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Suspended sediment transport in an ephemeral stream following wildfire

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[1] We examine the impacts of a stand-clearing wildfire on the characteristics and magnitude of suspended sediment transport in ephemeral streams draining the burn area. We report the results of a monitoring program that includes 2 years of data prior to the Cerro Grande fire in New Mexico, and 3 years of postfire data. Suspended sediment concentration (SSC) increased by about 2 orders of magnitude following the fire, and the proportion of silt and clay increased from 50% to 80%. For a given flow event, SSC is highest at the flood bore and decreases monotonically with time, a pattern evident in every flood sampled both before and after the fire. We propose that the accumulation of flow and wash load at the flow front is an inherent characteristic of ephemeral stream flows, due to amplified momentum losses at the flood bore. We present a new model for computing suspended sediment transport in ephemeral streams (in the presence or absence of wildfire) by relating SSC to the time following the arrival of the flood bore, rather than to instantaneous discharge. Using this model and a rainfall history, we estimate that in the 3 years following the fire, floods transported in suspension a mass equivalent to about 3 mm of landscape lowering across the burn area, 20% of this following a single rainstorm. We test the model by computing fine sediment delivery to a small reservoir in an adjacent watershed, where we have a detailed record of postfire sedimentation based on repeat surveys. Systematic discrepancies between modeled and measured sedimentation rates in the reservoir suggest rapid reductions in suspended sediment delivery in the first several years after the fire.

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1. Introduction

[2] Wildfires temporarily increase the supply of water and sediment to fluvial systems, often by orders of magnitude [*Doehring*, 1968; *Helvey*, 1980; *Wells*, 1985; *Meyer et al.*, 2001; *Moody and Martin*, 2001a]. In many landscapes, land use change and active fire suppression have reduced the frequency of small ground fires and increased the probability of intense crown fires that reach tree canopies and result in complete obliteration of the vegetative ground cover [*Pyne*, 1995]. Climate change, including 20th century warming, is probably an additional factor increasing the probability of stand-clearing wildfires in some environments [*Meyer et al.*, 1995; *Pierce et al.*, 2004]. By changing flow pathways and erosion processes, crown fires alter geomorphic processes over a large portion of the landscape, both within and downstream of burned areas. Understanding and predicting river channel and ecosystem evolution in burned landscapes could be improved with more detailed observations of the impacts of stand-clearing crown forest fire on the fluvial sediment transport processes and sediment budgets of streams draining burned watersheds.

[3] Stand-clearing fires increase the amount of water delivered to streams, leading to larger floods. In addition to eliminating interception storage of rainfall, crown fires also result in the incineration of all the vegetative ground cover, removing nearly all hillslope roughness elements that impede overland flow. Vaporization of litter on the forest floor may result in the emplacement of a discontinuous, chemically hydrophobic layer just beneath the soil surface [*DeBano*, 1981], so that relatively small rainstorms can generate overland flow in sheets, rills, and rivulets. Furthermore, wood ash produced by burning can clog soil pores, reducing infiltration and enhancing overland flow on burned hillslopes [*Swanson*, 1981; *Martin and Moody*, 2001]. Forest-clearing fires also increase the connectivity of hillslope overland flow [*Lavee et al.*, 1995], further enhancing the delivery of runoff to stream channels.

[4] The increased runoff caused by fires is usually accompanied by a temporary pulse in the amount of sediment supplied to streams. Fire-enhanced overland flow can erode hillslopes by exerting a tractive force on the soil surface

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[*Doehring*, 1968; *Inbar et al.*, 1998; *Prosser and Williams*, 1998; *Benavides-Solorio and MacDonald*, 2001; *Johansen et al.*, 2001; *Moody et al.*, 2005] and by delivering particles mobilized by raindrop impact to stream channels. Burning produces mobile, fine-grained wood ash, which is transported in suspension downstream, especially during the first few flow events following a fire [*Ranalli*, 2004; *Reneau et al.*, 2007]. Crown fires can also trigger both shallow and deeper-seated landslides by multiple mechanisms [*Wells*, 1987; *Meyer and Wells*, 1997; *Cannon et al.*, 2001; *Gabet*, 2003a]. In addition, fire mobilizes soil stored on hillslopes by removing the small-scale roughness elements behind which sediment is stored, drastically increasing dry ravel [*Anderson et al.*, 1959; *Krammes*, 1965; *Gabet*, 2003b; *Roering and Gerber*, 2005]. All these mechanisms, as well as others not listed here, significantly and temporarily increase the supply of ash and fine-grained sediment to streams draining burned areas.

[5] Fire-related pulses of sediment contain a wide range of grain sizes, and these heterogeneous mixtures are rapidly sorted by fluvial processes. Many previous studies of wildfire effects on fluvial processes and sediment transport have focused on the relatively coarse-grained bed load fraction: the fraction that is transported close to the bed and is therefore closely associated with channel changes. Fire-induced changes in water flow and the supply of bed load have resulted in severe erosion and/or aggradation [*Heede et al.*, 1988; *Florsheim et al.*, 1991; *Reneau et al.*, 1999; *Veenhuis*, 2002; *Lyman et al.*, 2005] downstream from burned areas, depending on the local balance between the upstream supply and downstream transport of coarse-grained sediment. Efforts to predict postfire changes such as these require modeling the mass balance of bed load or the bed material load (which also includes the suspendible portion of the grains found in the bed) using sediment routing models, which incorporate equations that relate the sediment transport rate to instantaneous measures of flow strength, such as discharge, shear stress or stream power [e.g., *Meyer-Peter and Muller*, 1948; *Einstein*, 1950; *Bagnold*, 1973; *Parker*, 1990].

[6] The current contribution focuses on the suspended load: the finer fraction that can be carried higher in the flow column by turbulent mixing. The suspended load includes both the suspendible bed material and the washload, which is the component of the load that is finer than what is generally found in the channel bed. The suspended load almost always increases dramatically following wildfires, possibly because of intensified surface erosion on hillslopes, stream beds and along streambanks [*Swanson*, 1981]. Increases in the suspended load supply following crown fires may have widespread impacts because fine-grained sediment can travel long distances quickly, and may cause accelerated sedimentation rates on alluvial fans and floodplains [*Meyer et al.*, 1995; *Meyer et al.*, 2001] as well as in reservoirs [*Lavine et al.*, 2006]. Some of the fines may also infiltrate the matrix of gravel channel beds, thereby impacting hydraulic and habitat conditions downstream from burned areas. Furthermore, nutrients [*Zinke*, 1977] and contaminants [*Paliouris et al.*, 1995; *Johansen et al.*, 2003] in forests are concentrated by the burning of organic material; these constituents often bind to fine sediment, so their fate, and ultimately the exposure of humans and ecosystems to these materials, depends on the rate and nature of suspended sediment transport following wildfires. Thus a capacity to forecast fine-sediment transport following fires would improve the basis for managing the human health and ecosystem consequences of wildfire. However, because the transport rate of the suspended load (especially the washload component) depends on multiple interacting hillslope and channel processes, it is difficult to forecast fine sediment transport following fires. In general predictions are hindered by a lack of sufficient field data and observations to guide the development of theories and numerical models.

[7] In this paper we present and analyze the results of a monitoring program that began as a study of sediment and contaminant transport by flash floods in an unburned watershed [*Malmon*, 2002] 2 years prior to the Cerro Grande fire in New Mexico. Following the fire in May 2000, we intensified our monitoring program to sample suspended sediment transport for three summers (locally the dominant season for runoff and sediment transport) following the fire. The circumstances provided a novel opportunity to directly compare prefire and postfire sediment transport characteristics in an ephemeral stream.

[8] After describing the field area and experimental setup, we present observations of suspended sediment concentration and particle size during floods before and after the fire. We introduce a new approach to analyzing suspended sediment data in ephemeral streams that clarifies patterns in our data set and allows us to develop a reasonable empirically based model to predict fine sediment transport from rainfall data. In the final section, we use this model and the record from a network of rain gages to estimate the amount of fine sediment delivered from the burned area in the 3 years following the fire. Finally, we use the empirical model and a separate rainfall record to estimate sedimentation in a reservoir in a nearby watershed, and compare our predictions to independent estimates derived from repeated surveys of the reservoir floor.

2. Field Area

2.1. Jemez Mountains and the Pajarito Plateau

[9] The field area is in the Jemez Mountains and Pajarito Plateau (Figure 1), a volcanic field on the western margin of the Rio Grande rift in north central New Mexico. The Jemez Mountains are underlain by Cenozoic volcanic rocks of a range of composition and texture [*Smith et al.*, 1970]. The Pajarito Plateau includes east-sloping mesas underlain by the early Pleistocene Bandelier Tuff. The plateau is dissected by a series of deeply incised canyons that head on the steep eastern flank of the Jemez Mountains (Figure 1). Mean annual precipitation increases from east to west, from 35 cm near the Rio Grande to about 65 cm on the mountain crests [*Bowen*, 1990]. Most of the rainfall, runoff, and sediment transport occurs between May and October, which includes the summer monsoon season [e.g., *Bowen*, 1990; *Malmon*, 2002; *Reneau and Kuyumjian*, 2004; *Shaull et al.*, 2005]. Winter precipitation usually falls as snow.

[10] Local geologic and physiographic factors exert important controls on the distribution of fires, vegetation, and soil properties in the study area. Before the fire, vegetation on the eastern flank of the Jemez Mountains consisted of ponderosa pine (*Pinus ponderosa*) and mixed

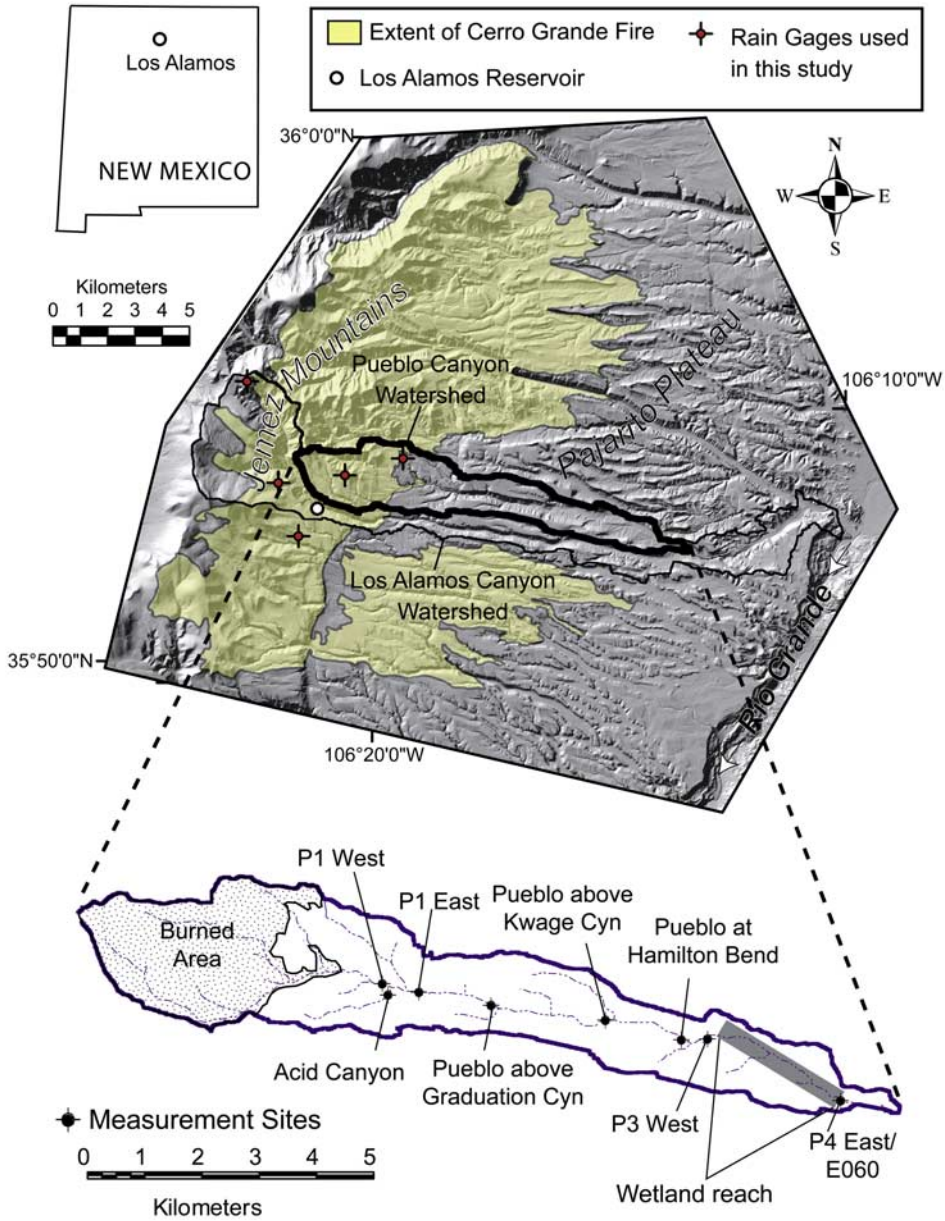

Figure 1. Map of the study area. Shaded relief map shows the Pueblo and Los Alamos Canyon watersheds, the extent of Cerro Grande fire, and the locations of rainfall gages used in this study. Inset map shows the locations of sampling stations along the channels in Acid and Pueblo Canyons, and the approximate location of an artificial wetland created by the effluent from a wastewater treatment facility in Pueblo Canyon.

coniferous forest; the plateau and canyons are dominated by ponderosa pine forest and piñon juniper woodlands [*Allen*, 1989; *McKown et al.*, 2003]. Prior to 1900, both ponderosa pine and mixed conifer areas in the Jemez Mountains were characterized by high-frequency, low-intensity fire regimes; mixed conifer forests also sustained occasional crown fires [*Touchan et al.*, 1996]. Following European settlement, land use change and fire suppression, possibly amplified by 20th century climate change, led to an increase in tree density and the likelihood of forest-clearing crown fires.

[11] The abundance and distribution of fine-grained sediment, the source material for the suspended sediment measured in this study, is also strongly influenced by physiographic and geologic factors. Field observations suggest that bedrock weathering in the Jemez Mountains in general produces little silt and clay, so much of the fine sediment on the mountain front has an external (eolian) origin. Soil samples collected along a hillslope transect in the low-severity portion of the burn area in the Jemez Mountains (Los Alamos Canyon watershed, Figure 1), contained an average silt/clay content of 86% in the <2 mm fraction (σ = 6%, n = 10; S. Reneau, unpublished data). The nonwelded and poorly welded tuff common on the Pajarito Plateau weathers to a range of grain size,

Figure 2. Photograph of steep hillside in the Jemez Mountains shortly after the Cerro Grande fire. Note the light colored streaks, indicating surface erosion by overland flow in rills, and levee-lined debris flow tracks. Photo credit: USDA Forest Service.

including silt to medium sand, as well as the coarse to very coarse sand-sized quartz and sanidine phenocrysts that appear to dominate the bedload. The other main sources of fine-grained sediment are from surface erosion of the colluvial soils on the canyon walls, and bank erosion of floodplain deposits along the canyon bottoms [*Graf*, 1996; *Malmon et al.*, 2004; *Reneau et al.*, 2004].

[12] The Los Alamos National Laboratory (LANL) was established on the plateau in 1943 as part of the Manhattan Project to create the first nuclear weapons, and it has remained in operation for weapons development and other research activities. Two small towns (total population about 18,000 in 2000) have grown around the laboratory on the urban/forest interface. In the absence of wildfire, rainfall over the sparsely vegetated and partially urbanized plateau surfaces generated most of the runoff in the canyons, and the Jemez Mountains contributed relatively little to the sediment budget [*Malmon*, 2002].

[13] The eastern Jemez Mountains and the Pajarito Plateau have been impacted by three large crown fires in the past several decades. The La Mesa (1977) and Dome (1996) fires, each about 6000 hectares, burned mostly uninhabited federal land. Following both fires, runoff from the mountains increased dramatically, although temporarily [*White and Wells*, 1982; *Veenhuis*, 2002]. Flooding was accompanied by locally significant channel changes [*Reneau et al.*, 1999] and presumably also by increased suspended sediment concentrations. Most of the major flooding occurred within the first 2 years following these fires, and suspended sediment concentrations have declined since that time [*Veenhuis*, 2002].

2.2. Cerro Grande Fire and Pueblo Canyon

[14] On 4 May 2000, the Cerro Grande fire began as a prescribed burn in Bandelier National Monument in the southeastern Jemez Mountains. The fire was amplified by high winds, low humidity, and a dense fuel load, and eventually burned 174 km^2 in Bandelier National Monument, the Santa Fe National Forest, LANL, San Ildefonso and Santa Clara Pueblos, and the town of Los Alamos, including 241 structures, making it the most costly fire in New Mexico to date. The most severely burned areas were in the steeper, montane portions of the watersheds (Figure 2). As a result of the loss of ground cover, decreased hillslope roughness, and the development of hydrophobic soils [*Interagency Burned Area Emergency Rehabilitation Team* (*BAER*), 2000], the primary locus of runoff and sediment production shifted west from the Pajarito Plateau to the burned portions of the Jemez Mountains (Figure 1). Postfire peak flows following rainfall over the burned area (Figure 3) were up to 2 orders of magnitude larger than those of prefire flows [*Shaull et al.*, 2005].

[15] Pueblo Canyon (drainage area: 22 km^2) was one of the most severely impacted watersheds after the Cerro Grande fire (Figure 1). The upper third of the watershed experienced high-severity burn (characterized by 100% tree mortality, complete loss of ground cover, and the development of hydrophobic soils [*Robichaud et al.*, 2000]). This resulted in a sequence of large floods with rapid rising limbs (Figure 3), the largest of which had a peak discharge estimated at 41 m^3/s in the lower canyon (below an artificial wetland, Figure 1) on 2 July 2001 [*Shaull et al.*, 2005]. In comparison, the largest prefire flood at the LANL gage E060 (Figure 1, installed 1992) was an estimated 0.3 m^3/s in

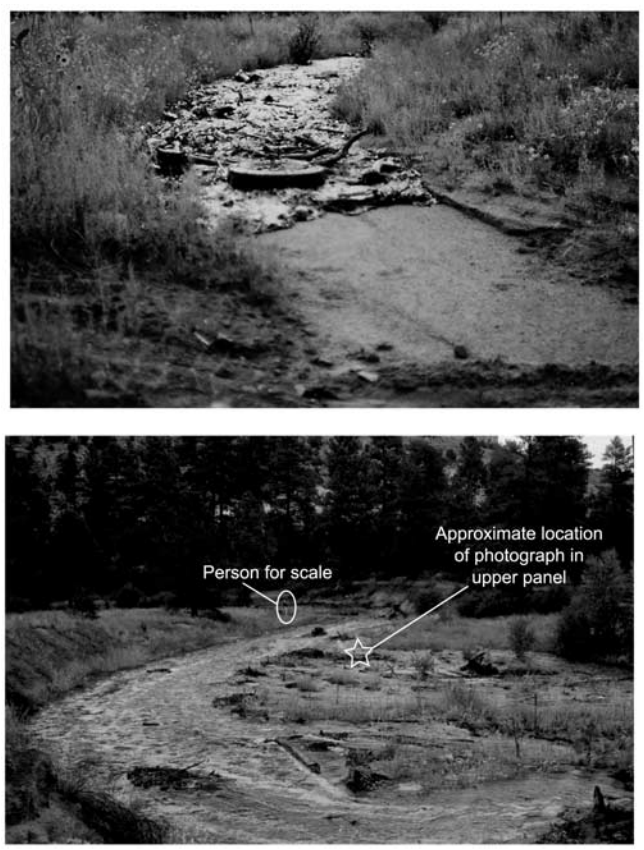

Figure 3. (a) Photograph of a flood bore traveling down Pueblo Canyon, 9 September 2000, following the Cerro Grande fire. The highest sediment concentration is at the flood bore, and decreases rapidly after the passage of the bore. The bore was advancing at approximately 2 m/s. Scale provided by automobile tire on bore face. (b) Photograph of the same site approximately 10–20 min later.

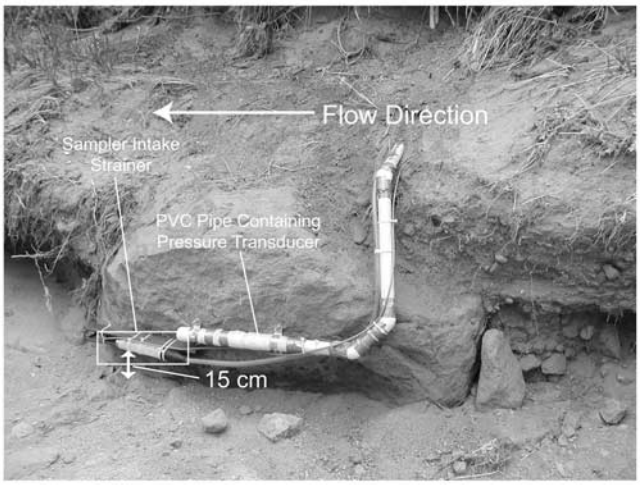

Figure 4. Photograph of a typical installation in Pueblo Canyon, summer 2002 (Graduation Canyon site). White tube structure contains pressure transducer for measuring flow depth. Intake strainer of the pump-operated suspended sediment sampler (ISCO brand) was bolted to boulder approximately 15 cm above the bed.

1999 [*Shaull et al.*, 2005]. The 2 July 2001 flood was generated by a storm with a 10–25 year recurrence interval (based on average 1-hour rainfall); locally it produced exceptionally intense shorter-duration rainfall, with one gage recording the most intense 30-min rainfall ever recorded by the large network of rainfall gages around LANL, having an estimated 90-year recurrence interval [*Reneau et al.*, 2003].

[16] The enhanced runoff caused by the fire was accompanied by increased sediment yields in the streams draining the burned area. The fire promoted surface erosion by a variety of hillslope erosion processes that were observed in the burn area, including dry ravel, rainsplash, sheet and rill erosion by overland flow [*Johansen et al.*, 2001], and small debris flows of ash and fine sediment [*Cannon et al.*, 2001]. This material was supplemented by accelerated floodplain erosion due to the greatly amplified postfire floods [*Lyman et al.*, 2005]. Postfire flooding caused a variety of channel changes in Pueblo Canyon. The channel bed aggraded up to 1.1 m in some reaches and incised up to 0.8 m in others [*Lyman et al.*, 2005]. Up to 0.5 m of floodplain deposition occurred at many cross sections, and channel widening by bank collapse was common. Postfire flooding and erosion in Pueblo Canyon caused concern because of damage to roads and sewer lines and because much of the Pueblo Canyon floodplains include post WWII era deposits containing plutonium bound to fluvially transported sand, silt, and clay [*Stoker et al.*, 1981; *Graf*, 1996; *Reneau et al.*, 2004]. On the basis of 42 repeated cross section surveys following the 2 July 2001 flood, *Lyman et al.* [2005] estimate a net deposition of 2400 m^3 in the lowest 10 km of Pueblo Canyon.

3. Methods and Data Sources

[17] Suspended sediment data from before the fire was obtained from two sources: (1) a sediment monitoring program and modeled sediment budget constructed for adjacent Los Alamos Canyon (Figure 1) in 1998 and 1999 [*Malmon et al.*, 2004]; and (2) simple single-stage samplers made from PVC pipe and tubing installed along the Pueblo Canyon channel in 1998 and 1999. Although floods were markedly different in the two canyons after the fire (partly because of the Los Alamos Reservoir (Figure 1), which impounds runoff from most of the burned area in the Los Alamos Canyon watershed), prefire floods in the two canyons were similar in the sense that the dominant runoff and sediment producing areas were the urbanized zones and the sparsely vegetated (piñon juniper) areas on the Pajarito Plateau. The data from the single-stage samplers in Pueblo Canyon may be biased low because the duration of sample collection is unknown and possibly long compared with the timescale of changes in discharge and sediment concentration during floods, and also because the corresponding crest stage gages recorded only the peak flow, not instantaneous discharge [*Malmon*, 2002]. In this paper, prefire sediment transport data are included for comparison with postfire data, but are not used in any of the sediment flux calculations reported in the paper.

[18] During the three summers following the Cerro Grande fire, we monitored water discharge and suspended sediment transport at a total of six different sites in Pueblo Canyon upstream of the wetland. Data also were collected at a seventh station in Acid Canyon, a short tributary to Pueblo Canyon that drains unburned, mostly urbanized areas (Figure 1). A typical installation (Figure 4) consisted of a pressure transducer that recorded flow depth at irregular time intervals (more frequently during higher flow) and an automated pump-activated water sampler (ISCO brand) programmed to sample at varying increments above a specified flow depth (every 5 min early in the flood, and at longer intervals on the recessional limb of the hydrograph). During the 9 September 2000 flood, samples were collected manually using a depth integrated sampler while wading in the flow, and stage was estimated visually from a staff gage. In Los Alamos Canyon before the fire, samples collected by ISCO samplers recorded concentrations and particle size distributions that were similar to samples collected contemporaneously using depth-integrated suspended sediment samplers [*Malmon*, 2002].

[19] None of the sites were operational throughout the entire study period, thus our record consists of observations of individual flow events at multiple stations rather than a continuous record. The pressure transducers generally recorded hydrographs with reasonable shapes, but converting flow depth to volumetric water discharge introduced considerable uncertainty, especially because fluctuations in channel bed elevation led to ambiguity in the water discharge estimates. This dynamic constitutes the most significant uncertainty in the sediment flux estimates, so we attempted to account for bed changes using repeat cross section surveys between floods. Stage-discharge relations were estimated by applying Manning's equation to surveyed cross sections (roughness = 0.04 for the channel and 0.1 for the floodplain based on field velocity measurements by *Malmon* [2002]).

[20] A total of 11 flood events were sampled at one or more of the nine sites with the programmable sampler; 218 samples were analyzed for suspended sediment concentra-

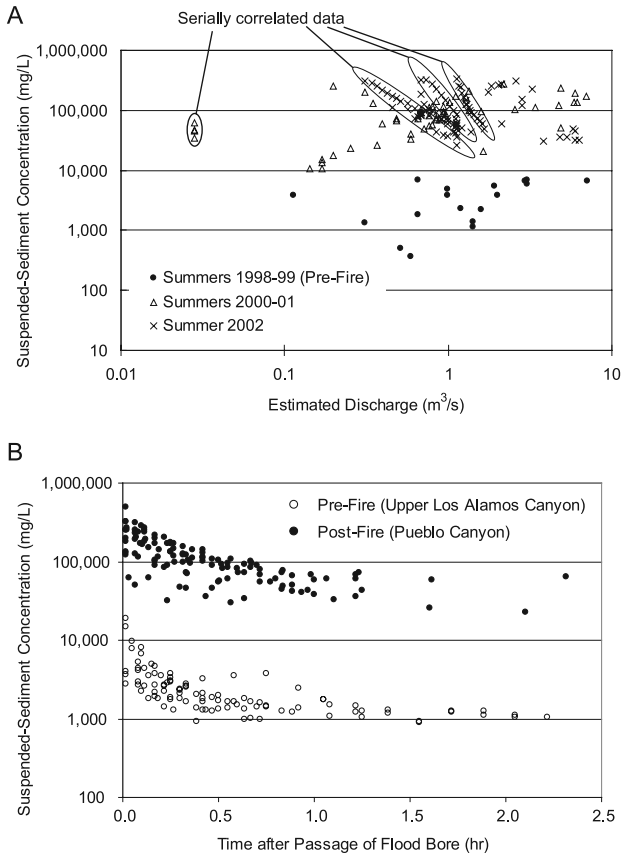

Figure 5. Comparison of measured suspended sediment concentrations (SSC) before and after the Cerro Grande fire (May 2000). (a) SSC plotted against estimated discharge. The circled points illustrate nonrandom scatter in data set, highlighting the fact that SSC sample data are serially correlated. Prefire data are from single-stage samplers and plotted against peak discharge, whereas postfire data are from automated pump-activated samplers and plotted against instantaneous discharge. (b) SSC plotted against time following the passage of the flood bore, in hours.

tion and 128 were selected for particle size analysis using a laser particle size analyzer at the Desert Research Institute in Reno, Nevada. All our samples were collected downstream of the burned area and upstream of the artificial wetland (Figure 1). The summer 2001 and 2002 data were impacted by construction activities in the floor of Pueblo Canyon for repairing (2001) and replacing (2002) a sewage pipeline that broke during the 2 July 2001 flood (peak flow estimated to be 41 m^3/s; [*Shaull et al.*, 2005]). These activities resulted in the mobilization of an unknown amount of sediment by increasing the amount of material susceptible to flood transport. The suspended sediment reported here includes wood ash derived from burn area slopes; we discuss the significance of this inclusion with respect to estimates of landscape erosion rates later in the paper.

[21] In this paper, we also incorporate secondary data from the following sources: a stream gage that is part of the LANL-gaging network (gage E060, *Shaull et al.* [2005]; Figure 1); suspended sediment concentration from nine grab samples collected at E060 (below the wetland) by the New Mexico Environment Department (NMED) [*Englert et al.*, 2004]; analyses by *Reneau and Kuyumjian* [2004] of rainfall data from a network of recording rain gages operated by LANL, the U.S. Geological Survey, and several interagency-operated Remote Automated Weather Stations (RAWS) installed after the fire; and sedimentation data based on repeat surveys of the Los Alamos Reservoir (Figure 1) over several years since the fire in the adjacent Los Alamos Canyon drainage basin [*Lavine et al.*, 2006].

4. Suspended Sediment Concentration in Flash Floods

4.1. Change in Sediment Concentration After the Fire

[22] Suspended sediment concentration (SSC) in flash floods in Pueblo Canyon increased dramatically in the years immediately following the fire; maximum SSC measured in floods increased from several thousand to several hundred thousand mg/L (Figure 5a). The prefire samples in Figure 5a are from single-stage samplers and may be biased slightly low for reasons noted above [*Malmon*, 2002]. Nonetheless, the data in Figure 5a illustrate the approximate magnitude of prefire and postfire sediment concentrations in Pueblo Canyon, and indicate that sediment concentrations increased by about 2 orders of magnitude in the years after the fire. The elevation in sediment concentration reflects multiple interacting factors as discussed above: enhanced mobilization of particles by rainsplash on hillslopes, increased overland flow and rill erosion, small-scale debris flows, and channel erosion during large postfire floods. In addition, the construction activities in the canyon bottom (discussed above) probably also contributed to elevated suspended sediment concentrations in the last 2 years of the postfire data set.

[23] *Gallaher and Koch* [2004] also reported elevated SSC in multiple canyons after the fire, citing our data and data compiled from other canyons. In their data set, samples collected throughout a hydrograph were combined in a splitter prior to laboratory analysis, thus producing a time-weighted average concentration. As explained in the next section, SSC varies systematically and nonlinearly with time, so their data set is missing crucial information about the concentration history during events that is necessary for estimating suspended sediment flux and for comparing their results with ours.

4.2. Relationship Between SSC and Time

[24] The standard method for analyzing suspended sediment data is to plot SSC against discharge (Figure 5a) and fit a regression equation (a sediment rating curve) to these data [*Leopold and Miller*, 1956; *Leopold et al.*, 1964]. One can then estimate the suspended sediment flux by applying the sediment rating curve to discharge hydrographs. This approach contains the implicit assumption that the fine sediment concentration is controlled primarily by flow magnitude, expressed as discharge. In the case of suspended sediment transport in small, ephemeral streams, especially following wildfires, SSC must be partly controlled by the intensity and spatial distribution of rainfall, as well as hillslope, channel, and floodplain processes. The complex interactions of many processes can lead to nonrandom

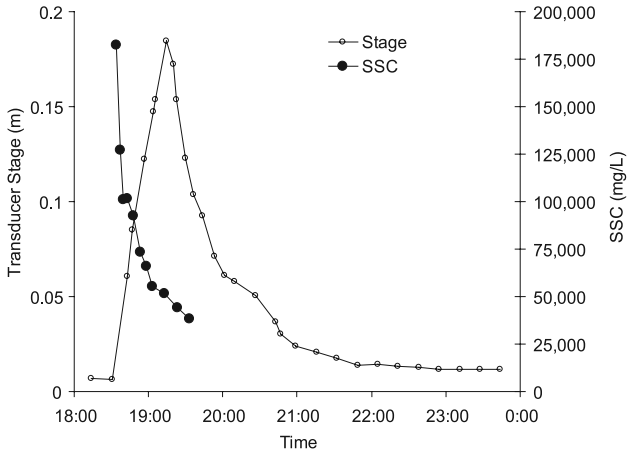

Figure 6. Comparison of stage and SSC during the flood on 31 July 2002 at the sampling station above Kwage Canyon (Figure 1). Stage increases for several minutes before the peak, and decreases afterward. In contrast, SSC is highest at the flood bore and decreases rapidly with time after the bore. This pattern was observed in every flood sampled both before and after the fire.

scatter in SSC data when plotted relative to discharge, which may not be the primary control on the suspended sediment transport rate (e.g., Figure 5a). Although a regression analysis may indicate a strong relationship between discharge and SSC, using a regression model such as a power law to compute sediment and contaminant fluxes would lead to a statistical violation, because the residuals are serially correlated (related in time). Discharge-suspended sediment relations have been computed for a number of ephemeral streams [*Negev*, 1969; *Renard and Laursen*, 1975; *Frostick et al.*, 1983; *Reid and Frostick*, 1987; *Sutherland and Bryan*, 1990; *Powell et al.*, 1996; *Bourke*, 2002; *Alexandrov et al.*, 2003], but these are usually characterized by poor statistical correlations. The poor quality of such relations is generally attributed to hysteresis in sediment concentration, with concentration generally higher on the rising limb than the falling limb of the hydrograph, although the converse has also been observed.

[25] More systematic trends are apparent when SSC is plotted relative to the time after the arrival of the flood bore at the local sampling location (Figure 5b). Although the postfire data in Figure 5b include samples from different locations and different events, there is a clear overall pattern in the data: Sediment concentration decreases rapidly following passage of the flood bore. The same trend is apparent in prefire sediment concentration data from the monitoring program in Los Alamos Canyon [*Malmon et al.*, 2004]. A pattern of monotonically decreasing SSC with time was evident in each of the events we sampled before and after the fire. It has also been observed in ephemeral channels elsewhere [*Dunkerley and Brown*, 1999].

4.3. Interpretation and Proposed Mechanism

[26] We interpret the suspended sediment concentration history in an event as implying that SSC is controlled by the availability of fine sediment rather than flow strength (as measured by discharge, shear stress, or stream power). This general explanation has been invoked to explain event and seasonal hysteresis in SSC in both ephemeral and perennial streams, including those with arid, temperate, tropical, and glacier-dominated watersheds [*Jeje et al.*, 1991; *Asselman*, 1999; *Lenzi and Marchi*, 2000; *Topping et al.*, 2000; *Richards and Moore*, 2003; *Sammori et al.*, 2004]. The interpretation that suspended sediment is controlled primarily by its supply from outside the channel is also supported by the poor temporal correlation between flow depth (and therefore shear stress) and sediment concentration during a typical event (Figure 6). The pattern might partially result from fine sediment mobilized on hillslopes and along channels shortly after the onset of runoff, which is primarily produced by infiltration excess overland flow. In addition, fine-grained sediment may be made available to the flood bore by bank collapse of floodplain material or deposition of fines in the bed on the recessional stages of the previous flow; this material may be remobilized at the onset of the subsequent flow [e.g., *Renard and Laursen*, 1975; *Malmon et al.*, 2004].

[27] In addition, we hypothesize that the observed pattern is also importantly, and perhaps dominantly, determined by in-channel processes intrinsic to the hydraulics of ephemeral stream flows, in the presence or absence of wildfire. In our field area and likely in other ephemeral channels, flow velocities at the flood peak are generally higher than the translational velocity of the flood bore [*Malmon*, 2002]. This may be due to greater momentum losses at the bore (Figure 3a), associated with water infiltration into the stream bed. On the basis of a scaling analysis of the equations governing flow as applied to ephemeral streams, *Mudd* [2006] recently showed that momentum loss due to water infiltration into ephemeral stream beds can be large compared with losses due to channel friction, and significantly affect flow velocity. Infiltration losses (and therefore momentum losses) are probably highest where the flood bore travels over unsaturated alluvium. As a result, water tends to accumulate near the flow front, producing the characteristic rapid rise to peak of flash flood hydrographs. In this model the fine-grained, suspended portion of the load (which travels close to the water velocity) would also accumulate at the flood bore, partly explaining the universal monotonically decreasing SSC observed in our data (e.g., Figure 6).

[28] Another factor contributing to the SSC history is the amplified water surface gradient of the flood bore. Because of the rapid stage rise at the flood bore, entrainment of the suspendible component of the bed material would also be enhanced near the flood bore because of the steepened slope of the water surface between the bore and the peak, and because of bed scour due to vertically oriented flow at the bore face. In the current study, this factor is likely to be of secondary importance, because of the high availability of fines from the burned area and on the basis of the grain size distribution of our samples (discussed below). However, the enhanced water surface gradient at the flood bore may play a greater role in the temporal pattern of SSC in nonburned, sand-dominated ephemeral streams, particularly those in lower-gradient valleys (i.e., in which the enhanced steepness of the rising limb would be relatively more important).

[29] Because the characteristic of monotonically declining SSC with time may be a common or possibly universal

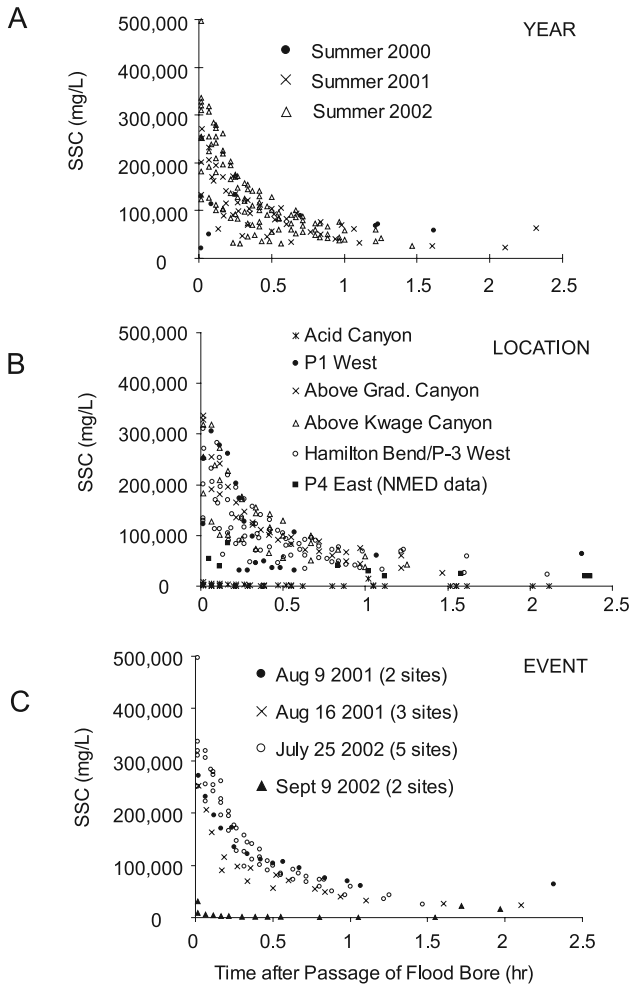

Figure 7. Postfire SSC data from Pueblo Canyon, plotted against time elapsed after the local passage of the flood bore. (a) Data labeled by year. (b) Data labeled by location (sampling sites in Figure 1). (c) Data labeled by date for four specific events.

characteristic of ephemeral stream flows, the traditional discharge-SSC rating curve methodology for computing suspended sediment flux may not be valid in many ephemeral streams. A possible alternative to the rating curve approach, which may be more valid for ephemeral streams, is to relate suspended sediment concentration to the time relative to the passage of the flood bore.

5. Other Characteristics of Suspended Sediment After the Fire

5.1. Spatial and Temporal Patterns in SSC

[30] In addition to improving flux calculations, plotting SSC data relative to the flood bore arrival time also helped clarify spatial and temporal patterns in the data set (Figure 7). We did not find any year-to-year decline that would indicate watershed recovery (to the extent that it is reflected in SSC) in the 3 years following the fire (Figure 7a, labeled by year). By contrast, survey data from the nearby Los Alamos Reservoir (discussed further below, and by *Lavine et al.* [2006] and *Reneau et al.* [2007]) indicate a strong trend of decreasing suspended sediment delivery over the first several years following the Cerro Grande fire. A possible explanation for this discrepancy is that the decline in the sediment yield with time following the fire was due to a reduction in flow volume, rather than declining SSC. In addition, the pipeline work discussed above may partially mask any postfire watershed recovery in suspended sediment concentration in our data set.

[31] No clear longitudinal patterns in SSC emerge from our data in Pueblo Canyon, which were all collected above an artificial wetland area in the lower part of Pueblo Canyon. Sediment concentration graphs are plotted by location in Figure 7b. Samples from Acid Canyon, a major tributary, plot much lower than samples from Pueblo Canyon because the watershed was not burned. Samples collected by NMED [*Englert et al.*, 2004] at the E060 gaging station (in the lower part of the wetland (Figure 1)) consistently plot lower than samples collected upstream (Figure 7b). This probably reflects the role of the wetland vegetation in dissipating floods and enhancing deposition of some of the suspended sediment load. Field observations [*Lyman et al.*, 2005] also indicate sedimentation in this reach. By contrast, a sediment routing model used by *Canfield et al.* [2005] to compute sediment transport in Pueblo Canyon predicted net erosion through this reach, which has a gradient slightly steeper than that upstream. The discrepancy might be explained if the aggradation observed in the wetland was due to deposition of suspended load, not bed load, as represented in the model with a shear stress-based sediment transport equation.

[32] Sediment concentration graphs for selected events (Figure 7c) suggest that each event exhibits a characteristic concentration time relation that remains constant along most of the length of Pueblo Canyon from P 1 West to P 4 West. This is also supported by data from events not plotted in Figure 7c. Other studies of suspended sediment in ephemeral streams have also observed that different events can exhibit distinctive SSC-discharge relations [*Lekach and Schick*, 1982; *Sharma et al.*, 1984; *Sutherland and Bryan*, 1990; *Cohen and Laronne*, 2005]. The sediment concentration in a particular flood is determined by a number of factors, including storm intensity, storm duration, time between storms, and the location of the rainstorm cell relative to the severely burned portions of the watershed. Our data are insufficient to quantitatively evaluate the relative importance of each of these factors, but given that SSC tends to be 2 orders of magnitude higher in the burned area than nonburned areas (Figure 5b), the relative location of rainfall and burned ground must be a primary factor in explaining our data set. For example, the 9 September 2002 flow (solid triangles) originated largely in Acid Canyon, the nonburned and partially urbanized tributary; thus the sediment concentration throughout the event is significantly lower than that measured in floods generated within the burned area (Figure 7c).

[33] While SSC typically decreases monotonically with time following the arrival of the flood bore, we find a notable lack of a relation between the initial (or peak) SSC and flood magnitude (Figure 8). One might expect that larger floods would be associated with higher SSC, since peak discharge might be a proxy for both rainfall intensity (and therefore the intensity of hillslope erosive processes)

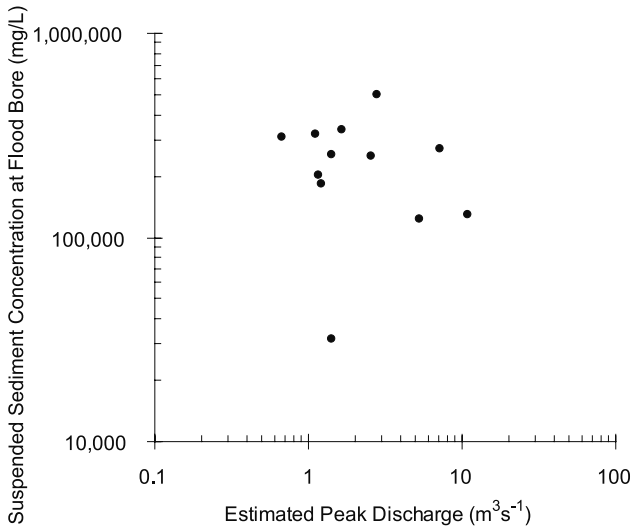

Figure 8. Maximum SSC plotted against estimated peak discharge. Several stations and dates are represented in this data set. No significant relation exists between peak sediment concentration and peak water discharge in this data set.

and flow strength. The lack of a relation in Figure 8 (and in analogous plots of peak SSC versus measures of rainfall intensity) emphasizes that suspended sediment transport in a particular flood is determined by a combination of factors other than water discharge or shear stress, as discussed above. The lack of a significant relationship between peak flow and peak suspended sediment concentration (Figure 8) further underscores that the standard rating curve technique may not be adequate for estimating suspended sediment transport in ephemeral streams.

5.2. Particle Size

[34] Our data indicate that the suspended sediment load became substantially finer following the fire. Prior to the fire, suspended sediment samples collected in both Pueblo and Los Alamos Canyons (Figure 9a) consisted of approximately 50% sand (particles coarser than 0.0625 mm diameter) and 50% silt and clay (particles finer than 0.0625 mm). Following the fire, the silt and clay fraction increased to 78%, indicating that the postfire erosion processes contributed largely fine grained material to flood flows in Pueblo Canyon.

[35] At least four separate factors contributed to the observed fining of the suspended load. One factor (discussed above in the "Field Area" section) is that the burned portions of the watershed contained a higher proportion of eolian-derived material compared with soils on the Pajarito Plateau, where most of the prefire floods were generated. In addition, the SSC values presented here include wood ash, which accounted for about 20% of the suspended sediment load in the first year following the fire, but was nearly negligible subsequently [*Reneau et al.*, 2007]. A third factor contributing to the fining of the sediment load after the fire is that unusually large magnitude postfire floods contained more sediment mobilized from erosion of fine-grained floodplain deposits in the valley floor. Finally, the trend documented in Figure 9 also represents the preferential erosion of fines (particularly eolian silt) from burned hillslopes, a phenomenon that has been observed following crown fires in the interior western United States [*Meyer and Wells*, 1997] and that can result in a coarse surface layer on recently burned hillslopes [*Morris and Moses*, 1987].

[36] The suspended sediment load tended to become finer with time during individual flow events. This pattern is characteristic of the data from both before and after the fire (Figure 9b), and may result from higher discharges and shear stresses near the flood bore, which are capable of mobilizing and suspending more sand from the channel bed, as well as preferential deposition of sand as discharge decreases in the recessional limbs of floods.

6. Sediment Delivery and Landscape Lowering in the Burn Area

[37] In this section we estimate the mass of suspended sediment delivered from the burned area in the Pueblo

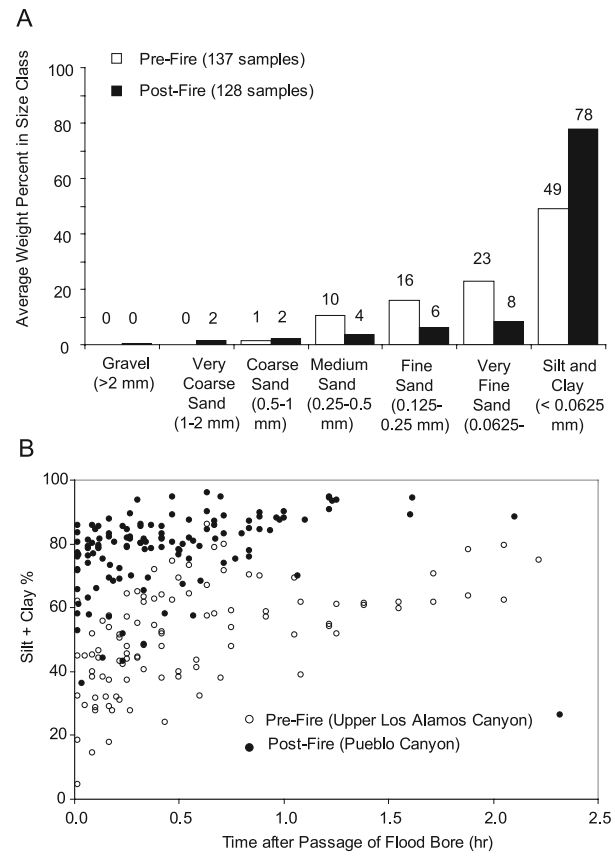

Figure 9. Suspended sediment particle size before and after the Cerro Grande fire. (a) Average particle size distributions of all suspended sediment samples for which particle size distribution were measured. Prefire data include 100 depth-integrated and pump samples from upper Los Alamos Canyon, and 37 samples from 14 single-stage samplers in Los Alamos, Pueblo, Acid, and DP Canyons. No significant particle size differences were noted among the different stations or sampling methods in the prefire data set. Postfire data are all from pump-activated samplers in Pueblo Canyon. (b) Percent silt and clay (particles smaller than 0.0625 mm) in suspended sediment samples over time during floods.

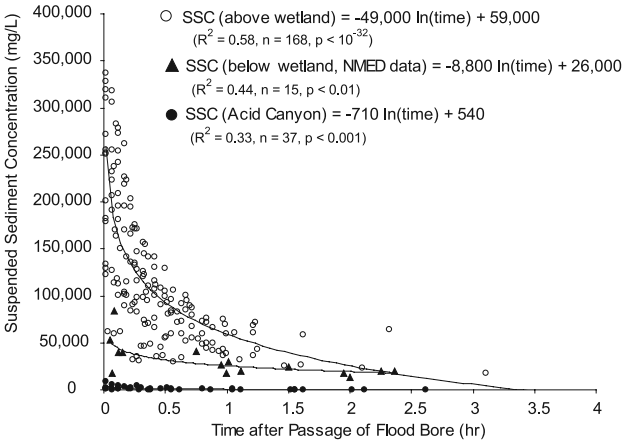

Figure 10. Logarithmic regression models fit to data from Pueblo Canyon above the wetland (open circles) and Acid Canyon (an urbanized and unburned tributary; solid circles) following the Cerro Grande fire. Triangles represent data collected by the NMED at gage E060, below the artificial wetland created by discharges from a wastewater treatment plant (see Figure 1). The regression model for Pueblo Canyon above the wetland was used to compute sediment fluxes. Fitted parameters all have units of mg/L.

Canyon watershed in the first 3 years after the fire. We use an empirical model that predicts the sediment yield (per km^2 of high and moderate severity burn) from 1-hour rainfall data, for which there exists a continuous record throughout the study period. We check our estimates by modeling fine-sediment deposition in the Los Alamos Reservoir (Figure 1) using rainfall data from the Los Alamos Canyon watershed. Sedimentation in the reservoir has been measured independently using repeated topographic surveys in the years following the fire [*Lavine et al.*, 2006].

6.1. Empirical Model of Suspended Sediment Yield

[38] Suspended sediment concentration in Pueblo Canyon can be modeled by fitting a time-dependent logarithmic decay function to the Pueblo Canyon suspended sediment data (Figure 10, open circles). A time-based rating curve provides a better fit to the data than a typical sediment discharge rating curve (e.g., Figure 5a) because it has a more realistic physical basis for ephemeral channels for the reasons discussed in the previous section. In addition, in general the uncertainty in discharge estimation for ephemeral streams is large compared with perennial streams, because of rapid changes in flow and water surface slope, as well as significant bed elevation changes [e.g., *Leopold et al.*, 1964]. The discharge rating curve method for computing sediment flux includes this discharge uncertainty twice: once in computing the rating curve itself, and a second time in multiplying the rating curve derived SSC by discharge to obtain the sediment flux. A time-based regression model (Figure 10) only incorporates this uncertainty one time, when SSC is multiplied by discharge.

[39] To estimate sediment yield from the burned portion of the watershed, we use a regression model based only on the subset of the data downstream of the burned area and upstream of the wetland (open circles, Figure 10). The open circles in Figure 10 represent all the timed samples collected in Pueblo Canyon between P1 West and P3 West (Figure 1). The logarithmic regression model fitted to these data predicts SSC as a function of time after the passage of the flood bore:

$$SSC = a^{*}\ln t + b \tag{1}$$

where SSC is the concentration (mg/L) of suspended sediment at time t, measured in hours after the arrival of the flood bore at the local sampling station, and $a = -49{,}000$ mg/L and $b = 59{,}000$ mg/L are fitted parameters ($R^2 = 0.58$, $n = 168$, $p < 10^{-32}$). Data from Acid Canyon and from the station near the mouth of Pueblo Canyon (E060) are also plotted for comparison; separate regression equations are fitted to these data in Figure 10, but the equations were not used in any further sediment discharge calculations.

[40] We searched our data set for discrete flood events for which the discharge hydrographs seemed qualitatively and quantitatively reasonable (on the basis of comparison with downstream gages and high-water indicators). We applied equation (1) to the hydrographs judged to be most reliable, and integrated the result to estimate the suspended sediment mass discharge associated with each hydrograph (Table 1). Four events were recorded at more than one station in Pueblo Canyon; for these events no systematic downstream variations in SSC or discharge were observed, and the sediment discharge estimates derived from different stations were averaged to produce a single suspended sediment discharge estimate for the event. Computed suspended sediment discharges were normalized by dividing each by 6.1 km^2, the area of high and moderate burn severity in the Pueblo Canyon watershed as computed by LANL's GIS Laboratory, on the basis of the assumption that all the fine sediment was produced from the burned area. This assumption seems reasonable within the range of uncertainty in the data, since both sediment concentration and water discharges from the burned area increased by more than an order of magnitude following the fire [*Johansen et al.*, 2001; *Gallaher and Koch*, 2004; *Shaull et al.*, 2005], and no systematic downstream changes in flux were observed between the burned area and the wetlands.

[41] Many variables control the sediment yield for an individual storm. We found a statistically significant relation between sediment yield and the maximum 1-hour rainfall over the burned area (Figure 11), determined by Thiessen averaging of data from three rainfall gages around the upper Pueblo Canyon watershed [*Reneau and Kuyumjian*, 2004]. Fluxes were plotted against the maximum 1-hour rainfall, rather than longer or shorter intervals, because floods are typically generated by high-intensity, short-duration rain, and because 1 hour is the shortest time increment measured at two of the gages.

[42] On the basis of this data set, estimated suspended sediment yield can be modeled with a linear regression equation:

$$y = cR - d \tag{2}$$

where y is the sediment yield (in metric tons per km^2 of high and moderate burn severity), and R is the maximum 1-hour,

Table 1. Estimated Suspended Sediment Fluxes During Measured Runoff Events in Summers 2000–2002

Date	Site	Computed Suspended Sediment Flux,[a] T	Estimated Suspended Sediment Yield From Burned Area,[b] T km^{-2}	1-hour Rainfall Over High and Moderate Burn Severity Portion of Watershed,[c] cm
		Summer 2000		
2 Aug 2000	P 1 West	1580	260	1.09
12 Aug 2000	Pueblo above Kwage Cyn	390	60	0.61
8 Sep 2000	Average, three stations	1480	240	1.32
12 Oct 2000	Pueblo above Kwage Cyn	210	30	0.48
24 Oct 2000	Pueblo above Kwage Cyn	1320	220	0.76
27 Oct 2000	Pueblo above Kwage Cyn	630	100	0.79
		Summer 2001		
4 Aug 2001	Pueblo near Hamilton Bend	220	40	0.41
9 Aug 2001	Average, two stations	1200	200	0.91
11 Aug 2001	Pueblo near Hamilton Bend	530	90	1.24
16 Aug 2001	Pueblo near Hamilton Bend	790	130	0.94
		Summer 2002		
25 Jul 2002	Average, four stations	470	80	0.94
31 Jul 2002	Average, five stations	1280	210	1.07

[a]Suspended sediment fluxes computed by applying equation (1) to estimated hydrographs.
[b]Event sediment yield per unit of high and moderate burn severity area in the Pueblo Canyon watershed (6.1 km^2).
[c]On the basis of Thiessen-averaging of multiple gages around Pueblo Canyon watershed [*Reneau and Kuyumjian*, 2004].

Thiessen-weighted rainfall (in cm). The fitted parameters are $c = 190$ and $d = 27$ ($R^2 = 0.42$, $n = 12$, $p < 0.05$). We use a linear regression equation to model the relation between rainfall intensity and sediment yield because the linear model is the simplest, and because there are not enough data or any field evidence that would support the application of a nonlinear model such as a power law. Although power laws are frequently used to extrapolate data in geomorphology, and such a model slightly improves the correlation as measured by R^2 (from 0.4 to 0.6, with a nonlinear exponent of 1.5), this relation would predict much higher sediment yields for rainstorms beyond the range of measured values (Figure 11). We have not observed any physical processes (such as deep, pore pressure induced slope failure) that would explain sediment yield increasing nonlinearly with rainfall intensity, although shortly after the fire, certain surface erosion mechanisms may have only operated above a small-to-moderate rainfall threshold.

6.2. Landscape Lowering Rate

[43] To obtain a landscape lowering rate for the burned area, we applied equation (2) to all the rainfall events for which the maximum weighted 1-hour rainfall exceeded 0.5 cm (Figure 12). The 0.5 cm rainfall threshold is based on field observations that smaller storms generally do not generate significant flows in the streams draining the burned or unburned areas [*Moody and Martin*, 2001b; *Malmon*, 2002; *Reneau and Kuyumjian*, 2004].

[44] Using this model, we estimate that approximately 20,700 metric tons (T) of suspended sediment were transported out of the burned area in the study period between May 2000 and October 2002 (Figure 12). An estimated 4,100 T (20% of the total) were transported in the 2 July 2001 event (Figure 12), produced by a rainstorm with estimated recurrence interval between 10 and 25 years (for the 1-hour rainfall) in the Pueblo Canyon watershed [*Reneau and Kuyumjian*, 2004].

[45] Assuming the suspended sediment derived dominantly from the 6.1 km^2 of severely burned area (a reasonable approximation based on field observations) this is equivalent to an average landscape lowering of ~3.4 mm over the burned area in the first 3 years following the fire (assuming a soil bulk density of 1 T/m^3), or an erosion rate

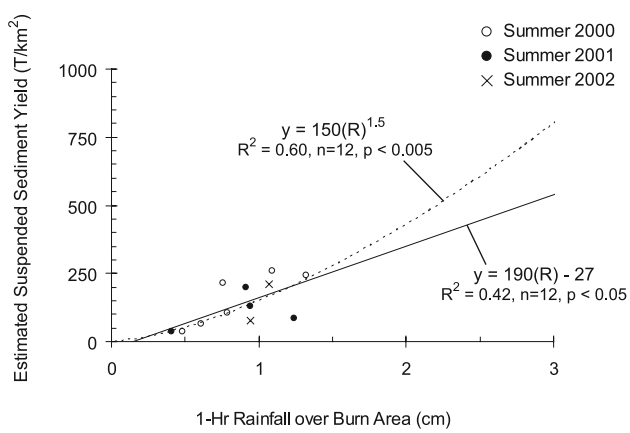

Figure 11. Computed suspended sediment yields in post-fire floods in Pueblo Canyon, plotted against the maximum 1-hour rainfall over the burned portion of the watershed. Data are from stations downstream of the burned area and upstream of the wetland. If fluxes were estimated at multiple stations for the same flood, only the average was included in this graph (see Table 1). Linear and power law regression equations computed from the 12 data points on this graph. Maximum 1-hour rainfall computed as an area-weighted average of rainfall data from three recording rain gages [*Reneau and Kuyumjian*, 2004]. Plotted sediment yields were normalized to the amount of burned area by dividing by 6.1 km^2 (the area of moderately and severely burned land in Pueblo Canyon watershed).

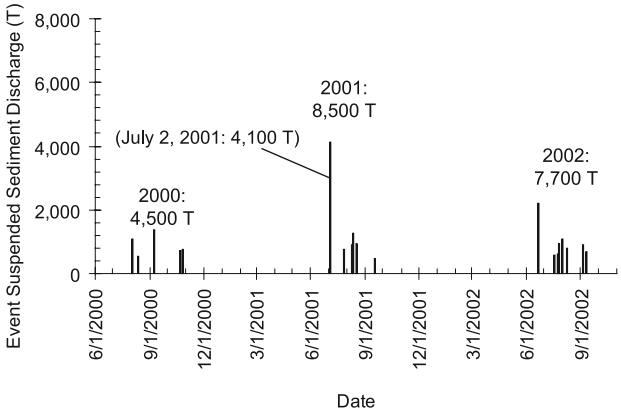

Figure 12. Time series of modeled suspended sediment delivery from the burned area in Pueblo Canyon in the 3 years following the Cerro Grande fire. Fluxes computed by applying equation (2) to the time series of daily maximum 1-hour rainfall over the burn area, computed from area-weighted averaging of data from three rain gages [*Reneau and Kuyumjian*, 2004]. Only storms with 1-hour rainfall exceeding 0.5 cm (0.2 in) were included in the calculation because smaller storms have not been observed to generate significant flow in the study area.

of 11 T ha^{-1} yr^{-1}. This estimate is of the same order of magnitude but lower than estimates of 46 and 70 T ha^{-1} for the erosion rate during the first year after the 1977 La Mesa fire (the first based on erosion pin estimates of landscape lowering, and the second based on a sediment trap with a contributing area of 92 m^2 [*White and Wells*, 1982]). This apparent decrease in the erosion rate with increasing watershed size could reflect (1) a net storage of fine-grained sediment in footslopes, and/or (2) the relative scarcity of significant rainfall the first summer (2000) following the fire in the Pueblo Canyon watershed. For comparison, *Shakesby and Doerr* [2006] compiled published postfire estimates of hillslope erosion rates using a variety of methods from moderate and severe fires worldwide. They also found that, in general, measured hillslope erosion rates are negatively correlated with the size of the area considered.

6.3. Sensitivity of Estimated Lowering Rate to Model Assumptions

[46] Several of the assumptions we made in these calculations are considered here with respect to the postfire erosion rate reported above. First, these estimations only include sediment transported in suspension, and do not include coarse sand and gravel that travel by sliding and rolling along the channel bed during most flows. In many fluvial systems, the suspended load accounts for a large to dominant fraction of the total sediment discharge [e.g., *Vanoni*, 1975; *Reid and Dunne*, 1996]. However, before the fire, the bed load accounted for an estimated 50% of the load, with much of this transported during snowmelt runoff, which carries a negligible amount of suspended load [*Malmon*, 2002]. As stated above, erosion on burned hillslopes preferentially entrained and delivered fine-grained, suspendible material, and increased the yield of suspended sediment by more than 2 orders of magnitude immediately after the fire [e.g., *Lavine et al.*, 2006]. However, the fires also introduced a component of coarse material into the channel network, much of which remains in storage [e.g., *Lyman et al.*, 2005, *Reneau et al.*, 2007]. Our exclusion of bed load may bias our lowering rate estimates low by a nonnegligible amount, but probably by much less than 50%.

[47] Second, these estimates of landscape lowering include fine-grained wood ash produced by burning, and thus would tend to overestimate the amount of surface lowering caused by the fire by a currently unknown amount. Qualitative field observations of floods, floodplain deposits, and examination of the postfire stratigraphy in the Los Alamos Reservoir suggest wood ash constituted a significant fraction of the SSC in the first few runoff events following the fire, but ash content in flood borne sediment decreased rapidly. Analyses of reservoir samples [*Reneau et al.*, 2007] indicate that about one-fifth of the suspended load consisted of ash in the first year following the fire, dropping to 4% in the second year, and to a negligible amount by the third year. Although the reservoir is in a different watershed, these values suggest the order of magnitude of overestimation of the lowering rate caused by the inclusion of the ash.

[48] Third, our modeled lowering rates assume a linear relationship between rainfall intensity and sediment yield. However, nonlinear increases in sediment yield with increasing rainfall intensity may occur in both burned and unburned watersheds, as some processes such as debris flow and hyperconcentrated flow may only operate above certain rainfall thresholds. Evidence for these processes was observed in the burned area [*Cannon et al.*, 2001]. A power law with an exponent of 1.5 can be fitted to the event sediment yield (Figure 11). The sediment yield computed using the power law is 22,200 T, 7% greater than the value of 20,700 T computed with the linear model. The difference of 1,500 T between the two estimates is relatively small; however, using a power law produces much higher yields for the larger events: 6,800 T versus 4,100 T for the 2 July 2001 storm, an event much larger than any of the events we sampled. Because of the poor constraint on the value of the exponent in the power law, and the possibility that such an equation may greatly overpredict sediment yield for larger storm events, we favor the linear model in this case. However, data from larger events are needed to further explore the relationship between rainfall intensity and sediment yield in large storms over burned watersheds.

[49] Finally, our calculations assume that all the sediment is produced in the moderately and severely burned areas, and furthermore, that all these areas contribute equally. In fact, some of the suspended sediment may have derived from outside the burned area, particularly in the urbanized areas or from exchanges of sediment with the channel bed or banks. In addition, sediment eroded from steeper areas of the watershed probably contributed disproportionately to the suspended sediment measured downstream of the burned area, and thus may have affected our lowering rate estimates. Because much of the burned area in the Pueblo Canyon watershed is underlain by the mesas formed on the Bandelier Tuff, there is a large proportion of relatively low-gradient hillslopes in the burned area (Figure 13). However, evidence of surface erosion was abundant on even these lower-gradient hillslopes after the fire. Thus while the steeper slopes may have contributed more sediment than

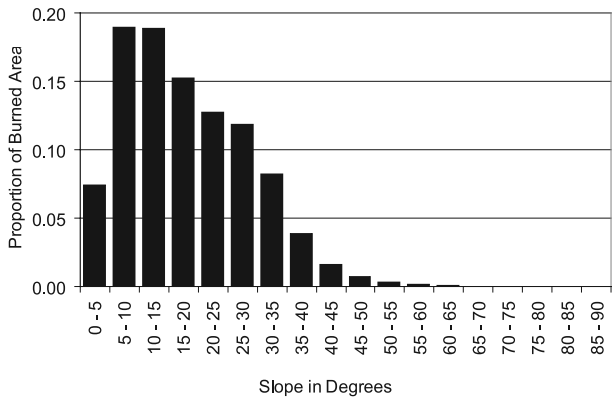

Figure 13. Distribution of slope for the moderate and high burn severity area within the Pueblo Canyon watershed.

gentler slopes, a large fraction of the watershed is underlain by hillslopes less prone to debris flow generation compared with other watersheds draining the Cerro Grande burn. The assumption that all the slopes contributed equally to the sediment yield estimate is flawed but necessary because of the lack of a quantitative basis for scaling erosion with hillslope gradient. Comparison of our sediment yield estimates with those in other burned watersheds should also consider the range of hillslope gradient in our study area (Figure 13).

6.4. Test of the Empirical Model Using Reservoir Sedimentation Data

[50] The Los Alamos Reservoir (Figure 1) provides an opportunity to test our empirical model of postfire sediment delivery against independent data in an adjacent watershed. The reservoir was constructed in 1943 for water storage for the new laboratory and town of Los Alamos. The reservoir was drained following the fire to provide flood control to the canyon downstream. The reservoir floor was first surveyed using a total station following the drainage of the reservoir and a single postfire storm (2 June 2000) that had deposited an estimated 1,800 metric tons (T) of fine sediment rich in ash [*Lavine et al.*, 2006]. The reservoir was subsequently surveyed seven additional times, most recently in July and August 2005. Sedimentation amounts for several intervals during the first 3 years after the fire, concurrent with our sediment sampling study in Pueblo Canyon, are based on data from *Lavine et al.* [2006]. For the current analysis, we have excluded deposition of the coarse portion of the load in the delta at the upstream end of the reservoir. Thus the survey-based sedimentation data only represent deposition of the fine-grained portion of the sediment load included in our model (mostly fine sand to clay). We assume the reservoir trapped 100% of the fine sediment that entered the pool at the upstream end (an approximation supported by the observation that postfire floods were mostly dissipated by this reservoir and by comparison with sediment transport data from a downstream gage [*Gallaher and Koch*, 2004]), although small amounts of fine sediment were released during reservoir draining and overflow events. Volumes were converted to mass using a bulk density of 1.12 T/m^3 based on 18 samples from a 4-m thick section of postfire sediment exposed by sediment excavation operations between August 2001 and April 2002.

[51] To predict suspended sediment yield to the reservoir, we used equation (2) along with rainfall data for the moderate and high-severity burn portion of the Los Alamos Canyon watershed. The relation from Figure 11 was applied to the daily maximum 1-hour precipitation record for the burned area upstream of the reservoir (on the basis of Thiessen averaging of four recording rain gages in and around the watershed; Figure 1), for days exceeding 0.5 cm precipitation from May through October. The record was divided into the same four time intervals for which sedimentation estimates are available. The modeled and measured sediment yields are compared in Figure 14.

[52] The total sediment yields are almost identical over the 3-year study period: The model, based on rainfall, predicts 28,300 T of suspended sediment delivery to the Los Alamos Reservoir through 23 July 2003, compared with an estimated 28,700 T based on reservoir sedimentation data. This comparison suggests that the empirical model developed above produces reasonable predictions of the magnitude of suspended sediment delivery from the burned area in the 3 years following the fire. However, the near perfect agreement between the modeled and measured data over the entire study period is almost certainly a coincidence, considering the simplicity of the model and the uncertainties in model input and reservoir survey data. In fact, systematic discrepancies between predicted and measured sediment delivery for specific time intervals may indicate a negative trend in sediment delivery over

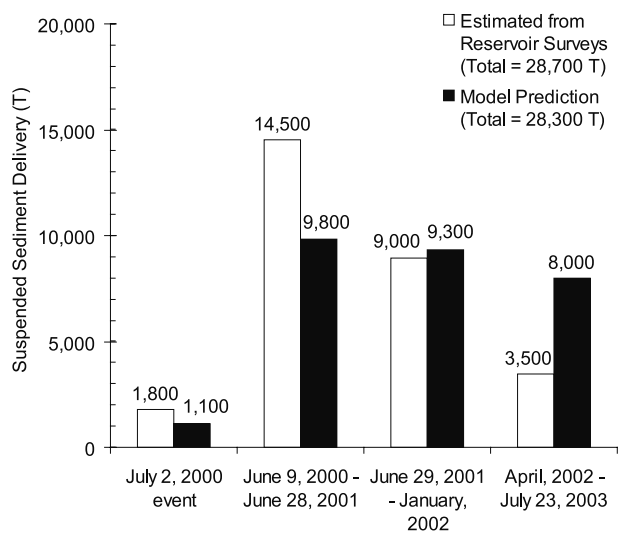

Figure 14. Comparison of modeled suspended sediment yield from the Los Alamos Canyon burn area (Figure 1) with rates estimated from repeat surveys of the Los Alamos Reservoir [*Lavine et al.*, 2006]. Modeled data were derived by applying equation (2) to the time series of daily maximum 1-hour rainfall (exceeding 0.5 cm) over the burn area in the watershed draining to the reservoir. Rainfall amounts based on area-weighted averaging of data from four rain gages in and around the upper Los Alamos Canyon watershed.

the 3-year postfire period: The model underpredicted fine sediment delivery in the first two measurement intervals (covering May 2000 through June 2001) and overpredicted in the last measurement interval (April 2002 through July 2003). A likely explanation for this discrepancy is postfire watershed recovery in the Los Alamos Canyon watershed, including vegetation regrowth, fire remediation activities over part of the burned area, as well as depletion of the mobile soil cover and exposure of patches of bedrock in the first year or two following the fire. Because we were not able to observe a decreasing trend in our suspended sediment data set (possibly because of channel disturbance in Pueblo Canyon in 2001–2002), our model did not account for postfire changes in the sediment-rainfall relation. However, the systematic discrepancies between predicted and measured sedimentation rates in the reservoir suggest that the decreasing sedimentation rates in the reservoir in the years after the fire [*Lavine et al.*, 2006] are probably due to decreasing erosion rates rather than differences in rainstorm frequency and intensity. The trend of decreasing sediment yields over several months and years after a fire, likely due to revegetation, which proceeded most rapidly during the first summer, are consistent with the findings of others in steep, burned watersheds [e.g., *Meyer and Wells*, 1997; *Meyer*, 2004].

7. Discussion and Conclusions

[53] This study was designed to examine the characteristics and magnitude of suspended sediment transport in an ephemeral channel following a major wildfire, using detailed field measurements. We observed that SSC increased by up to 2 orders of magnitude following the fire, and that the proportion of silt and clay in suspension increased from about 50% before the fire to 78% afterward. We found little to no year-to-year variations in SSC in floods due to watershed recovery in the years after the fire, an effect possibly masked in our data set by human disturbance of the channel. The data exhibit relatively little spatial variation in SSC along the ~10 km study reach located downstream of the burned area and upstream of an artificial wetland (although concentrations were lower below the wetland). The maximum sediment concentration in floods was not correlated to the size of the flood; instead, concentrations appeared to be more closely linked to characteristics of individual storms, including short-duration rainfall intensity and the location of thunderstorm cells relative to the most severely burned portion of the watershed.

[54] While we observed no apparent relation between maximum sediment concentration and peak flow, we found a statistically significant relation between event sediment yield and maximum 1-hour rainfall over the burned portion of the watershed. Using this relation and a rainfall record, we estimate a total suspended sediment yield of approximately 20,700 T (equivalent to about 3.4 mm lowering over the burn area) in the 3-year period following the fire, which includes one flood (2 July 2001) produced by a rainstorm with an estimated recurrence interval of about 10–25 years [*Reneau and Kuyumjian*, 2004]. This model prediction was checked by using the same regression model and data from different rain gages to predict the volume of fine-grained sediment deposition in Los Alamos Reservoir, in an adjacent burned watershed. While the comparison indicated that our modeled sediment yields were of the correct order of magnitude, systematic discrepancies between modeled and measured yields seem to indicate decreasing yields over time (accounting for rainfall), and suggest that the bulk of the fine-grained sediment produced by this fire was carried by floods in the first 1–2 years after the fire.

[55] Our data set demonstrates that sediment concentration in our field area (and likely in many other ephemeral streams) is always highest at the flood bore and decreases rapidly with time, a relation that can be approximated well with a logarithmic regression model. This pattern was also observed in a nearby canyon prior to the fire, and has been observed in ephemeral streams elsewhere. We interpret this pattern to imply that sediment availability plays a more important role in governing SSC than transport capacity, and that significantly more sediment is available close to the flood bore because of both channel and hillslope processes. The fact that washload concentration is highest at the flood bore and decreases monotonically may relate to the observation [*Malmon*, 2002] that the water velocity at the flood peak is generally faster than the propagation velocity of the flood bore, possibly because of greater momentum losses at the flow front compared with the flow peak. We speculate that this dynamic may cause water and sediment traveling at water velocity to accumulate just behind the flood bore in ephemeral stream flows. This may also partially explain the characteristically steep rising limbs of ephemeral stream hydrographs. The observation that SSC is poorly correlated with discharge contradicts many previous analyses and predictive models of suspended sediment transport in both burned and unburned watersheds, which often relate the sediment transport rate to instantaneous water discharge (using suspended sediment rating curves) or to flow strength (using shear stress or stream power-based sediment transport models). Future data collection efforts and predictive models of suspended sediment transport in ephemeral channels (in the presence or absence of wildfires) might be improved by assimilating the apparently robust observation about the close correlation between sediment concentration and time after the passage of the flood bore.

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