Sediment delivery after a wildfire

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ABSTRACT

We use a record of sedimentation in a small reservoir within the Cerro Grande burn area, New Mexico, to document postfire delivery of ash, other fine-grained sediment carried in suspension within floods, and coarse-grained sediment transported as bedload over a five-year period. Ash content of sediment layers is estimated using fallout 137Cs as a tracer, and ash concentrations are shown to rapidly decrease through a series of moderate-intensity convective storms in the first rainy season after the fire. Over 90% of the ash was delivered to the reservoir in the first year, and ash concentrations in suspended sediment were negligible after the second year. Delivery of the remainder of the fine sediment also declined rapidly after the first year due to the occurrence of higher-intensity storms in the second year. Fine sediment loads after five years remained significantly above prefire averages. Deposition of coarse-grained sediment was irregular in time and was associated with transport by snowmelt runoff of sediment stored along the upstream channel during short-duration summer floods. Coarse sediment delivery in the first four years was strongly correlated with snowmelt volume, suggesting a transport-limited system with abundant available sediment. Transport rates of coarse sediment declined in the fifth year, consistent with a transition to a more stable channel as the accessible sediment supply was depleted and the channel bed coarsened. Maximum impacts from ash and other fine-grained sediment therefore occurred soon after the fire, whereas the downstream impacts from coarse-grained sediment were attenuated by the more gradual process of bedload sediment transport.

Keywords: sediment load, sedimentation rates, erosion rates, fires, cession, New Mexico.

INTRODUCTION

Sediment delivery to streams can be highly episodic as a result of the influence of high-magnitude, low-frequency events, such as major storms or wildfires (Benda and Dunne, 1997). Fires are recognized as major catalysts for erosion and sediment transport in many landscapes, and a large fraction of the total long-term erosion can be associated with short periods after fires (Swanson, 1981; Meyer and Pierce, 2003; Roering and Gerber, 2005). Intense fires result in loss of ground cover and reductions in infiltration rates due to development of hydrophobic layers or surface sealing with ash or fine sediment, enhancing runoff and surface erosion (Shakesby and Doern, 2006). Landslides and debris flows in burned areas can also enhance sediment supply (Meyer and Wells, 1997; Cannon, 2001). Another aspect of sediment delivery after fires is the transport of ash into streams, which can have major impacts on water quality and aquatic communities (Gresswell, 1999; Ranalli, 2004). Sediment delivery downstream from burned areas or other sites of increased erosion is modulated by differential transport of various-sized particles. Deposition of debris flows and the coarsest sediment supplied from low-order basins often occurs where energy decreases on alluvial fans or close to drainage confluences (Benda and Dunne, 1997; Meyer and Wells, 1997). Extensive aggradation can also occur downstream due to deposition of bedload when the transport capacity of higher-order streams is exceeded (Moody and Martin, 2001), resulting in initial export of only part of the eroded sediment. These deposits can then constitute secondary sources for sediment, prolonging the effects of the original disturbance, or instead be preserved as relatively long-lived landforms. In contrast, finer sediment carried in suspension can be transported longer distances and have more immediate and widespread effects, impacting aquatic communities and water supplies further from the source of sediment.

The magnitude and duration of the impacts of fire and the relative production and fate of fine versus coarse sediment are affected by various factors including local topography, soils, vegetation, climate, burn severity, and the intensity of subsequent storms. In this paper, we use the sedimentation record in a small reservoir to document five years of sediment delivery in a montane watershed that was affected by wildfire, compare it with the prefire conditions, and highlight the contrasting fate of coarse and fine sediment and the significance of ash in the fine component.

SETTING

The May 2000 Cerro Grande fire burned ~17,400 ha in the eastern Jemez Mountains and Pajarito Plateau of northern New Mexico. Over much of its extent it was a stand-replacing crown fire that resulted in major hydrologic changes associated with widespread tree mortality, loss of ground cover, and creation of hydrophobic soil conditions (BAER, 2000). This paper focuses on the sedimentation record in the Los Alamos Reservoir, which was constructed in 1943 with a spillway capacity of ~41,000 m³ and is located within the burn area in Los Alamos Canyon. The reservoir was drained after the fire to help provide flood protection to downstream facilities, and sediment was later excavated to maintain storage capacity. All of the coarse sediment supplied from the upstream burn area was trapped in the reservoir, and a comparison of reservoir sedimentation with suspended sediment flux at a downstream station indicated >95% trapping efficiency for fine sediment.

The watershed above the Los Alamos Reservoir (16.6 km², 2320-3180 m in elevation) is mostly underlain by Miocene to Pleistocene dacite lavas and rhyolite tuffs of the Jemez volcanic field. Particle size analyses indicate that soils here have a bimodal textural distribution, largely composed of a mixture of silt and clay, inferred to beolian-derived, and locally derived gravel, with lesser amounts of sand. Average annual precipitation is ~65 cm, about half of which occurs in relatively high-intensity, short-duration convective storms during the summer monsoon season; much of the remainder consists of snow. Above the reservoir, 5.4 km² of the watershed experienced 0% to over 100% tree mortality (BAER, 2000), including some of the steepest parts of the basin, and 5.3 km² experienced low burn severity and minimal hydrologic changes, as evidenced by preservation of ash and charred duff five years later. Before the fire, the area of high and moderate burn severity largely supported a mixed conifer forest that was dominated by Douglas fir, white fir, and ponderosa pine. Fuel load was high, due largely to a major reduction in fire frequency since the 1890s associated with land use changes and fire suppression (Touchan et al., 1996), which contributed to the intensity of the fire. After the fire, hillside processes included sheetwash and rill
eroded and the generation of small debris flows (Cannon et al., 2001). Flood magnitude and suspended sediment flux in downstream canyons increased by at least two orders of magnitude (Gallaher and Koch, 2004). The transport of ash from the burn area contributed to a decline in water quality, including high concentrations of fallout radionuclides such as $^{137}$Cs that had accumulated in forest litter (Katzman et al., 2001; Johnsen et al., 2003; Gallaher and Koch, 2004). Extensive postfire rehabilitation measures were undertaken in the Cerro Grande burn area, of which the most effective was the application of straw mulch on relatively low-gradient hillslopes (Dean, 2001); ~0.6 km$^2$ of the watershed above the reservoir was treated with straw mulch in May 2000.

METHODS

Total station surveys of the bottom of the Los Alamos Reservoir were performed annually from June 2000 through July 2005. Surveys occurred at the beginning of, or just before, the summer monsoon season, supplemented by additional surveys in other seasons; this allowed for approximately annual calculations of sediment volume (Lavine et al., 2006), which were converted to sediment mass using bulk density measurements. During excavation of sediments in October 2001, samples were collected for bulk density, particle size, and radiochemical analyses from a 4.5 m stratigraphic section in the middle of the reservoir that included the period of highest sedimentation rates. The dates of some specific stratigraphic layers were determined by comparing their upper elevations with elevations obtained from previous surveys of the reservoir floor. Dates of other layers were inferred based on field observations of runoff events and by comparison with rainfall records in the burn area (Lavine et al., 2006). Concentrations of the fallout radionuclide $^{137}$Cs were used as a tracer to calculate the ash content in postfire sediment and to evaluate how this changed over time. Field observations of erosion and deposition from the upstream watershed provided supplemental information on the supply of sediment to the reservoir.

Calculation of Ash Content

Because the concentrations of many constituents in ash are elevated relative to prefire sediments (e.g., Katzman et al., 2001), the concentrations of specific constituents in prefire and postfire sediments and in ash can be used to estimate ash contents of postfire sediment samples. The concentration of a constituent in a postfire sediment sample, $C$, is

$$C = C_a f_a + C_f f_f,$$

where $C_a$ is the concentration in ash, $C_f$ is the concentration in the remaining sediment, and $f_a$ and $f_f$ are the fractions of ash and other sediment in the sample, respectively. Concentrations commonly vary inversely with particle size, and we use a simple linear regression between concentration and particle size (based on data from prefire sediment samples) to approximate this relation:

$$C_a = a + b f_f,$$

where $a$ and $b$ are the intercept and slope, and $f_f$ is the silt and clay fraction of prefire samples. The silt and clay fraction of a postfire sample, $f_f$, is the sum of $f_{sf}$ and $f_s$. Using these relations (and assuming Equation 2 holds for the nonash portion of postfire samples), $C$ can be given as

$$C = C_a f_a + (a + b(f_f - f_s))(1 - f_f),$$

which can be rearranged as

$$f_f = (C - a - b f_f) [C_a - a - b(1 + f_f - f_s)]^{-1},$$

with $f_f$ determined by iteration. We assume that changes in soil particle size distribution that may accompany fires have negligible influence on these calculations, although an increase in sand-sized particles by aggregation of clay particles (Giovannini and Lucchesi, 1997) could lead to an overestimation of the ash content of coarse-grained samples.

In this study, we use $^{137}$Cs concentrations to calculate ash contents of postfire sediment samples (Table DR1). Using data from prefire active channel and floodplain samples in McDonald et al. (2003), we obtain an intercept of 0.02 and a slope of 0.85, with units in pCi/g ($n = 16$, excluding one outlier; $R^2 = 0.54, p = 0.02$). We use the average $^{137}$Cs concentration in Cerro Grande ash of 13.0 pCi/g as $C_a$, and a systematic uncertainty in calculated ash content of ~32% is imparted by the variability in $^{137}$Cs in ash ($\sigma = 4.1$ pCi/g; $n = 13$).

RESULTS

Analyses of sediment from the Los Alamos Reservoir reveal temporal trends in ash delivery from the Cerro Grande burn area over the first two rainy seasons after the fire. Figure 1 shows $^{137}$Cs concentration as a function of silt and clay content for different runoff events, and it displays the inverse relations between particle size and $^{137}$Cs and systematic declines in $^{137}$Cs over time. A sample of prefire reservoir sediment (1943–2000) plots close to the regression obtained from prefire samples of McDonald et al. (2003). Using Equation 4, we estimate that sediment from 28 June and 16 July 2000 contained ~39 ± 13% ash in the silt and clay fraction, and that by summer 2001, this had declined to 6 ± 2%. Elevated $^{137}$Cs in a sample of 2 June 2000 sediment from the reservoir (not shown), which was the first runoff event after the Cerro Grande fire, indicates an ash content of ~77 ± 24% in the silt and clay fraction of the first event.

Delivery of ash to the reservoir largely occurred in response to a series of relatively moderate convective storms in summer 2000, which had estimated average 1 h and 2 h rainfall totals less than a 1 yr return period event (17 and 23 mm; Reneau et al., 2003) (Fig. 2). An estimated 42% of the ash delivery occurred in five storms from 2 June to 16 July 2000, and an additional 33% in a storm on 18 July 2000. Erosion and sediment transport on 18 July was disproportionately high relative to the rainfall total, which may have been facilitated by high antecedent moisture conditions and/or high intensity rainfall of limited areal extent that was not recorded at the gauges. Only minor amounts of ash were supplied in summer 2001 despite two more intense storms with 1–2 yr return periods.
Figure 2. Estimated cumulative ash deposition in Los Alamos Reservoir following Cerro Grande fire. Estimated 2 h average precipitation for selected events is shown in parentheses (amounts are Thiessen averages using four gauges in or near watershed with 1 h measurement intervals; storm runoff is mainly in response to short-duration rainfall, and use of 2 h amounts reduces effect of maximum rainfall intensity straddling measurement intervals).

Figure 3. Annual sedimentation in Los Alamos Reservoir, distinguishing coarse-grained sediment in delta (dominantly coarse to very coarse sand and gravel) from ash and other fine-grained sediment (dominantly fine sand to clay). Measured sediment volumes and conversions to mass are presented in Table DR2 (see text footnote 1).

Figure 4. Coarse sediment delivery to Los Alamos Reservoir versus snowmelt runoff. Runoff equals totals measured February through May at gauging station 3 km downstream from reservoir. Coarse sediment delivery in 2001–2004 strongly correlates with runoff, suggesting a transport-limited system associated with abundant, easily mobilized sediment in channel bed. In contrast, comparatively lower delivery in 2005 suggests a reduction in available sediment.
first storm. Our data show that the percent of ash in suspended sediment progressively decreased through the first rainy season, and was low in the second rainy season (Fig. 1). In the study area, over 90% of the ash transport to the reservoir occurred in the first year, largely in floods generated by convective storms (Fig. 2). The decreasing ash content over time is consistent with the common generation of debris flows in the first significant rainfall events after a fire and the inferred importance of ash in debris-flows generation from burned slopes (Cannon, 2001; Cannon et al., 2001). The decreasing supply of ash and other fine sediment may be in part related to development of rill networks that isolate parts of the slopes from surface runoff (Collins and Dunne, 1986) or compaction that decreases the erodibility of surface soils (Meyer and Wells, 1997), as well as depletion of fines from soils.

The rapid decline in transport of fine-grained sediment, which represents the suspended load in runoff, contrasts with the more prolonged delivery of coarse-grained sediment, which represents bedload transport (Fig. 3). Field observations indicate that aggradation of the valley bottom upstream from the reservoir occurred during short-duration summer floods, and that these deposits then provided the source for bedload-size sediment during snowmelt runoff events that extended for 1–4 mo. Significant transport of coarse sediment in relatively long-duration snowmelt runoff, following initial delivery to channels during short-duration summer storms, has also been observed in other areas after fires (e.g., Moody and Martin, 2001). Differences in the timing of transport of fine-grained versus coarse-grained sediment are consistent with data collected downstream in Los Alamos Canyon prior to the Cerro Grande fire, where essentially all the suspended sediment transport occurred in flash floods, but a significant portion of bedload transport occurred during snowmelt runoff (Malmon et al., 2004). In this environment, high-energy flash floods generated from convective storms are most effective at mobilizing and transporting fine-grained sediment, yet less effective at sustained transport of coarse-grained sediment. Maximum impacts from ash and other fine-grained sediment thus occur soon after a fire, whereas the pulse of coarse-grained sediment can be significantly attenuated and delayed pending flows capable of sustained bedload transport.

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