

15

Spatial and temporal variability in stream sediment loads using examples from the Gros Ventre Range, Wyoming, USA

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Abstract

Sediment transport rates (dissolved, suspended, and bedload) measured over the course of several years are reported for two streams in the Gros Ventre Mountain range in western Wyoming, USA: Little Granite and Cache Creeks. Both streams drain watersheds that are in relatively pristine environments. The sites are about 20 km apart, have runoff dominated by snowmelt and are underlain by a similar geological setting, suggesting that sediment supply and rates of transport in the two watersheds may be comparable. Yet, estimated sediment yields for the two sites appear substantially different. On average, sediment load per unit watershed area was about 40% greater at Little Granite Creek than Cache Creek, with larger differences during wetter years. Moreover, while there were differences for all components of the sediment load, suspended, and bedload fractions showed the most noteworthy contrast where nearly three times more material was exported from Little Granite Creek on an annual basis. Speculatively, this is attributed to contributions of sediment from several chronic sources in the Little Granite Creek watershed.

Similar to other studies of sediment transport in gravel-bed streams, the range of measured bedload and suspended sediment in this study were quite variable. An assessment of annual differences in the 13 years of bedload record for Little Granite Creek indicated that variability could not be ascribed to between-year differences. Instead, the data appear to represent the same population of highly variable transport rates. However, the inability to distinguish between years could be due to the infrequency with which data were collected each year. Seasonal variability was evident in the suspended sediment record of Little Granite Creek where there were higher rates on the rising limb of the snowmelt hydrograph, indicative of a flushing of sediment with the onset of snowmelt.

Baseline data on rates of sediment transport provide useful information on the inherent variability of stream processes and may be used to assess departure due to natural or anthropogenic disturbances. In August 2000, wildfire burned portions of

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the Little Granite Creek watershed, presenting an opportunity to quantify increases in sediment loads associated with large-scale disturbance. The results of 3 years of post-fire monitoring showed substantial increases in suspended sediment transport on the rising limb of the snowmelt hydrograph and during several summer thunderstorms. Suspended sediment yields calculated for the post-fire years were higher for the first year and have decreased over time, indicating a return to baseline levels within a few years following the wildfire. In contrast, there were no detectable increases in the rate of bedload transport over the pre-burn values suggesting differences in the rapidity with which the two sediment components respond to disturbance.

1. Introduction

A primary difficulty in generalizing sediment transport processes in mountain streams involves accounting for spatial and temporal variability in sediment supply common to these systems. On a large scale, both sediment supply and stream sediment loads in upland watersheds are influenced by a number of factors, including topography, geology, vegetation, land management, and natural disturbances (Walling, 1988). Given this, similarities in rates and processes might be inferred across regions influenced by similar geologic and climatic factors. Yet, while similarities in processes for streams draining the same geographic region often occur, interactions occurring at smaller scales may well create conditions unique to an individual watershed (Walling and Webb, 1982). In complex terrain, there are often large differences in lithology, hillslope processes, and erosion rates occurring over short distances, even within the same watershed, that can affect sediment transport processes in channels downstream.

Total sediment export from a watershed occurs as dissolved load, in suspension, and as bedload. Much of the attention on sediment loads in channels draining steep-land environments is given to coarse sediment that is transported sporadically along the channel bottom as bedload (Ryan and Dixon, 2002). This emphasis is given because coarse sediment comprises the lag deposit in which the channel conduit is formed and is the template for many aquatic functions. The cutoff between sediment moved as bedload and suspended load is somewhat arbitrary and overlapping. Depending on current velocity and turbulence, sediment sizes moved as bedload under moderate flow may be moved in suspension during increased discharge. Though arguably the processes are related, the two components are treated separately based on the differing methods used to collect suspended or bedload materials. Moreover, dissolved and suspended loads often comprise a greater proportion of the total sediment load of steep-land streams (Dietrich and Dunne, 1978; Alvera and Garcia-Ruiz, 2000). While less important in forming the physical structure of coarse-grained channels (Parker, 1978a,b), suspended and dissolved loads have biological significance (Wohl, 2000). For instance, suspended sediment concentration (SSC) affects light available for photosynthesis in aquatic plants and excessive infiltration of fines into the channel substrate poses hazards to fish and macroinvertebrates in hyporheic environments (Waters, 1995). Hence, all three components should be addressed in assessing sedimentation effects on channel form and aquatic function.

In order to gain improved understanding of stream processes and baseline sediment yields, a series of field studies were carried out in two watersheds near Jackson, Wyoming, USA. The original intent of the studies varied, but the result was a compilation of an extensive database on dissolved, suspended, and bedload transport rates that can be used to develop estimates of sediment yield with a relatively high level of confidence. Little Granite Creek and Cache Creek are both located in the Gros Ventre Mountain range near Jackson Hole and are upland contributors to the Snake River. The geology of the Gros Ventre range consists primarily of Paleozoic and Mesozoic sedimentary rock formations, many of marine origin. The formations are deformed and largely unstable; parts of the Gros Ventre range are characterized by some of the highest densities of landslides in the United States ([Wyoming State Geological Survey, 2001](#)). The area is also influenced by active faulting and a relatively high risk of earthquakes. Hence, sediment delivery to stream systems from an unstable landscape is comparatively high for many of the watersheds in this area. However, despite landscape scale similarities common to the Gros Ventre range, there are substantial differences in measured sediment loads from the Little Granite and Cache Creek watersheds, suggesting variation in sediment delivery and transport within a province of complex terrain.

The overall goal of this paper is to compare and contrast sediment loads from two proximal watersheds in an effort to elucidate processes occurring at local scales and the factors that control them. Specifically, three topic areas are addressed in this paper. First, the rating curves developed for each of the three sediment components are presented and the records are assessed for annual and seasonal variations. Second, estimates of annual sediment yield are compared and differences are tentatively linked to overall patterns of mass wasting in the two watersheds. Third, the effects of disturbance on the rates and patterns of instream sedimentation are evaluated for the Little Granite Creek watershed, portions of which were burned by wildfire in August 2000.

2. Study sites

Little Granite Creek and Cache Creek are two small mountain watersheds located on the Bridger-Teton National Forest ([Fig. 15.1](#)). Cache Creek drains a 27.5 km² area of steep terrain and inner gorges largely under mixed subalpine forest and meadow vegetation cover. Elevations range from 2057 m at the gauge site to 3141 m at Cache Peak. The basin is a long, oblique shaped watershed, oriented in a northwest direction. The Cache Creek site is at a United States Geological Survey (USGS) gauge (13018300) and is part of the Hydrologic Benchmark Network (HBN) established by the USGS in 1958. The original goal of the HBN program was to establish a network of gauges located at pristine sites to provide a baseline against which the influence of environmental factors on streamflow and water chemistry could be evaluated ([Cobb and Biesecker, 1971](#)). The program was active for over 30 years at some locations. The USGS established the recording gauge station at Cache Creek in 1963 and the gauge has been in continuous operation since then. Water quality monitoring, initiated in 1965, was discontinued at Cache Creek in 1995 due to declining funding. During the

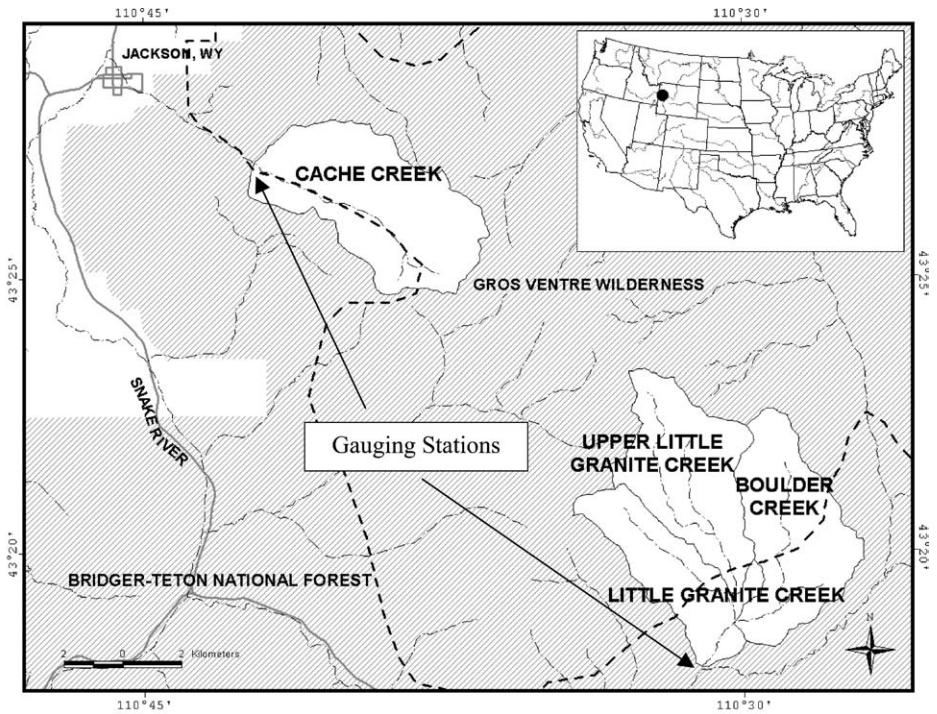


Figure 15.1. Location of Cache and Little Granite Creek watersheds in western Wyoming, USA. Dark dashed line indicates boundary of the Gros Ventre Wilderness area located to the north of the line. Stipple pattern indicates area administered by the Bridger-Teton National Forest.

active period, some water quality measurements were taken on a monthly basis while others were taken bi-monthly, semi-annually, or annually.

Little Granite Creek drains a 54.6 km² area near the site of a former USGS gauging station (13019438) that was active between 1982 and 1993. The sediment sampling program at this site began in 1982 as part of environmental monitoring in conjunction with planned exploration and extraction of fossil fuels in the upper basin. Though the exploratory effort was eventually abandoned, sediment monitoring was continued by the USGS through 1993. The database was expanded when additional bedload samples were collected by US Forest Service (USFS) personnel during high flow in 1997 (Ryan and Emmett, 2002). Basin elevation ranges from 3329 m at an unnamed high point to 1948 m at the confluence of Little Granite and Granite Creeks. The basin is rounded in shape and much of the valley area upstream of the sampling site is characterized by relatively open valley bottoms with mixed subalpine forest and meadow vegetative cover. The watershed is oriented toward the south to southeast. Upper Little Granite and Boulder Creeks, primary tributaries to Little Granite Creek also discussed in this paper, drain 19.7 and 20.7 km² areas, respectively (Fig. 15.1). Boulder Creek was burned in August 2000 and Upper Little Granite Creek served as a control watershed in a study on the effects wildfire on stream sedimentation (Ryan et al., 2003).

2.1. *Geology*

The geology of the Cache Creek basin is varied but consists primarily (60%) of deformed sedimentary rock formations ranging in age from Paleozoic to Cretaceous including: limestone, dolomite, shale, siltstone, sandstone (Love and Christiansen, 1985). Pleistocene or Pliocene conglomerates (15%) are also present and include clasts of limestone in a partially lithified carbonate matrix. The main channel cuts through this unit in a narrow inner gorge above the gauging station. Unconsolidated units, consisting of alluvium, colluvium, Quaternary landslide debris, and a large slump block, make up about 23% of the surficial area. A small portion of upper Cache Creek was glaciated and these surfaces are largely stabilized by alpine meadow and lodgepole/subalpine forest cover.

The geology underlying Little Granite Creek is also varied and composed primarily of deformed sedimentary rocks of Cretaceous and Tertiary age, including conglomerate, sandstone, claystone, and limestone (Love and Christiansen, 1985). The upper portion of the basin was glaciated and is mantled by till and glacial outwash, likely correlative of Bull Lake and Pinedale aged deposits (as generalized in Leopold and Emmett, 1997). At high elevations, these surfaces are largely devoid of vegetation cover and actively contribute sediment to the channels, particularly during snowmelt runoff.

Primary sources of sediment at both sites are from mass wasting, including active earthflows from unstable hillslopes and slumping from undercut terraces and road cuts. Scour from the channel bed and banks also contribute substantially to the sediment load. However, the type of landslides and recency of movement are quite different in the two watersheds, with substantially more active instabilities occurring in Little Granite Creek. Areas affected by landslides were identified using landslide maps generated by the Wyoming State Geological Survey (2004) overlain on topographic coverage. Relative activity and type of slide was further delineated using aerial photography of the watersheds taken in 1994 and 2001 and through field reconnaissance in 2004.

2.2. *Climate*

While no permanent climatic station exists within either watershed, there are three stations in the vicinity from which climatic conditions may be inferred. These include a station in the town of Jackson (elevation 1900 m), the Granite Creek automated SNOTEL (snow telemetry) station (elevation of 2063 m), and the Phillips Bench SNOTEL (elevation 2500 m) (Western Regional Climate Center, 2003). Snow cover is typically present at all stations between November and March. Precipitation at the lower station averages 400 mm per year and is fairly well-distributed between seasons. Mean annual precipitation at the middle elevation is about 800 mm annually, with the majority of precipitation occurring between November and January in the form of snow. Mean annual precipitation at the higher elevation is about 1120 mm annually, with snow accumulating between November and May. The mean annual temperature at the Jackson site is 3.3°C, 1.5°C at the Granite Creek site and 1.3°C at the Phillips Bench site.

2.3. *Runoff patterns*

Runoff at both sites is generated primarily by the melting of snow in the spring, with peak flows occurring between mid-May and mid-June. Flow typically peaks earlier in the year at Little Granite Creek (late May) than at Cache Creek (early June) due to the differences in aspects between the watersheds. While thunderstorms are common in the summer, they typically produce only small rises in the hydrograph. The 1.5-year return interval flow (a surrogate for the bankfull discharge) at Cache Creek is $1.7 \text{ m}^3 \text{ s}^{-1}$, as estimated using Log Pearson III analysis on the annual maximum flood series for the period 1962–1998 (US Interagency Advisory Committee on Water Data, 1982). The 95% confidence limits on this estimate are 1.44 and $1.97 \text{ m}^3 \text{ s}^{-1}$. The calculated 1.5-year return interval flow at Little Granite is $5.95 \text{ m}^3 \text{ s}^{-1}$ and the 95% confidence limits on this estimate are 3.71 and $8.38 \text{ m}^3 \text{ s}^{-1}$. The confidence bands on the estimates are relatively wide due to uncertainty associated with a limited (10 years) record of flow (Linsley et al., 1975).

2.4. *Land use*

The primary former land use in Cache Creek consisted of two small coal mines that provided coal for local needs; these were abandoned in the 1930s. Small-scale logging and grazing by cattle also occurred prior to 1940 (Clark et al., 2000) but the basin was closed to these activities to protect the primary water supply to the town of Jackson. The upper basin is in a wilderness area (Fig. 15.1) and is nearly pristine. Outside of the wilderness boundary, an old roadbed follows the course of Cache Creek approximately 4.5 km upstream from the gauging station. Though closed to motorized traffic beginning in the 1960s, the roadway and trail network is very heavily used for summer and winter recreation. At a few locations, the eroding roadbed impinges on the stream channel and contributes sediment to Cache Creek, though these sources tend to be small.

Upland land uses in Little Granite Creek include cattle grazing for a few months in summer and dispersed recreation (camping, hiking, horseback riding, and hunting). A gravel access road parallels the stream for about 2.4 km in the lower end of the watershed and this is undercut by the stream channel at several places. Former land uses include coal extraction and mining camps in the valley near upper Little Granite Creek. These former and present uses are small in scale and their influence on sediment delivered to the channel are relatively nominal, though the influence of the mining camps may have been more substantial when they were active.

2.5. *Sediment monitoring sites*

The channel near the Cache Creek site is single thread, stable, and incised into terraces. The area of the floodplain is small and discontinuous. The active channel width ranges from 5 to 7 m and mean depth at bankfull stage is 0.40 m. Water surface slope at bankfull in the vicinity of the gauge is 0.024. The bed surface consists primarily of cobbles and coarse gravel with a few concentrations of boulders; D_{16} is 10 mm, D_{50} is

45 mm, and D_{84} is 115 mm. In the subsurface, D_{16} is 4 mm, D_{50} is 20 mm, and D_{84} is 58 mm. The channel form alternates between areas of irregularly spaced step-pools to plane-bed morphology (as defined by [Montgomery and Buffington, 1997](#)). Riparian vegetation in the vicinity of the stream consists of willows and a sedge/grass mixture with some coniferous trees. The valley bottom is densely forested by Douglas Fir.

The channel in the vicinity of the Little Granite Creek study site is also single thread and plane bed, with slight sinuosity. Channel width and mean depth at bankfull are 9.8 and 0.43 m, respectively. Mean water surface slope at bankfull flow is 0.020. Bed material at the surface ranges from gravel to small boulders; D_{16} is 24 mm, D_{50} is 90 mm, and D_{84} is 208 mm. In the subsurface, D_{16} is 2.5 mm, D_{50} is 17 mm, and D_{84} is 41 mm. Channel banks are largely stable and densely vegetated by willow and lodgepole pine.

3. Methods

3.1. Bedload measurements

Samples of bedload were collected using a pressure-difference bedload sampler ([Helley and Smith, 1971](#)). The body of the sampler is constructed of 1/4-inch thick cast aluminum with an expansion ratio of 3.22 and fitted with a catch bag of 0.25 mm nylon mesh. The orifice through which bedload passes is 76 mm $\times$ 76 mm so the sampler is capable of capturing grain sizes up to small cobble. The same type of sampler was used to collect bedload at both sites. The Helley–Smith sampler has a high trapping efficiency for the predominant range of bedload moved in the two watersheds ([Emmett, 1980](#)) and has been used successfully to predict total bedload yield from other small mountain streams ([Ryan and Porth, 1999](#)). Bedload was sampled using the single equal width increment (SEWI) method ([Edwards and Glysson, 1998](#)), which involves placing the sampler at equally spaced positions (about 0.5 m apart) along a cross-sectional transect. Typically, two complete traverses of the channel are made and all materials collected from both traverses are combined into a single sample that represents a spatially and temporally averaged rate of transport. The samples were oven dried and sieved using standard methods for grain size analysis ([Folk, 1968](#)). Rates of transport were calculated using the total mass of the sample divided by the total sampling time and by the width of the sampler to obtain the unit bedload transport rate ($\text{kg m}^{-1} \text{s}^{-1}$). This value is multiplied by the width of the channel to obtain the mean transport rate (in kg s^{-1}) through the cross-section.

Bedload measurements were taken primarily during periods of snowmelt runoff. This is because summer and fall rainstorms tend to be small and have minimal influences on water stage (and, hence, bedload transport) ([Ryan and Emmett, 2002](#)) and so they are not regularly sampled. Bedload measurements were obtained during snowmelt runoff in 1999 at Cache Creek and between 1982 and 1997 at Little Granite Creek. A total of 60 bedload samples were collected at Cache Creek at flows up to 1.3 times the bankfull discharge. Although bedload data were collected for only one snowmelt period at this site, we presume that these data are representative of the period being compared. This is based on an observation of overall system stability and

lack of annual differences in the other sediment records that would suggest substantial changes in sediment supply occurring in Cache Creek. Furthermore, data were collected from a relatively wide range of flows, thereby alleviating some of the difficulties encountered when attempting to fit a model to a limited bedload dataset (as discussed in the analysis of annual variability described in Section 4.1.). At Little Granite Creek, more than 120 measurements of bedload transport were acquired at flows ranging from about 0.05 bankfull (approximately $0.3 \text{ m}^3 \text{ s}^{-1}$) to nearly twice the bankfull discharge ($11.3 \text{ m}^3 \text{ s}^{-1}$). Daily bedload yield for both sites was estimated from bedload rating curves (Ryan and Emmett, 2002; Ryan et al., 2005b) and USGS records of mean daily discharge. These values were summed by water year to estimate annual bedload yield for the years 1983–1992, the common period of record for these two sites. Annual yield is expressed as load (metric tonnes t) per unit contributing basin area (km^{-2}).

3.2. *Suspended sediment measurements*

Suspended sediment observations at Little Granite Creek were obtained from USGS records taken between 1982 and 1993 (US Geological Survey, 2004). There were about 170 observations made during this period for flows up to two times the bankfull discharge (Ryan and Emmett, 2002). USGS data collected between 1968 and 1996 at Cache Creek (US Geological Survey, 2004) were supplemented by measurements taken by USFS personnel in 1999. About 290 measurements of suspended sediment were made for this site. Samples were collected at several, equally spaced positions on the cross-section using depth integrating samplers, such as a DH-48 (Federal Inter-agency Sedimentation Project, 2005) while wading or from sampling bridges. Samples were filtered, dried, and weighed to determine the total organic/inorganic mass of suspended sediment. SSC is expressed as the total mass of material per volume of liquid sample. Concentration was converted to transport rate (kg s^{-1}) by multiplying by instantaneous flow observed at the time the sample was collected. Suspended sediment rating curves were developed from flow observations and transport rates. Estimates of daily suspended sediment yield obtained using these curves were summed to determine annual yield for the suspended component.

3.3. *Data on total dissolved load*

Total dissolved load was obtained from USGS records for both sites (US Geological Survey, 2004) and, for Little Granite Creek, from unpublished data from the Bridger-Teton National Forest. Altogether, 156 observations of total dissolved concentrations were made for Little Granite Creek. Samples were collected on a monthly basis between 1981 and 1984, and more frequently between 1985 and 1992. Water quality samples were collected on a near-monthly basis at Cache Creek between 1966 and 1982 (US Geological Survey, 2004). The sampling frequency was reduced to bi-monthly between 1982 and 1995. A summary of the complete set of 272 water quality samples from Cache Creek collected under the HBN program is provided in Clark et al. (2000).

Total dissolved concentration was determined either by drying water samples at 180°C or from specific conductance measurements converted to an estimate of total dissolved concentration using a conversion factor (Stednick, 1991). Conversion factors were selected based on the single value that gave the best correspondence between measurements obtained with both methods. These were applied to observations where only specific conductance was measured. A conversion factor of 0.55 was used in estimating dissolved concentrations at Cache Creek. The conversion factor for Little Granite Creek was 0.6. Total dissolved concentration was converted to transport rate (kg s^{-1}) by multiplying by the instantaneous flow observed at the time the sample was collected. Mean daily and total annual dissolved yields were estimated from rating curves, as described for the bedload and suspended load components.

3.4. Discharge measurements

Discharge at the time samples were collected was determined either from USGS records (when available) or from flow rating curves developed using direct measurements and stage readings from staff plates installed near the sampling sites. Discharge was calculated from the product of mean velocity, interval width, and total depth determined at numerous subsections, then summed for the channel cross-section (Buchanan and Somers, 1969; Nolan and Shields, 2000). Mean velocity was measured using a Price AA and/or mini-current meters at 0.6 depth.

4. Results

4.1. Annual and seasonal variation in sediment loads

Rating curves fit to measurements of sediment transport typically exhibit considerable variability about the curve (Fig. 15.2). The range of measured bedload values for a given discharge can vary by one or more orders of magnitude, indicating that stream flow alone is not the only factor affecting rates of transport. Both short- and long-term fluctuations in sediment supply, including those occurring at seasonal and annual timescales, can contribute to variability demonstrated in records of sediment transport (Gomez et al., 1989). While the bedload data collected at Little Granite and Cache Creeks were of insufficient frequency for detecting changes in seasonal patterns (i.e., hysteresis), the 13 years of record from Little Granite Creek permitted a comparison of data collected annually. Typically, there were too few data (4–12 observations) or the data were collected over too narrow a range of flow to permit the comparison of bedload models fit to annual data. In previous work, an assessment of the adequacy of sample size indicated that a minimum of 20 samples were required to define a relationship (Troendle et al., 1996) and between 60 and 80 samples were required to discriminate between means in groups of bedload samples on the order of 30%, for varying levels of power (Ryan and Porth, 1999). Since there were too few samples collected each year for this level of assessment, the observations from any one year were compared with data from all other years to determine if they fell outside of

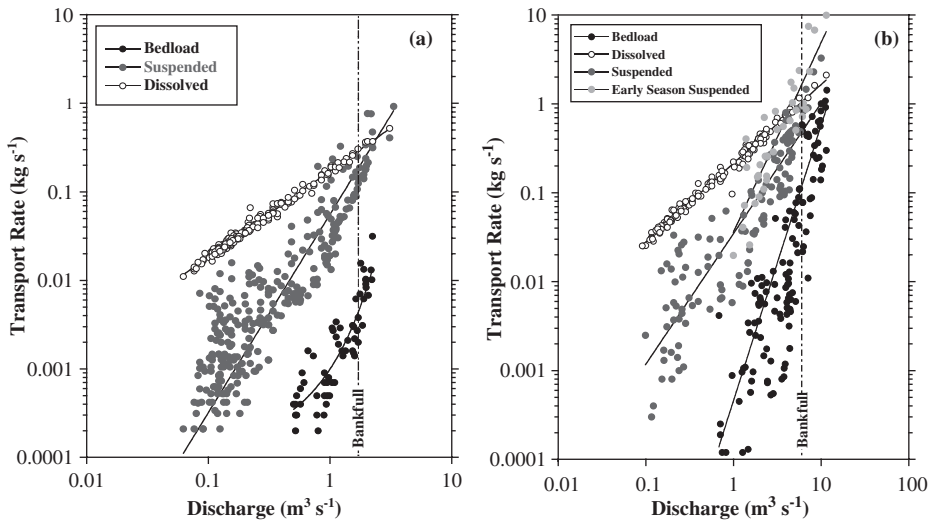


Figure 15.2. (a) Rating curves for Cache Creek. The form of the equation that best fit the data was used, with no a priori decision as to the form of the function. The curve for bedload data is an exponential fit [$y = a_1(e^{b_1x})$] while the curves for suspended sediment and dissolved load are power fits in the form [$y = b_2(x^{c_2})$], where x is the discharge and y is the measured transport rate. The data are displayed on log-log scale so that the three components can be shown simultaneously. (b) Rating curves determined for Little Granite Creek. The curves are power fits in the form [$y = b_2(x^{c_2})$]. A substantial number of large suspended samples were collected on the rising of the seasonal hydrographs, justifying two curves to better define the suspended sediment rating.

the 95% confidence limits of the predicted values (Fig. 15.3). The dependent variable “transport rate” was log-transformed to linearize the data and improve normality and heterogeneous variance problems. In most comparisons, measured transport rates in a given year consistently fell within the 95% confidence intervals determined for data collected in all other years. The years that differed to some degree were: (1) 1987 where the four measured points were close to the limits of the upper confidence band (Fig. 15.3c) and (2) 1993 where 5 of the 12 points were close to the lower confidence band (Fig. 15.3e). Still, values for these 2 years are comparable to those measured for other years and it is therefore likely that the data represent the same population of transport rates. In short, there is a high degree of variability in transport rates and overall variability in the dataset cannot be ascribed to annual differences in one or more years. Correspondence between annual measurements was also suggested by Leopold (1994) using a smaller portion of the same dataset.

Similar to observations from the bedload dataset, there were no substantial differences in suspended sediment transport measured between years for either site (separation of data by year not shown). However, a larger number of samples permitted an assessment of seasonal effects in the suspended sediment records. Data from the rising limb of the snowmelt hydrograph were separated from the recessional limb and models were fit to both groupings. Measurements of suspended sediment on the rising limb from Little Granite Creek were often twice those obtained from comparable discharges on the falling limb (Fig. 15.2b). This is likely due to early season flushing of sediment

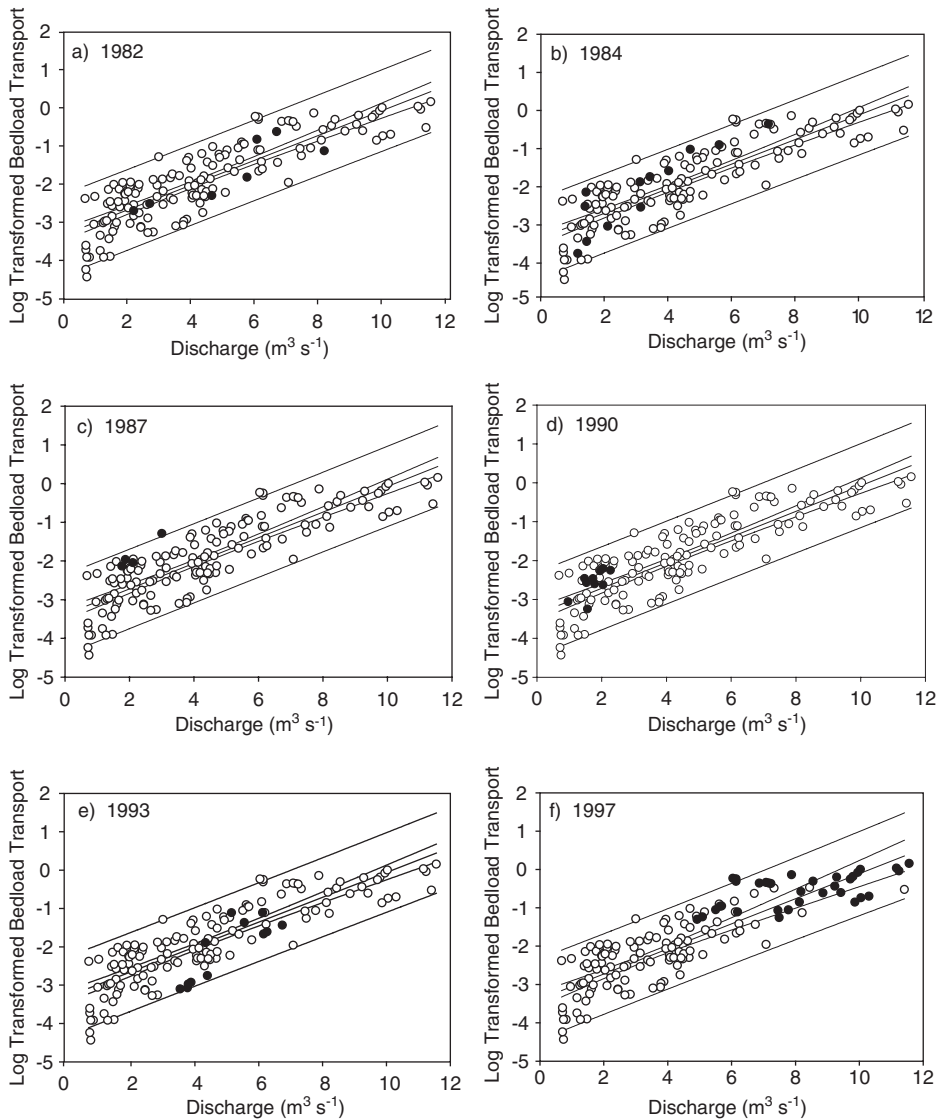


Figure 15.3. (a–f). Bedload transport rates (log transformed) measured at Little Granite Creek for some individual years (1982, 1984, 1987, 1990, 1993, and 1997). Lines shown are the 95% confidence bands on the mean (inner band) and prediction values (outer band) for all other years (open circles), exclusive of the data for the year of comparison (black circles).

associated with the onset of snowmelt runoff (e.g., Reid et al., 1985). Therefore, two rating curves were used to characterize suspended sediment transport at this site. This separation becomes important later in the assessment of the impacts of wildfire because there are distinctions in suspended sediment transport occurring on different parts of the hydrograph in the post-fire record. Only one function was fit to suspended

sediment data collected at Cache Creek because no early season difference was apparent in the data.

Dissolved concentration typically decreases with increasing discharge, reflecting dilution in the channel. Concentrations at low flows in Little Granite Creek ranged from 250 to 300 mg L⁻¹ and were about 160 mg L⁻¹ at higher discharges. In Cache Creek, there was no significant relationship between dissolved concentration and discharge. The mean estimate over the entire range of flow was 178 mg L⁻¹ (± 17 mg L⁻¹, standard deviation). Calculated dissolved loads are determined largely by the amount of discharge at the time of sample collection and so no separation in curves due to seasonal or annual affects is typically manifest (Fig. 15.2a and b).

4.2. *Estimates of annual sediment yield from two watersheds*

Substantial differences in estimates of annual sediment yield (based on the rating curves) were calculated for Little Granite and Cache Creek sites for the common period of record (1983–1992). Typically, the estimate of total load per unit watershed area from Cache Creek was 40% lower than that estimated for Little Granite Creek. The 10-year average for Cache Creek was determined to be about 80 vs. 135 t km⁻² for Little Granite Creek (sum of three components in Fig. 15.4). Predicted differences between total load were more substantial in wetter years (1983, 1984, 1987) and more nominal in drier years (1987, 1990, 1992) (Fig. 15.4). Similarity in sediment loads in drier years is due to the equivalence and the high contribution of the dissolved load to the total yield – about 60 t km⁻² in both watersheds. The mean annual dissolved load for the 10-year period was 70 t km⁻² (about 80% of the total) at Cache Creek and 90 t km⁻² at Little Granite Creek (about 70% of the total).

In contrast to dissolved loads, estimates of the suspended load and bedload components showed greater dissimilarity between the two watersheds. On an average, annual suspended load was 37 t km⁻² at Little Granite Creek and 13 t km⁻² at Cache Creek (Fig. 15.4). An average of 1.3 t km⁻² of bedload was estimated for Cache Creek (less than 2% of the total load) while the annual bedload yield for Little Granite Creek averaged 6 t km⁻² (5% of the total load). This indicates that about three times the amount of non-dissolved solids are transported per unit watershed area in Little Granite Creek relative to Cache Creek, with suspended sediment contributing the greatest portion of the non-dissolved load in both watersheds.

Speculatively, dissimilarities in suspended load and bedload may be attributed to gross differences in hillslope erosion processes that deliver more coarse sediment to Little Granite Creek. An evaluation of landslides compiled by the [Wyoming State Geological Survey \(2001\)](#) reveals about five times the number of landslides in the Little Granite Creek watershed (118) compared to Cache Creek (23). Inspections of aerial photographs and field reconnaissance showed that many of the slides in both watersheds are large, slow-moving, earthflow types that involve large portions of hillslope ([Varnes, 1978](#)). Several of the slides identified at Little Granite Creek directly impinge on stream channels. Where these slides impinge, the toeslopes are actively raveling and, in at least three cases, the channel has been pushed into the far side of the valley bottom, creating a second set of slides where the hillslope is undercut. These

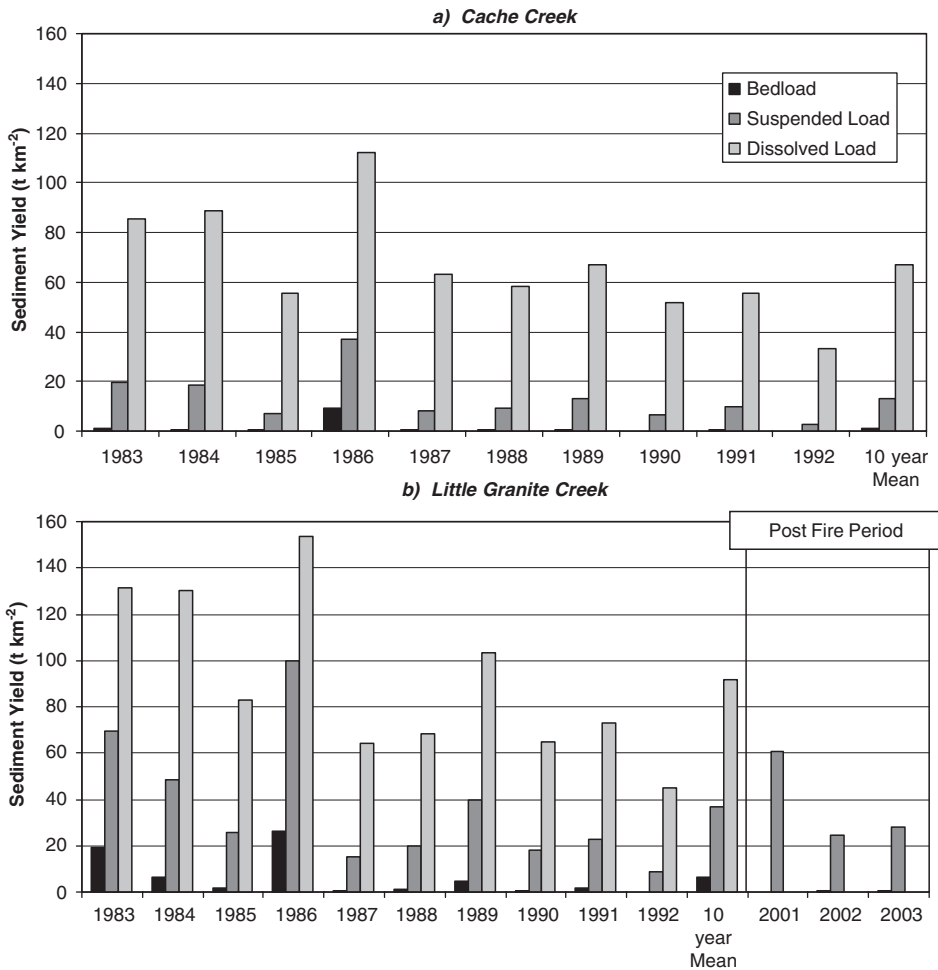


Figure 15.4. Estimates of mean annual yields determined for bedload, suspended load, and dissolved load at (a) Cache and (b) Little Granite Creeks between 1983 and 1992. Data from 2001–2003 in (b) are yields estimated for the period following wildfire in the Little Granite Creek watershed, discussed in Section 4.3.

slides are a chronic source of fine-to-coarse sediment in this basin as materials deposited in and adjacent to the channel are reactivated during high runoff. Additionally, the upper portion of the Little Granite watershed was glaciated and there are active sources of sediment from glacial and landslide debris that contribute to the relatively high suspended sediment load during snowmelt runoff. By contrast, large, chronic sources of sediment largely lack connectivity with the stream network in Cache Creek, which flows through a stable inner gorge above the gauging station. The upper portion of Cache Creek was glaciated to a lesser extent than Little Granite Creek and most of these surfaces are stabilized by subalpine meadow and forest vegetation. Hence, differences in the suspended and bedload portions of these two watersheds may be linked to variation in geologic controls, patterns of mass wasting,

and the chronic contributions of sediment derived from impinging landslides and glacial debris. The link between sediment sources and loads in Little Granite Creek and Cache Creeks is an area of on-going investigation.

4.3. Variation in sediment loads following wildfire

Natural and anthropogenic disturbances in watersheds often cause increases in sediment loads in channels downstream from the disturbed area. The net effect is typically difficult to predict and depends both on the nature of the disturbance and the sequence and intensity of precipitation following the event. Often there is little baseline data against which the effects of the disturbances may be compared. In August 2000, a substantial portion of the Little Granite Creek watershed was burned by wildfire, presenting an opportunity to quantify increases in sediment loads due to the destruction of vegetation and loss of soil cohesion during high severity burns. Specifically, about 75% of the forest vegetation in the Boulder Creek watershed (Fig. 15.1) was moderately to severely burned. This watershed constitutes nearly 40% of the area of the Little Granite Creek watershed and so there was high potential for increased sediment loading in the years following the fire.

The Little Granite Creek study site was re-instrumented in 2001–2003 so that changes in timing and increases in sediment loads could be assessed. Methods and instruments similar to those used in previous years were deployed in 2001 and 2002, though only bedload and suspended sediment loads were assessed. The primary modification in methods was the use of automated water samplers in addition to DH-48 suspended sediment samplers (complete description of methods provided in Ryan et al., 2003). The automated samplers had been programmed to collect water once every 4 h between May and October in the first 2 years post-fire, generating about 800 samples per year. In 2003, turbidity sensors were deployed and these measurements were correlated with suspended sediment samples to derive estimates of sediment concentration (Ryan et al., 2006). Because the change in methods in 2003 gave results that have greater uncertainty, only results from 2001 and 2002 are presented herein. No bedload was measured in 2003.

Similar to areas throughout the western United States, snow pack and resulting stream flows were relatively low in Little Granite Creek in water years 2001 and 2002 (Ryan et al., 2003). During this 2 year period, discharge exceeded bankfull for only a few hours during a prolonged rainstorm coincident with snowmelt runoff in May 2001 and during a period of rapid warming in May 2002. Later in the summers of both years, small increases in runoff occurred in response to low-to-moderate intensity thunderstorms but none exceeded bankfull. Rates of bedload transport measured during snowmelt runoff in these years showed no increase, falling within the range of pre-burn values (Fig. 15.5). This suggests that either few, new sources of coarse sediment were introduced following the burn or that there is a lag period between the introduction of new sediment and the time it takes to reach the mouth of the watershed. Based on an absence of changes in surveyed cross-sections in the burned watershed (Ryan et al., 2003) and the lack of debris-flow generating landslides identified during field reconnaissance, the former is surmised.

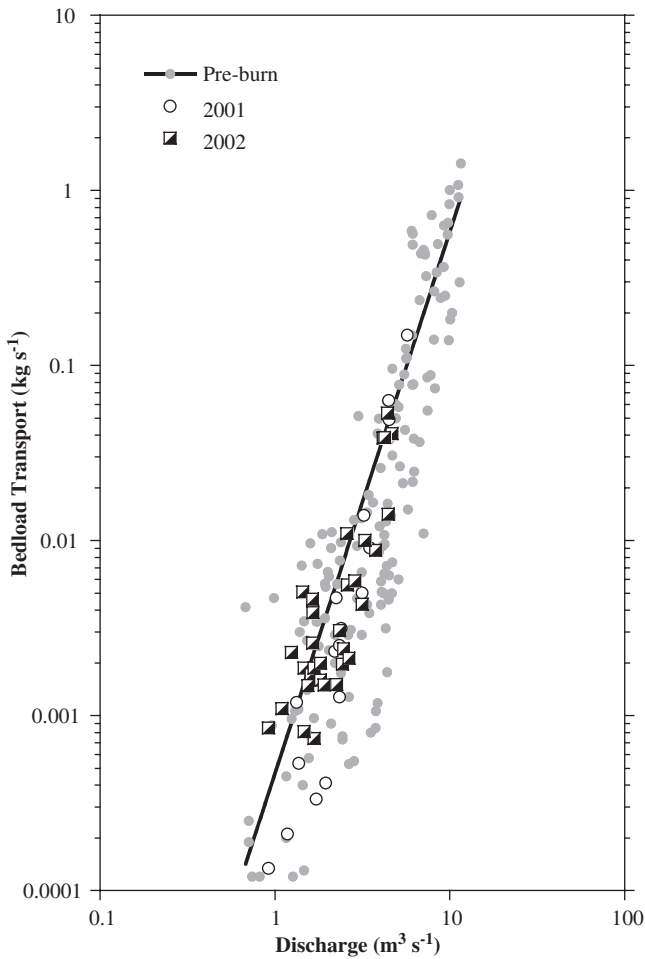


Figure 15.5. Comparison of rates of bedload transport measured in 2001 and 2002 against pre-burn values (in gray). Range of values from both post-fire years overlap those measured between 1982 and 1997.

In contrast, there were some substantial increases in suspended sediment loads relative to both the pre-burn period and to measurements obtained from the control site, Upper Little Granite Creek (Fig. 15.1). The magnitude of these increases varied for different parts of the runoff season (Fig. 15.6). For instance, measured rates of suspended sediment transport were about 3–5 times higher on the rising limb of the snowmelt hydrograph relative to pre-burn values, while there were no substantial differences on the falling limb. In mid summer, though low-to-moderate intensity thunderstorms ($10\text{--}20\text{ mm h}^{-1}$) typically raised the water stage by only a small amount, there were increases in suspended sediment between one and two orders of magnitude associated with these storms. However, they did not exceed some baseline values measured for that part of the hydrograph prior to burning.

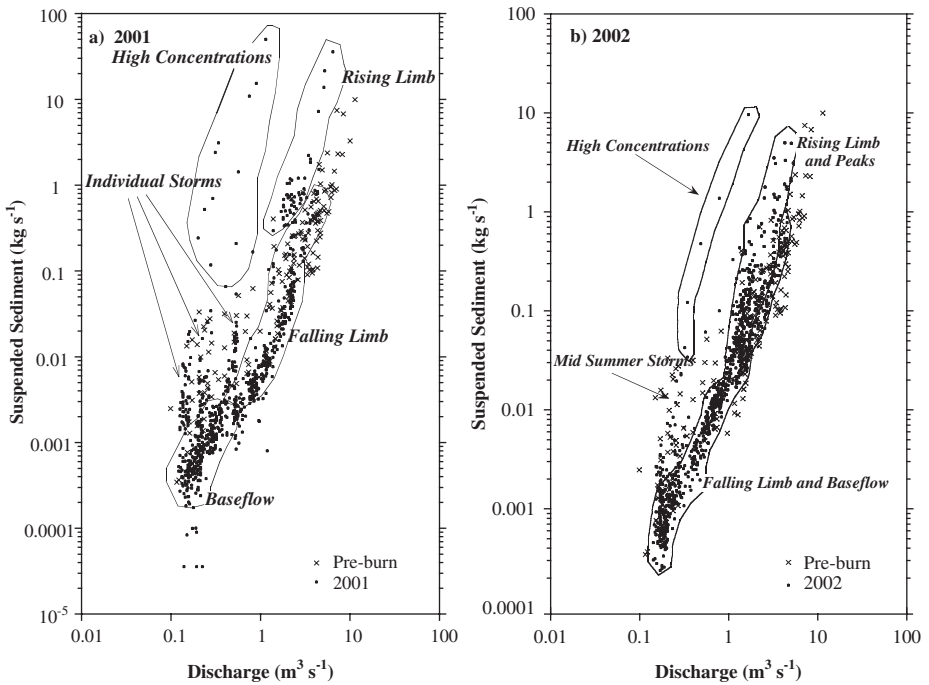


Figure 15.6. Comparison of rates of suspended sediment transport measured in (a) 2001 and (b) 2002 against pre-burn values (x). Black solid lines approximate the ranges of values measured for different parts of the hydrograph.

In late summer 2001, two larger rainstorms produced the highest SSCs measured at Little Granite Creek to date (Fig. 15.6a, High Concentrations). A brief (< 15 min) but intense rainfall (50 mm h^{-1}) on August 9 generated several fine-grained, organic rich mudflows from gullies within the burned area. The tracks of these flows could be traced across alluvial fans areas and into the stream network. SSC associated with this event was $25,000 \text{ mg L}^{-1}$ and it took over a week for measured concentrations to return to baseline values. By contrast, concentrations measured 280 mg L^{-1} in the control watershed, returning to baseline within 8 h. A second series of storms on September 13 produced another substantial spike in suspended sediment. The measured peak concentration was about $48,000 \text{ mg L}^{-1}$ or about four orders of magnitude greater than baseline, whereas peak concentration in the control watershed was 1300 mg L^{-1} , or about the same level observed during snowmelt runoff. Concentrations measured at Lower Little Granite during these two events were in the range of hyperconcentrated flow (Costa, 1984; Rickenman, 1991).

The relationship between stream sediment concentrations and summer thunderstorms in 2002 differed from 2001 in that smaller increases in suspended sediment loads were associated with two moderate storms (Fig. 15.6b). The difference in response is attributed to the combined influences of: (1) lower intensity storms in 2002 and (2) vegetation regrowth on hillslopes and riparian areas (Dwire et al., 2006) reducing the supply of sediment. It may also be attributed to increased sediment

storage in the channel due to: (1) tree fall in the reach above the study site and (2) new beaver ponds constructed in the interim period.

In the period between 2001 and 2003, calculated annual suspended sediment yields decreased, becoming more comparable to those estimated for the pre-burn period. Total suspended yield in 2001 was 61 t km^{-2} (Fig. 15.4b) which was 5.25 times higher than the yield predicted from a regression relationship between annual flow and (pre-burn) suspended sediment yield (11.6 t km^{-2}). In 2002 and 2003, the estimates were 24.6 and 28 t km^{-2} , both of which were 1.7 times higher than that predicted from the regression. This indicates that suspended sediment yields are beginning to return to baseline levels within a few years following the wildfire. This observation concurs with others who suggest the erosion impacts are greatest in the first year post-fire and steadily decline over the next few years, returning to baseline values within 3–5 years (e.g., Robichaud et al., 2000; Moody and Martin, 2001).

5. Discussion and conclusions

In this paper, data from two watersheds draining the Gros Ventre Mountain range of western Wyoming, both with extensive numbers of observations on sediment transport, were explored. At the onset, the two sites were thought to be similar in terms of sediment supply and the relative contributions of bedload, suspended load, and dissolved load to total sediment yield. However, there were apparent differences in sediment loads exported from the two watersheds that imply spatial variability in processes across this province of complex and varied terrain. Our estimates indicate that about 40% more sediment per unit watershed area was exported from Little Granite Creek relative to Cache Creek. Most of this difference was in the suspended sediment and bedload portions where three times more material was estimated to have been exported over the 10-year period of common record. Tentatively, these patterns are linked to differences in rates and modes of hillslope mass wasting that deliver more coarse sediment to Little Granite Creek. An assessment of a landslide database and field reconnaissance indicated that large, deep-seated landslides in the Little Granite watershed impinge on the channel and are chronic sources of sediment. Moreover, raveling deposits of glacial and landslide debris in the upper watershed contribute to the suspended sediment load during periods of snowmelt and high intensity rainfall. By comparison, landslides in the Cache Creek watershed are fewer in number and appear less connected to the stream network. Hence, differences in geologic controls in an area of complex terrain may account for the observed dissimilarity in suspended load and bedload; this is an area of on-going investigation in these watersheds.

Similar to other studies of sediment transport in gravel-bed streams, measured rates of bedload and suspended sediment in this study were quite variable for a given discharge. High variability has been ascribed to annual and seasonal difference in sediment supply, often in connection with large individual storms, rapid snowmelt, or mass wasting events (e.g., Alvera and Garcia-Ruiz, 2000; Lenzi et al., 2003; Richards and Moore, 2003). However, we were unable to distinguish between-year differences in the datasets from Little Granite or Cache Creeks; measurements for a given year typically fell within the range of those measured for all other years taken together. The inability

to distinguish between years could be due to the infrequency with which the highly variable data were collected. However, there were also no documented large-scale disturbances or activities in either watershed during the common period that would account for a sustained, measurable spike in the sediment loads. Hence, the between-year similarity is likely valid. Seasonal variability was evident in the suspended sediment records at Little Granite Creek when more material was transported on the rising limb of the snowmelt hydrograph, justifying the use of two rating curves. Similar patterns may be occurring in the bedload component, but measurements were made too infrequently to identify a such an effect. In general, data on the temporal aspects of bedload transport are particularly difficult to obtain, outside of a few instrumented watersheds (e.g., Bunte, 1996; Lenzi et al., 1999; Laronne et al., 2003). Consequently, much of the temporal variability in bedload observations remains unexplained, though newer technologies may provide insight into these processes in the future (Ryan et al., 2005a).

Substantial increases in sediment load are often manifest following large-scale disturbances in the watershed. In August 2000, wildfire burned portions of the Little Granite Creek watershed, presenting an opportunity to quantify increases in sediment loads associated with large-scale disturbance of forest cover. The primary impact on sediment load was elevated rates of suspended sediment transport observed on the rising limb during snowmelt and during high intensity, late-summer thunderstorms; rates measured during other flow periods were comparable to pre-burn values. The high rainfall intensities generated mudflows from shallow soil slips in severely burned areas (similar to that described by Wells (1987)). These were fine-grained, organic rich flows that transitioned into hyperconcentrated flows (based on measured sediment concentrations) as they moved from burned areas into the channel network. With time, the suspended sediment load appears to be returning to baseline values as vegetation re-growth in the watershed stabilizes burned areas, reducing the erosion of sediment from these surfaces. In contrast, there was no quantifiable increase in bedload associated with disturbance by wildfire. This is attributed to several related factors, driven by the finding that large-scale, coarse-grained debris flows were not generated in the burned area during the high-intensity storms. Hence, there may not have been a lot of new coarse sediment introduced to the system. Moreover, if substantial coarse sediment had been introduced in the upper part of the watershed, much of it may remain in storage or be exported out of the watershed slowly over time and so the increased transport signal may not show up in the record for decades. Even more problematic, given the inherent variability of the measured rates of bedload transport and the substantial number of samples needed to detect small differences, the effects of large-scale disturbance may not be readily detected in the bedload record. Hence, methods other than comparisons of bedload transport data may be needed to quantify the impacts of large-scale watershed disturbances on these geomorphic processes.

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