during the brief (<30 min, noted by light gray bar on Fig. 6A) but intense rainfall (average storm intensity at five gages was 19.6 mm h^{-1}) on 9 August. This storm lasted between 5 min (Boulder Creek, high elevation) and 19 min (Upper LGC, lower rain gage). Spatial storm intensity was likewise variable, ranging from 2.25 to 49.8 mm h^{-1}. Several fine-grained, organic-rich mudflows from steep, unchannelized swales within burned headwall areas were generated, the tracks of which could be traced overland across alluvial fans and denuded riparian areas and into the stream network. Peak concentration associated with this storm was 25,000 mg L^{-1} at Boulder Creek and 8000 mg L^{-1} at Lower LGC and measured concentrations returned to pre-storm values at both sites after a week. By comparison, measured SSC was 150 mg L^{-1} at Upper LGC, returning to pre-storm values within 8 h. The third increase in SSC occurred during the series of storms on 13 September described previously that caused the rapid rise in discharges at sites below the burn. Measured concentrations peaked at about 48,000 mg L^{-1} at Boulder Creek and 44,000 mg L^{-1} at Lower LGC following this storm. For comparison, peak concentration in the control watershed was 1300 mg L^{-1}, or about the same level typically observed during snowmelt runoff.

The general relationships between SSCs and flow in 2002 differed from 2001 as overall concentrations were not as high but were still elevated relative to the pre-burn period. The highest concentrations occurred primarily during snowmelt and were between 500 to 1500 mg L^{-1} on the first peak for all three sites (Fig. 6). Statistically, Upper and Lower LGC were similar for the two snowmelt peaks ($p = 0.34$ and 0.06, respectively), and both sites were significantly lower than Boulder Creek ($p < 0.011$) (Fig. 6 and Table 2). SSCs measured on the first peak of Lower LGC were about double those of the pre-burn period. They were, however, more comparable to (and slightly less than) the pre-burn period during the second peak (Table 3). SSCs on the falling limb were also comparable and slightly less than those measured during the pre-burn period. During summer, the most substantial rainstorms that caused a noticeable change in discharge occurred on 22 June (basin average $I_{30} = 9.2$ mm h^{-1}) and between 6 and 8 September (basin average I_{30} ranging from 0.75 to 8.4 mm h^{-1}). Measured SSC was about 5000 mg L^{-1} at the burned sites during the first storm and 1000 mg L^{-1} during the extended, low intensity storms in September (Fig. 6B). The MRPP indicated similarity in SSCs generated during storms in 2001 and 2002 ($p = 0.25$). This result is largely due to the very large delta (δ) values generated by the wide dispersion of storm data in 2001.

Sedimentation patterns in 2003 were more difficult to characterize because of missing or infrequently collected data on the rising and falling limbs and during baseflows. However, evidence suggests that the system continues to recover as the data that are available show concentrations either declining or remaining at about the same level as 2002 (Fig. 7). The few SSCs measured on the rising limb on Lower LGC were similar to pre-burn values and to both Upper LGC and Boulder Creek (Tables 2 and 3). During the peak, SSCs on Lower LGC were typically <1000 mg L^{-1} (excluding a brief spike) and <300 mg L^{-1} on the falling limb of the snowmelt hydrograph (Fig. 6C). During summer, several small thunderstorms occurred but none exceeded a basin average of 10 mm h^{-1} and the estimated SSCs were no greater than those measured for the pre-burn period at baseflow (Fig. 7).

5.3. Composition of suspended load

The organic and inorganic composition of the suspended loads in 2002 and 2003 varied between hydrograph periods, likely reflecting fluctuations in flow energy, sediment, and organic matter supply (Fig. 9). The hydrograph periods listed here are comparable to those described previously though more subcategories are used (i.e., individual storms are presented separately). Fine inorganic sediment (dark green bar) was the largest component of samples (50–60%) at nearly all flows, but comprised a larger percentage during storms when it ranged on average from 70–85% of the sample mass. More generally, the increase in SSC during storms came primarily from an increase in fine inorganic sediment and secondarily from an increase in (mostly fine) organic matter content. Transport of coarse sediment was restricted primarily to rising, peak, and falling limb of snowmelt where samples consisted of 25–35% sand (light green bar) and 5–10% coarse organic sediment (red bar). Because the storms in 2002 and 2003 were relatively small, the prevalence of finer sediment and more organic material suggests that source was from readily remobilized fines that had settled on the channel bed and/or from continued overland flow from burned surfaces. It also underscores the fact that these smaller blackwater flows were not particularly high energy.

The primary differences between samples collected at burned and unburned sites were that (i) total SSC was higher below the burned sites and (ii) the samples contained more organic matter, particularly those associated with the few storms. Total organic

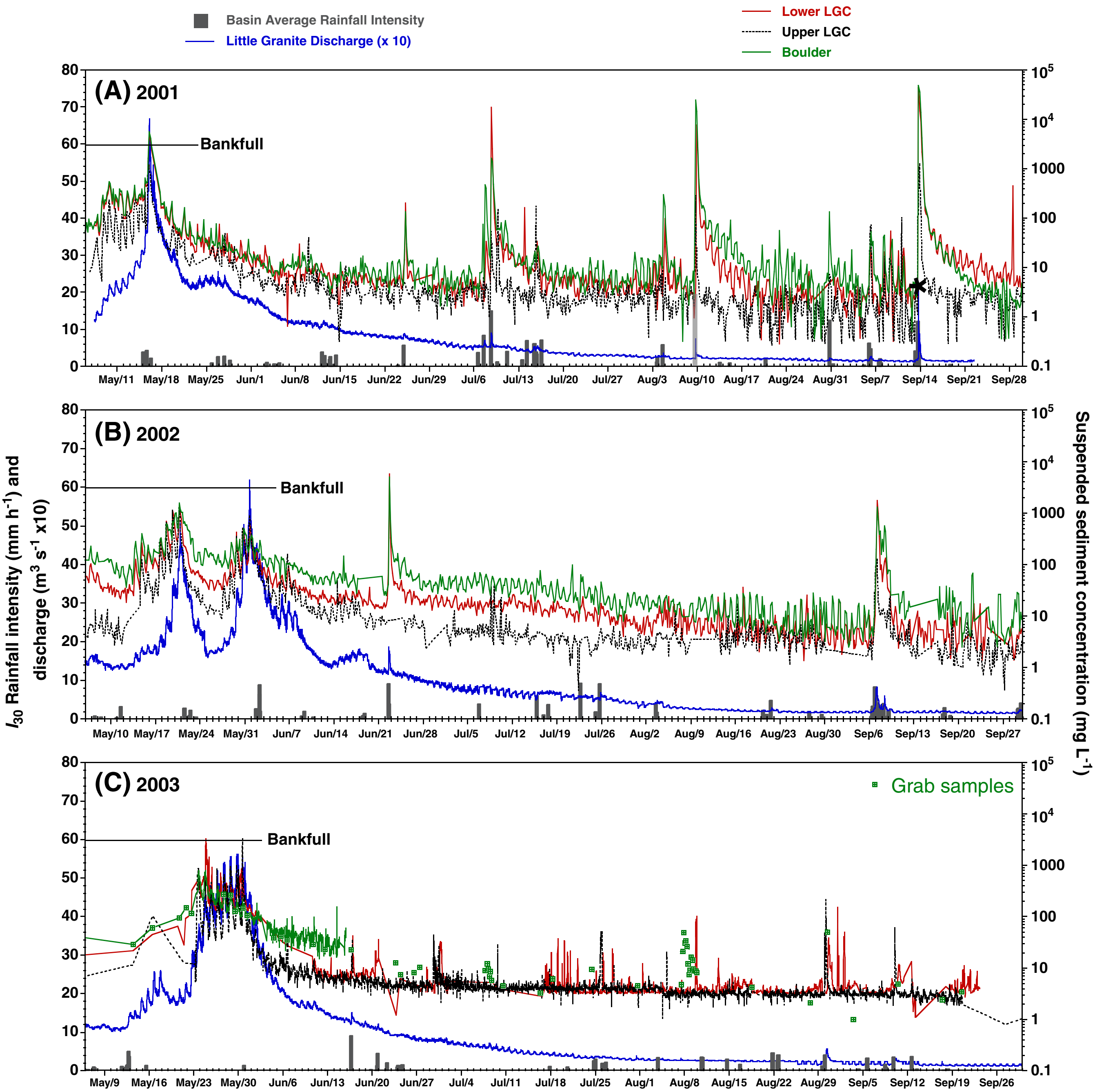


Fig. 6. Suspended sediment concentration measured or estimated for Lower and Upper Little Granite and Boulder Creeks in A) 2001, B) 2002, and C) 2003. Note that sediment data are plotted on a log-scale so that the wide range of values could be shown. This tends to exaggerate small variations in values at low concentrations and minimize large differences at high concentrations. Darker gray bars represent the basin-averaged I_{30} rainfall intensity. Light gray bar in (A) indicates basin average intensity for a storm on 9 August that was less than 30 min. Flow data for Lower Little Granite (blue line) are shown to demonstrate the overall pattern of snowmelt and storm discharges. However, the timing and magnitude of runoff events between the three sites often varied, particularly during snowmelt.

matter concentration was 1.5 to 2 times higher at Boulder Creek than Upper LGC during snowmelt runoff and between 10 and 100 times higher during the storms. Presumably, a substantial portion of the organic matter from Boulder Creek was composed of burned materials (charcoal and ash). Although no similar analyses was conducted for samples collected in 2001, visually, the dried samples retained from that year were considerably darker and contained small, visible pieces of charcoal, suggesting still higher concentrations of organic matter relative to samples collected in 2002 and 2003.

5.4. Seasonal suspended sediment yield at three sites

Comparisons of suspended sediment yield by season and hydrograph periods provide useful information on the relative contributions of sediment from the three sites. Data were normalized by basin area and truncated to similar timeframes for comparison purposes (typically mid-May to 30 September). In 2001, sediment exported from Boulder Creek was about 3.5 times greater than that exported from Upper LGC over the same time period (Fig. 10A). Over half of the difference in sediment yield at Boulder Creek (44 t km^{-2})

Table 2
MRPP results comparing suspended sediment concentrations at three sites in Little Granite Creek watershed by hydrograph period.

Year	Hydrograph period	Site	Comparison site	n	Median (mg L^{-1})	Median absolute deviation	Delta observed (δ)	Delta expected (δ)	MRPP standardized test statistic (T)	Probability of a smaller or equal delta	Reject similarity?
2001	Rising limb	Little Granite Cr		51	221	67.3					
		Boulder Creek		59	234	117					
		Upper Little Granite		47	61.4	38.6					
		Boulder Creek	vs. Little Granite				144	144	0.125	0.40	No
		Upper Little Granite	vs. Boulder Creek				124	153	−23.4	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				101	133	−27.5	<0.001	Yes
2001	Peak flow	Little Granite Cr		8	979	688					
		Boulder Creek		6	2170	1720					
		Upper Little Granite		16	90.1	50.1					
		Boulder Creek	vs. Little Granite				[a]–	–	–	0.72	No
		Upper Little Granite	vs. Boulder Creek				917	1280	−7.14	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				845	1050	−5.75	<0.001	Yes
2001	Falling limb	Little Granite Cr		115	21.3	10.5					
		Boulder Creek		156	18.0	9.71					
		Upper Little Granite		141	7.33	3.40					
		Boulder Creek	vs. Little Granite				37.6	37.6	0.313	0.48	No
		Upper Little Granite	vs. Boulder Creek				24.4	26.4	−28.9	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				1.94	2.18	−35.0	<0.001	Yes
2001	Baseflow	Little Granite Cr		465	4.26	1.50					
		Boulder Creek		529	6.07	2.33					
		Upper Little Granite		590	2.32	0.810					
		Boulder Creek	vs. Little Granite				5.76	5.96	−54.4	<0.001	Yes
		Upper Little Granite	vs. Boulder Creek				4.91	5.85	−277	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				2.67	3.01	−177	<0.001	Yes
2001	Storms	Little Granite Cr		132	20.5	9.68					
		Boulder Creek		111	49.6	30.6					
		Upper Little Granite		18	20.5	14.6					
		Boulder Creek	vs. Little Granite				2117	2120	−0.369	0.25	No
		Upper Little Granite	vs. Boulder Creek				2460	2470	−0.711	0.15	No
		Upper Little Granite	vs. Little Granite Cr				118	118	−0.336	0.20	No
2002	Falling limb	Little Granite Cr		27	93.9	26.0					
		Boulder Creek		37	237	113					
		Upper Little Granite		33	51.4	22.4					
		Boulder Creek	vs. Little Granite				166	207	−14.9	<0.001	Yes
		Upper Little Granite	vs. Boulder Creek				51.4	22.4	−18.4	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				80.9	85.8	−4.73	0.004	Yes

(continued on next page)

Table 2 (*continued*)

Year	Hydrograph period	Site	Comparison site	*n*	Median (mg L^{-1})	Median absolute deviation	Delta observed (δ)	Delta expected (δ)	MRPP standardized test statistic (T)	Probability of a smaller or equal delta	Reject similarity?
2002	Peak flow 1	Little Granite Cr		32	246	130					
		Boulder Creek		15	575	253					
		Upper Little Granite		19	140	77.7					
		Boulder Creek	vs. Little Granite				356	381	−3.60	0.01	Yes
		Upper Little Granite	vs. Boulder Creek				406	459	−4.45	0.01	Yes
		Upper Little Granite	vs. Little Granite Cr				348	349	−0.039	0.34	No
2002	Peak flow 2	Little Granite Cr		62	75.0	34.5					
		Boulder Creek		32	193	71.8					
		Upper Little Granite		41	119	67.9					
		Boulder Creek	vs. Little Granite				114	130	−13.3	<0.001	Yes
		Upper Little Granite	vs. Boulder Creek				165	172	−3.74	0.01	Yes
		Upper Little Granite	vs. Little Granite Cr				150	152	−1.80	0.06	No
2002	Falling limb	Little Granite Cr		196	19.0	3.28					
		Boulder Creek		209	47.8	11.9					
		Upper Little Granite		138	11.5	4.06					
		Boulder Creek	vs. Little Granite				17.4	26.2	−166	<0.001	Yes
		Upper Little Granite	vs. Boulder Creek				21.9	31.8	−133	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				9.20	10.3	−51.7	<0.001	Yes
2002	Baseflow	Little Granite Cr		422	6.50	2.90					
		Boulder Creek		380	13.0	6.48					
		Upper Little Granite		435	3.46	0.960					
		Boulder Creek	vs. Little Granite				8.07	9.00	−105	<0.001	Yes
		Upper Little Granite	vs. Boulder Creek				6.28	8.95	−283	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				0.311	0.371	−161	<0.001	Yes
2002	Storms	Little Granite Cr		41	39.6	17.8					
		Boulder Creek		47	85.6	38.1					
		Upper Little Granite		13	13.0	2.64					
		Boulder Creek	vs. Little Granite				427	429	−0.569	0.24	No
		Upper Little Granite	vs. Boulder Creek				319	335	−5.71	0.002	Yes
		Upper Little Granite	vs. Little Granite Cr				358	364	−1.70	0.07	[b]no
2003	Falling limb	Little Granite Cr		11	44.6	23.8					
		Boulder Creek		9	59.6	31.0					
		Upper Little Granite		8	12.6	7.60					
		Boulder Creek	vs. Little Granite				120	121	−0.267	0.32	No
		Upper Little Granite	vs. Boulder Creek				[a]–	–	–	0.04	Yes
		Upper Little Granite	vs. Little Granite Cr				[a]–	–	–	0.21	No
2003	Peak flow	Little Granite Cr		48	280	112					
		Boulder Creek		16	326	95.6					

Table 2 (*continued*)

Year	Hydrograph period	Site	Comparison site	*n*	Median (mg L^{-1})	Median absolute deviation	Delta observed (δ)	Delta expected (δ)	MRPP standardized test statistic (*T*)	Probability of a smaller or equal delta	Reject similarity?
2003	Peak flow	Upper Little Granite		50	111	51.9					
		Boulder Creek	vs. Little Granite				306	308	−0.807	0.16	No
		Upper Little Granite	vs. Boulder Creek				222	246	−7.05	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				292	308	−7.08	<0.001	Yes
2003	Falling limb	Little Granite Cr		40	7.73	1.31					
		Boulder Creek		58	111	74.8					
		Upper Little Granite		94	5.86	0.838					
		Boulder Creek	vs. Little Granite				69.9	85.6	−19.0	<0.001	Yes
		Upper Little Granite	vs. Boulder Creek				37.6	65.8	−65.1	<0.001	Yes
		Upper Little Granite	vs. Little Granite Cr				15.7	17.8	−15.6	<0.001	Yes
2003	[c]Baseflow	Little Granite Cr		286	3.74	0.441					
		Upper Little Granite		511	3.60	0.555					
		Upper Little Granite	vs. Little Granite Cr				1.51	1.55	−27.9	<0.001	Yes
2003	[c]Storms	Little Granite Cr		15	12.4	4.99					
		Upper Little Granite		38	21.1	11.3					
		Upper Little Granite	vs. Little Granite Cr				30.2	30.7	−1.25	0.11	No

[a] An MRPP exact test could be used rather than an estimation of the test statistic because of the low numbers of observations.
[b] Picked up only one storm in Upper Little Granite in 2002 compared two storms at other sites.
[c] Not enough data from Boulder Creek for testing baseflow and storms because of excessive instrument fouling.

was attributed to specific storms (24 t km^{-2}), rather than snowmelt. About the same amount of sediment per unit watershed area was exported from Boulder Creek as Lower LGC, with about 45% of the sediment load generated during snowmelt peak and about 35% generated during storms. Although the very highest SSCs were observed during storms (outliers on Fig. 7), they were relatively brief occurrences (Fig. 6) and the concurrent discharges were relatively low (typically <0.2 bankfull). Hence, yield estimates were

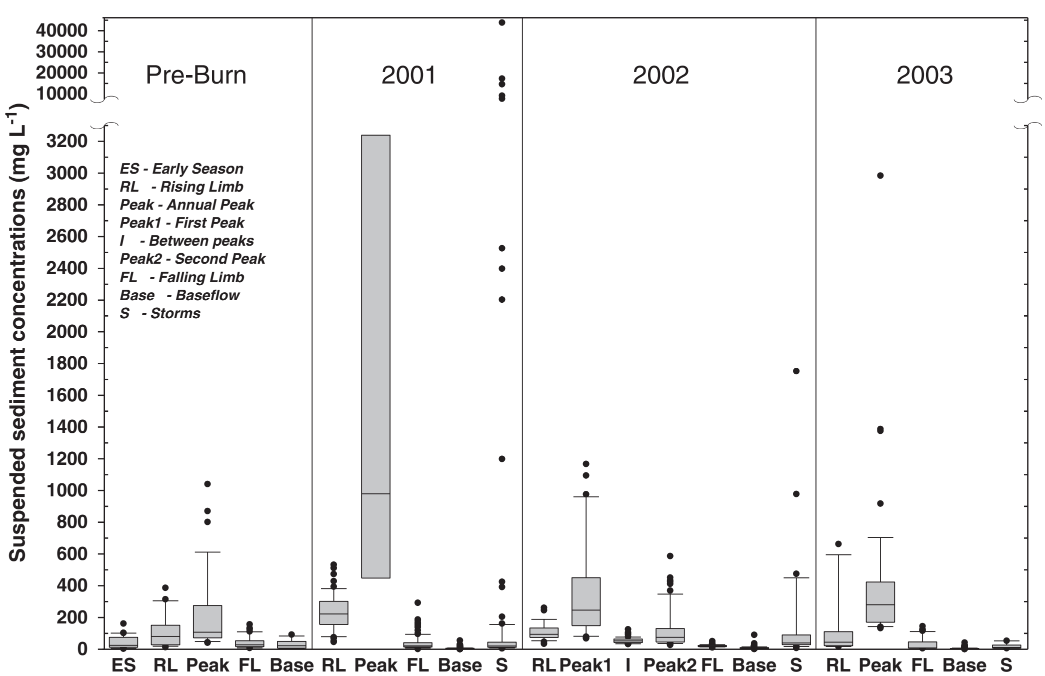


Fig. 7. Suspended sediment concentrations by hydrograph period compared with composite pre-burn values from the 1982–1993 period at Lower Little Granite Creek. The box represents the 25th to the75th percentiles while the 10th and 90th percentiles are presented as lines and caps. The horizontal line in the box is the median value. Outliers are depicted as black circles.

Table 3
MRPP results comparing suspended sediment concentrations before and after wildfire at Lower Little Granite Creek.

Pre-burn flow period (composite of data between 1992 and 1993)	Post-burn year and flow period	n	Median SSC (mg L^{-1})	Median absolute deviation	Median postburn/ median pre-burn	Delta observed (δ)	Delta expected (δ)	MRPP standardized test statistic (T)	Probability of a smaller or equal delta	Reject Similarity?
Early season baseflow		30	25	18	–	–	–	–	–	–
Pre-burn rising limb		23	81	54						
Pre-burn rising limb	vs. 2001 rising limb	51	222	67	2.7	118	138	−12.7	<0.001	Yes
Pre-burn rising limb	vs. 2002 rising limb	27	94	26	1.2	80.8	82.2	−1.11	0.121	No
Pre-burn rising limb	vs. 2003 rising limb	11	45	24	0.55[a]	129	127	0.742	0.779	No
Pre-burn peak runoff		34	107	52						
Pre-burn peak runoff	vs. 2001 peak flow	8	979	688	9.2	540	697	−12.1	<0.001	Yes
Pre-burn peak runoff	vs. 2002 peak flow 1	32	246	130	2.3	269	282	−3.35	0.014	Yes
Pre-burn peak runoff	vs. 2002 peak flow 2	62	75	34	0.70[a]	151	154	−2.24	0.040	Yes
Pre-burn peak runoff	vs. 2003 peak flow	32	280	112	2.6	295	313	−6.94	0.000	Yes
Pre-burn falling limb		44	28	17						
Pre-burn falling limb	vs. 2001 falling limb	115	21	11	0.77[a]	39.5	39.5	−0.15	0.296	No
Pre-burn falling limb	vs. 2002 falling limb	196	19	3.3	0.70[a]	12.3	13.9	−38.7	<0.001	Yes
Pre-burn falling limb	vs. 2003 falling limb	42	7.8	1.4	0.28[a]	39.3	41.0	−3.66	0.012	Yes
Pre-burn baseflow		15	22	17						
Pre-burn baseflow	vs. 2001 baseflow	465	4.3	1.5	0.19[a]	4.19	4.74	−80.6	<0.001	Yes
Pre-burn baseflow	vs. 2002 baseflow	422	6.5	2.9	0.30[a]	6.41	6.85	−37.7	<0.001	Yes
Pre-burn baseflow	vs. 2003 baseflow	310	3.7	0.44	0.17[a]	3.77	4.63	−79.6	<0.001	Yes
	2001 storms	132	20	9.7						
2001 storms	vs. 2002 storms	41	40	18	1.9	1270	1270	−0.336	0.250	No
2001 storms	vs. 2003 storms	15	12	5.0	0.60[a]	1370	1370	−0.575	0.146	No

[a] Ratios where the post-fire median is less than the pre-fire median.

not as substantial as might be expected for such extreme concentrations. While SSCs during snowmelt were elevated to a lesser extent, the discharges were greater and sustained for a longer period of time and so the total estimated yield for the entire hydrograph period was substantial.

In 2002, the majority of SS for all sites was generated on the rising limb and during snowmelt (Fig. 10B). Only one snowmelt peak was observed at Boulder Creek, with a rising limb that was sustained longer than those of the two snowmelt peaks measured at the other sites. This sustained rising limb appears to explain the higher sediment yields per

Fig. 8. Photograph of low flow carrying ash and small pieces of charcoal following a small summer thunderstorm in 2001. Normally, flows are clear and channel bottom is visible. These are referred to as blackwater flows in this paper.

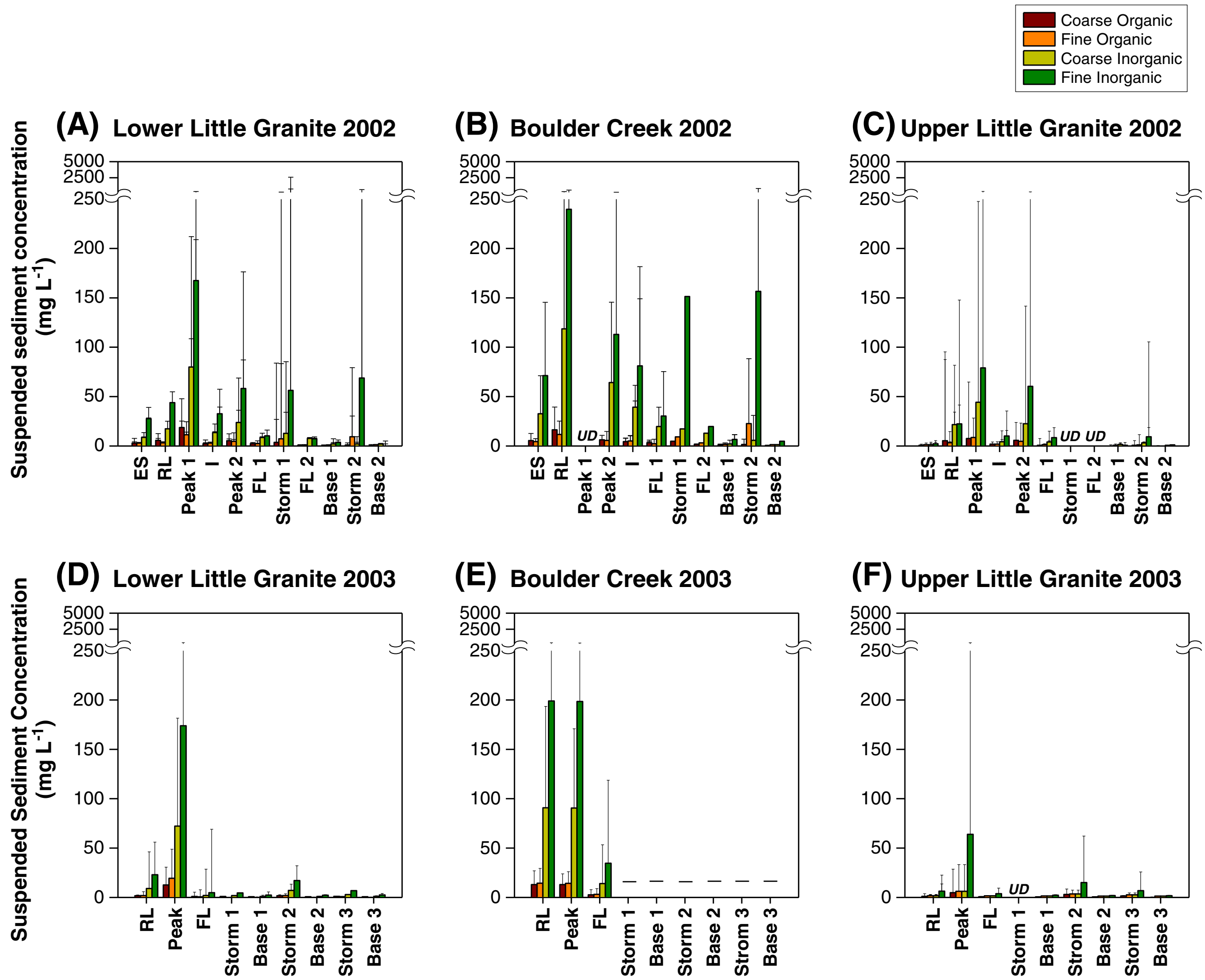


Fig. 9. Plots of four size/organic matter components measured at the three sites in 2002 and 2003. Column height represents median value for the hydrograph period. The lowest cap is the mean value and the highest cap is the 90th percentile. Columns replaced by "UD" indicate that the hydrograph period was undefined (that is, no change in the hydrograph or sediment record was observed). The symbol "-" in subplot E indicates data were insufficient for calculations. Abbreviations for hydrograph periods are as defined in Fig. 7.

unit area produced from Boulder Creek during the rising limb (red portion of bar, Fig. 10B). Concentrations remained elevated on the falling limb of the hydrograph at Boulder Creek and almost 20% of the total yield occurred during this period. The few storms that occurred were relatively small and with lower concentrations than observed in 2001. Storms accounted for only 6% of the total seasonal sediment at Boulder Creek and 11% at Lower LGC. The differences in sediment yield between Boulder and Lower LGC suggests the possibility that the main stem moved sediment during storms that had been stored during the recessional limb of the snowmelt hydrograph.

In 2003, seasonal sediment yields could only be calculated for Lower and Upper LGC because the flow and sediment records from Boulder Creek were inadequate for computing comparable estimates (Fig. 10C). Total sediment yields per unit watershed area between the Upper and Lower sites are similar, indicating that sedimentation is in decline as the system recovers from the effects of the burn upstream.

5.5. Annual suspended load and bedload

Bedload was measured only during the snowmelt runoff season when coarse sediment is most likely to be transported. Rates of bedload transport measured in 2001 and 2002 were similar to those measured before the fire, with all observations falling within the range of pre-burn values (data not shown here but are presented in Ryan and Emmett, 2002; Ryan and Dixon, 2008). When integrated over discharge, no detectable change in coarse sediment yield that would be attributed to changing sediment supplies from the burned area upstream was observed (Fig. 11). In contrast, estimated annual suspended sediment yields were substantially elevated relative to estimates derived for the pre-burn period. Total estimated suspended yield in 2001 was 61 t km^{-2}, which was 5.25 times higher than the predicted yield (11.6 t km^{-2}) for that amount of flow. Over time, total suspended yield decreased, becoming more comparable to that estimated for the pre-burn period. In 2002 and 2003, the total estimated yield was 24.6 and 28 t km^{-2}, respectively, both of which were about 1.7 times higher than that predicted given the relative discharge.

6. Discussion and conclusions

The magnitude of hydrologic and sedimentologic changes observed in watersheds following wildfire depend largely on the severity of the burn, landscape susceptibility to erosion, and the timing and magnitude of storms that follow the fire. In this study, increases in suspended sediment concentrations and sediment yields following a moderately sized wildfire were compared to sediment metrics obtained prior to burning and from a control watershed. Notably, the first three years post-fire were warm and dry, with low snowpacks in winter and only a few storms generated during the summers. Of the more substantial storms, only one was associated with a significant increase in stream discharge that exceeded a pre-burn baseline level of runoff response. The single event occurred

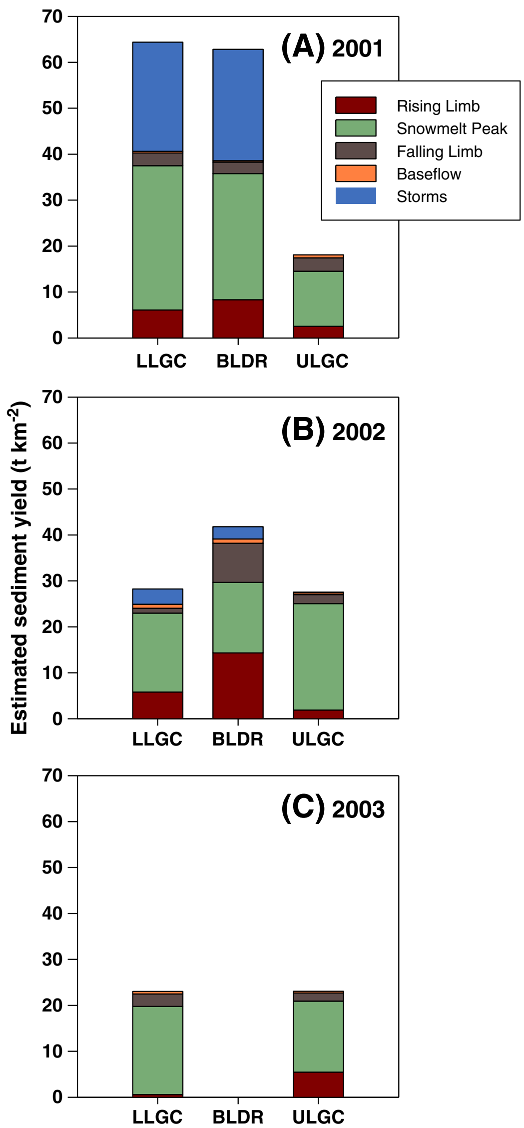


Fig. 10. Seasonal sediment yields separated by hydrograph periods in A) 2001, B) 2002, and C) 2003.

during a series of storms with an estimated recurrence frequency of less than 2 years.

In contrast to post-fire flow responses, several substantial, though short-lived, spikes in suspended sediment concentration were measured below the burned area. The most pronounced increases were observed the first year post-fire during rainstorms and, to a lesser extent, during the rising limb of the annual hydrograph and snowmelt runoff. Concentrations were nine times greater than those measured prior to the burn during peak runoff and several orders of magnitude greater during summer flows. The possibility exists that the pre-burn values fail to adequately represent the baseline conditions at Little Granite Creek in that higher SSCs may have occurred Pre-burn and have gone unmeasured as lower flows and concentrations tend to be overrepresented in these types of records (Thomas, 1988). However, it is unlikely that pre-burn SSCs reached levels measured in Lower LGC at relatively low discharges (less than one-half bankfull) without a substantial change in sediment supply to the system. Therefore, the baseline data are probably a reasonable representation of the range of conditions commonly encountered in this watershed under the typical supply of sediment.

Over time, the magnitude of spikes in SSC declined (2002 and 2003), presumably because of the combined influence of lower intensity storms and changing sediment availability as portions of the burned landscape stabilized, as described by Scott (1993). Regrowth of riparian vegetation, while sparse in the first year post-fire, increased substantially during the second and third years and appeared to be intercepting shallow sediment flows from hillslopes in some locations. By the third year, cover of clonal shrubs (*Ribes lacustre, Rosa woodsii, Spiraea betulifolia*) had increased by over 60% (Dwire et al., 2006), further reducing the pathways by which sediment entered the stream system.

The composition of suspended sediment samples varied between snowmelt runoff and rainfall-triggered events in 2002 and 2003, reflecting overall differences in flow energy and sediment supply. Samples collected below the burned sites during snowmelt runoff contained more sand and larger organic matter, indicative of higher, sustained discharges. In contrast, samples collected during storms contained primarily ash and silt-to-clay sized particles, suggesting lower energy flows. There were also between-site differences in organic matter concentrations, presumably due to the relative contributions of burned organic material. Values were 1.5 to 2 times higher during snowmelt runoff and between 10 and 100 times higher during storms at Boulder Creek compared to Upper LGC. While no similar analyses were performed on samples collected in 2001, these

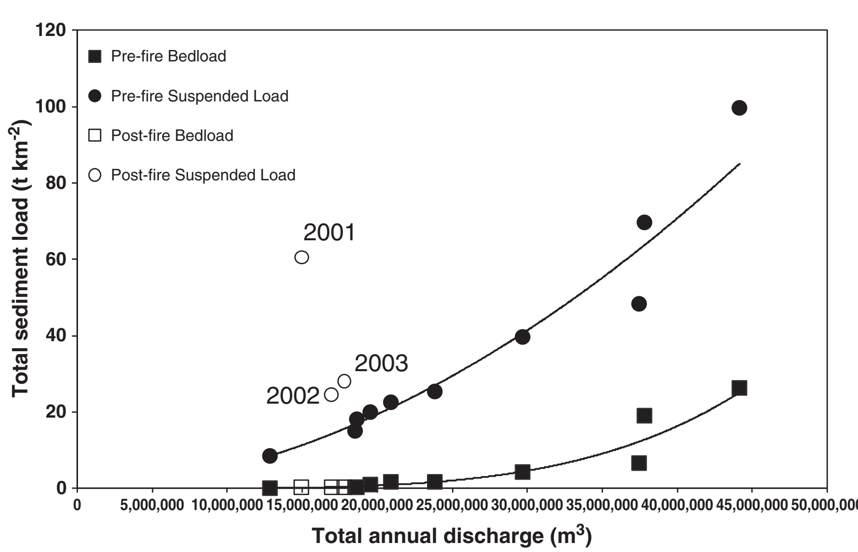


Fig. 11. Annual sediment loads (suspended load and bedload) estimated for pre-burn and post-burn periods. Lines are fit only to pre-burn data.

appeared to contain a relatively high amount of sand and coarse organic material, particularly during the 9/13/01 storm that generated a significant increase in discharge. Speculatively, the load of burned organic matter that washed through the channel network during the first year post-fire was more substantial than the concentrations from the subsequent years, which likely represent declining trends. A notable lack of coarse sediment in the storm samples in the two later years underscores the fact that they were not particularly high energy.

Despite relatively low flows over much of the runoff season, the estimated suspended sediment yield in the first post-fire year was about five times greater than that predicted for comparable annual flows for the pre-burn period. More of the total sediment load was exported during snowmelt runoff (54%) than during summer storms (44%). In 2002, SSCs were still elevated, but by 2003 they were beginning to return to levels observed in the unburned watersheds and during the pre-burn period. Over time, storms contributed less sediment to the overall budget (11% in 2002 and 1% in 2003). This observation concurs with others who have found that erosion impacts are greatest in the first year post-fire and steadily decline over the next few years, returning to baseline values within three to five years (e.g., Ewing, 1996; Robichaud et al., 2000; Moody and Martin, 2001a). Notably, no discernable change in coarse sediment moved as bedload was observed in this study. This is not entirely unexpected because no obvious new sources of coarse sediment were introduced as would be evidenced by an increase in the number of landslides or widespread channel incision or bank erosion. In short, the processes that led to substantial increases in suspended sediment concentration did not appear to be particularly erosive in channels. Observed sources of sediment were primarily from organic rich surficial materials moved presumably during overland flow without widespread channel incision. Moreover, it could take years for any new coarse sediment that may have been introduced in the upper basin to reach the areas where bedload was measured.

The results from the post-fire monitoring at Little Granite Creek lacked some of the more spectacular post-fire responses that have been reported in other studies in recently burned watersheds (Meyer and Wells, 1997; Cannon et al., 2001a,b; Gabet and Bookter, 2008; Moody and Martin, 2001a, among many others). Generally, there is a continuum of responses that have been recognized in watersheds following fire, ranging from 1) only moderate increases in runoff, to 2) increased runoff with a moderate increase in sediment, to 3) substantial flooding and sediment movement, to 4) significant flooding, widespread debris flows and channel incision and aggradation. Previous work has also demonstrated that frequently occurring rainfall intensities (2–10 year return interval) are capable of generating debris flows from burned areas (e.g., Cannon et al., 2008). In the Little Granite watershed, a few higher intensity storms occurred, but these were not outside of the range that frequently occur in the region (1–2 year return frequency) and they did not appeared to trigger a substantial sedimentation response beyond the first year. Moreover, while blackwater and sediment laden flows were observed, there was no physical evidence of debris flows (as would be identified by channel incision into previously unchanneled areas) observed during areal reconnaissance following these storms. While there are many landslides that have been mapped in the watershed and high pre-burn sediment loads suggest active mass wasting processes, the lack of physical evidence suggests that the types of mass wasting processes and watershed conditions within the burned area were not particularly conducive to the generation of debris-flows. Flow and sedimentation patterns demonstrated here may be typical of those observed during times of continued drought and in the absence of widespread, significant rainfall (e.g., Petticrew et al., 2006).

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