A FIVE-YEAR RECORD OF SEDIMENTATION IN THE LOS ALAMOS RESERVOIR, NEW MEXICO, FOLLOWING THE CERRO GRANDE FIRE

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The Cerro Grande fire of May 2000 burned approximately 17,400 ha in the eastern Jemez Mountains and the Pajarito Plateau in the vicinity of Los Alamos, New Mexico. Changes in surface characteristics from the fire resulted in significant increases in runoff and erosion relative to pre-fire conditions. This study documents five years of sedimentation in the Los Alamos Reservoir, providing a unique data set for evaluating changes in post-fire erosion rates and watershed recovery in a montane watershed. The reservoir was built in 1943 for water storage and supply, with an upstream drainage basin area of about 16.5 km^2, elevations of 2320 to 3180 m, and largely supported a mixed conifer forest prior to the fire. Thirty two percent of the basin experienced moderate to high burn severity, including some of the steepest parts of the basin; 32% experienced low burn severity and 36% was unburned. Draining of the reservoir in June 2000 allowed for detailed surveying of the top of pre- and post-fire sediments. The initial total station survey, in combination with a detailed 1943 as-built drawing, indicated ~1600 m^3 of sediment was deposited during 1 post-fire event and ~8600 m^3 in the previous 57 years. Average sediment deposition was ~150 m^3/yr prior to the fire, equivalent to an average basin-wide denudation rate of soil of ~ 0.009 mm/yr. When the total station survey was repeated in June 2001, a large delta consisting of sand and gravel had formed at the head of the reservoir. The remainder of the reservoir basin contained predominantly fine to very fine sand, silt, and ash. These combined facies constituted ~21,800 m^3 of sediment accumulated in one year, equivalent to an average basin-wide denudation rate of ~1.3 mm/yr or ~140 times the average pre-fire rate. Assuming that all of the sediment deposited during the first year after the fire was derived from the high- and moderate-severity burn areas (5.4 km^2), yields an average denudation rate of ~4.0 mm/yr for those areas, ~450 times the pre-fire rate. Surveys performed in the second year after the fire record ~8000 m^3 of sedimentation between June 2001 and April 2002, when the reservoir was excavated to retain storage capacity. Subsequent surveys document reduced sedimentation as compared with the first two years (Figure 1): between April 2002 and July 2003 ~4000 m^3 of sediment, with some coarse-grained material forming a small delta; between July 2003 and July 2004 ~4800 m^3 of sediment, with ~3700 m^3 comprising a coarse-grained delta; and between July 2004 and July 2005 ~4500 m^3 of sediment, with ~3500 m^3 comprising a coarse-grained delta. The total amount of sediment deposited in the reservoir during the 5-year period after the fire was ~43,100 m^3, ~70% fine-grained sediment and ~30% coarse-grained sediment. About half of the post-fire sedimentation occurred in the first year. Delivery of fine-grained sediment to the reservoir decreased rapidly after the first year, although higher-intensity rainstorms occurred in 2001 to 2003 than in 2000, reflecting reduced hillslope erosion associated with watershed recovery. In contrast, delivery of coarse-grained sediment varied with the magnitude of snowmelt runoff, associated with remobilization of sediment previously deposited along the upstream channel, and did not vary systematically over time.

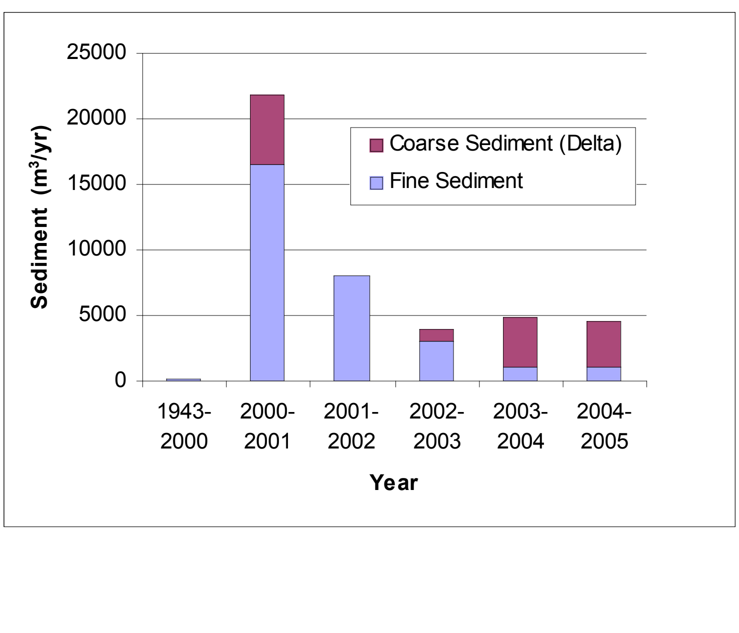

Figure 1. Plot of annual sedimentation in the Los Alamos Reservoir, distinguishing coarse-grained sediment in the delta that predominantly reflects snowmelt runoff and fine-grained sediment that predominantly reflects suspended transport in summer floods. Note the annual decrease in the amount of fine sediments, and the non-systematic variations in the deposition of coarse-grained sediment in the delta.

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INTRODUCTION

The Cerro Grande fire of May 2000 burned approximately 17,400 ha in the eastern Jemez Mountains and the Pajarito Plateau in the vicinity of Los Alamos, New Mexico (BAER, 2000; Figure 1). Changes in surface characteristics caused by the fire resulted in significant increases in runoff and erosion relative to pre-fire conditions. This study documents five years of sedimentation in the Los Alamos Reservoir, providing a unique data set for examining post-fire erosion and sediment delivery in a montane watershed. The drainage basin above the dam has an area of about 16.6 km^2, elevations of 2320 to 3180 m, and supported a predominantly mixed conifer forest prior to the fire dominated by ponderosa pine, Douglas fir, and white fir. Thirty two percent of the basin experienced moderate to high burn severity, with complete loss of groundcover and development of hydrophobic soil conditions, including some of the steepest parts of the basin; 32% experienced low burn severity and 36% was unburned (Figures 1b, 1c). A variety of geologic units are present in the watershed above the reservoir, including dacite (the dominant rock type), nonwelded to welded tuffs, and conglomerate. Approximately 50% of the precipitation in the area is from high-intensity, short duration summer rainstorms (during the “summer monsoon”) with most of the remainder from winter snowfall (Bowen, 1990).

The sedimentation record within the Los Alamos Reservoir offered a unique opportunity to study post-fire sediment delivery, including changes over time associated with watershed recovery, and to compare pre-fire and post-fire rates. The reservoir was built for water storage and supply in 1943. Serendipitously, it provided sufficient capacity to capture 15 months of delivered material from upstream burned areas after the fire, while allowing for draining and access for detailed surveys. Only a few overflows, carrying ash and suspended solids, occurred in the five years following the fire. Prior to the fire, the reservoir received minor amounts of sediment and had never been dredged, preserving a 57-year record of sedimentation. Because of concerns about potential post-fire flood damage to facilities downstream from the reservoir, it was drained several times and excavated when it was full of sediment to retain storage capacity. Subsequent partial excavation of a coarse-grained delta also occurred. We were able to coordinate our surveys with times when the reservoir was drained and before and after it was excavated, leading to a 5-year record of the amount and type of sedimentation following the fire. Local precipitation data allowed putting this record into the context of short-term and long-term precipitation, and examination of stratigraphy exposed in excavations allowed understanding of the effects of specific storm events.

METHODS

Total station surveys were performed annually at the Los Alamos Reservoir at the beginning of, or just before, the summer monsoon season, supplemented by additional surveys in other seasons. This allowed for yearly estimates of sedimentation. Eight surveys were performed: June 8 and 12, 2000; June 28-29, 2001; October 27-28, 2001; January 2002; April 2, 2002; July 23-25, 2003; June 30, 2004; and July 11, 2005. Total station survey measurements are accurate to within 3 mm/km in both horizontal and vertical directions (Geodimeter, 1998). Most surveys involved obtaining >300 points on the surface of the depositional packages in the reservoir. Surveyed points were gridded using kriging (Deutsch and Journel, 1992) to create surfaces for making contour maps (Figure 2). An additional contour map was provided from a detailed as-built survey from 1943. The volume of sediment deposited between surveys was determined using Surfer © software, by calculating the difference between surveys.

In October 2001, during excavation of sediments from the reservoir, we were able to study, survey, and sample the detailed stratigraphy of the first 15 months of post-fire sediments (Figures 3 and 4), which was when sedimentation rates were highest. Samples were collected for bulk density, particle size, and radiochemical analyses. The dates of some specific stratigraphic layers were determined by comparing elevations of surveyed points in the excavation with previous surveys. Precipitation records from weather stations in and near the watershed (Figure 1b) assisted in relating the stratigraphic record to seasonal variations in precipitation and/or individual storms. Remote Automated

Weather Stations (RAWS, http://www.losalamos.dri.edu/index.html) installed after the fire provide a record of short-duration precipitation for 2000 to 2003, and a snowpack telemetry (SNOTEL) site provides a longer term record (1981-2005, ftp://ftp.wcc.nrcs.usda.gov/data/climate/mtn_prec/table/history/new_mexico/06p01s.txt). The return periods of individual storms affecting the burn area were estimated using data for 1 and 2 hour rainfall recorded at the RAWS sites and locally-derived precipitation-frequency relations (Reneau et al., 2003). These estimates used Thiessen averages (Dunne and Leopold, 1978, p. 75) applied to the high and moderate burn severity parts of the watershed. Longer-term seasonal precipitation was estimated using the SNOTEL record (Table 1).

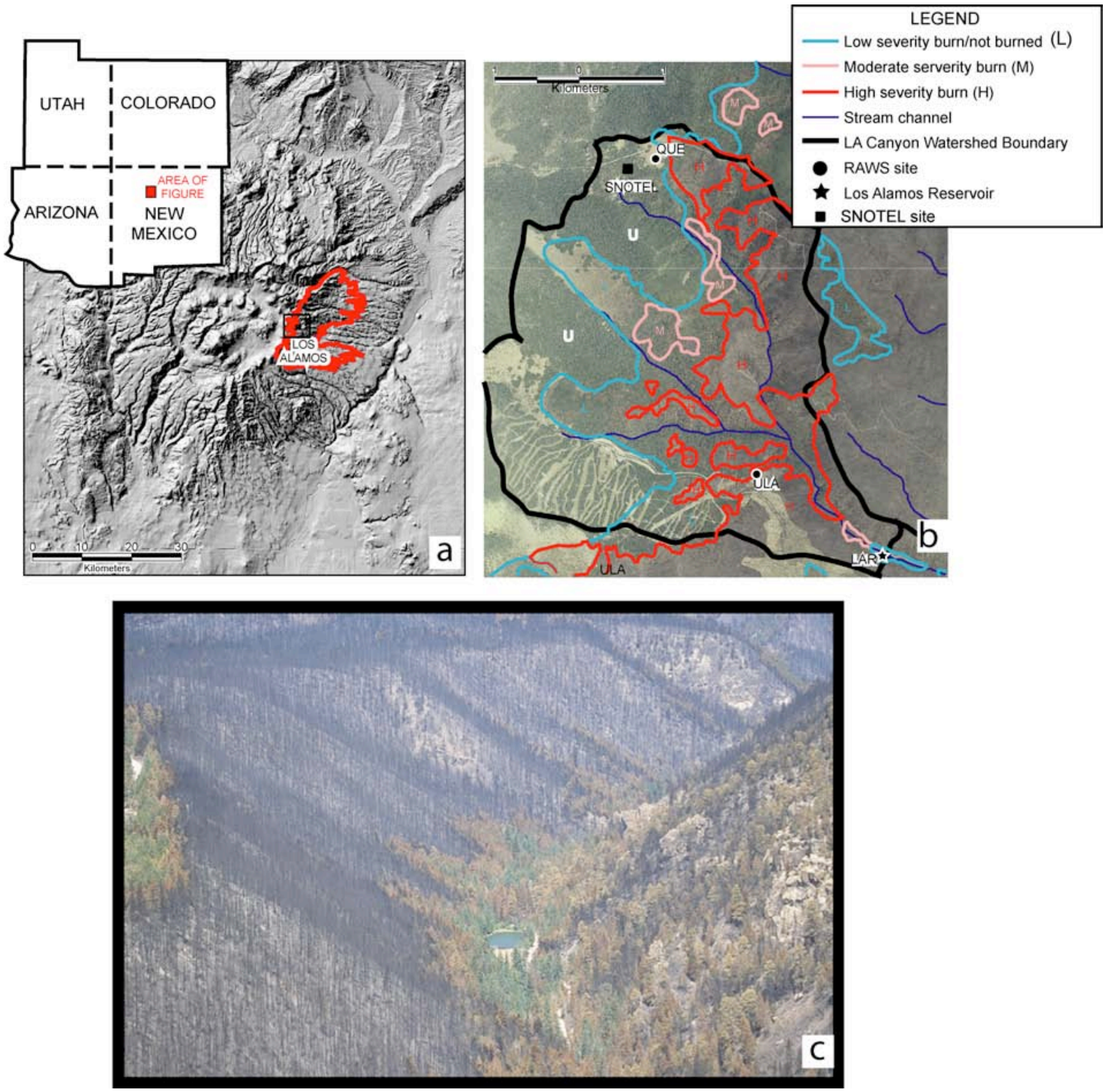

Figure 1. a) Map showing the location of the Cerro Grande fire in north-central New Mexico. Black outline shows area of Figure 1b. b) Aerial photograph showing burn severity in the Los Alamos Reservoir (LAR) watershed; QUE and ULA are RAWS sites; "U" indicates unburned areas; some of the high-severity burn areas have been treated with straw mulch (e.g., southeast of ULA RAWS). c) Oblique-aerial photograph of Los Alamos Canyon and reservoir, looking upstream, shortly after the Cerro Grande fire.

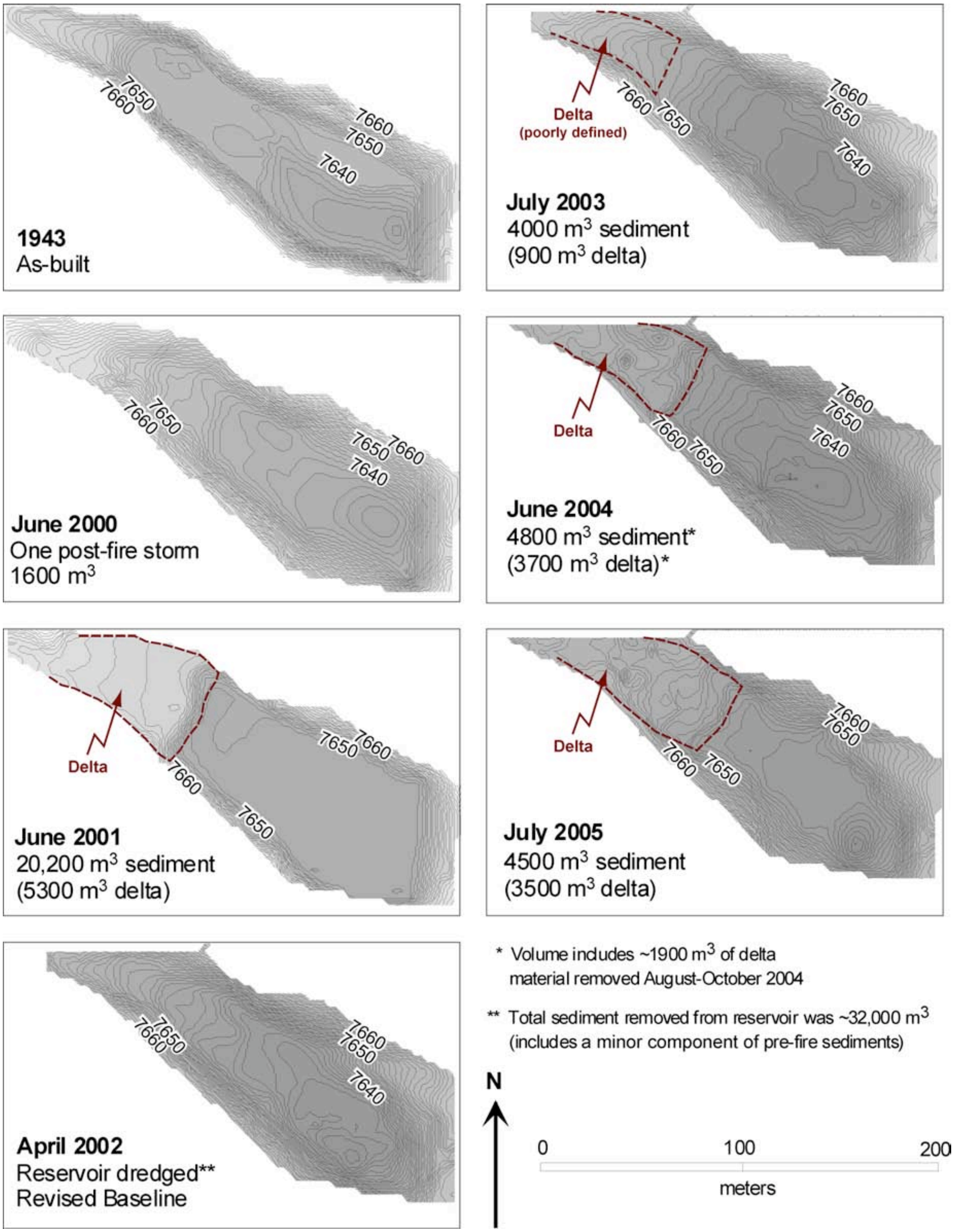

Figure 2. Series of contour maps showing changes in the topography of the reservoir basin based on total station surveys and an as-built survey (1943). Contour interval is 1 foot (0.3 m). Volumes shown reflect amount of sediment deposited between surveys.

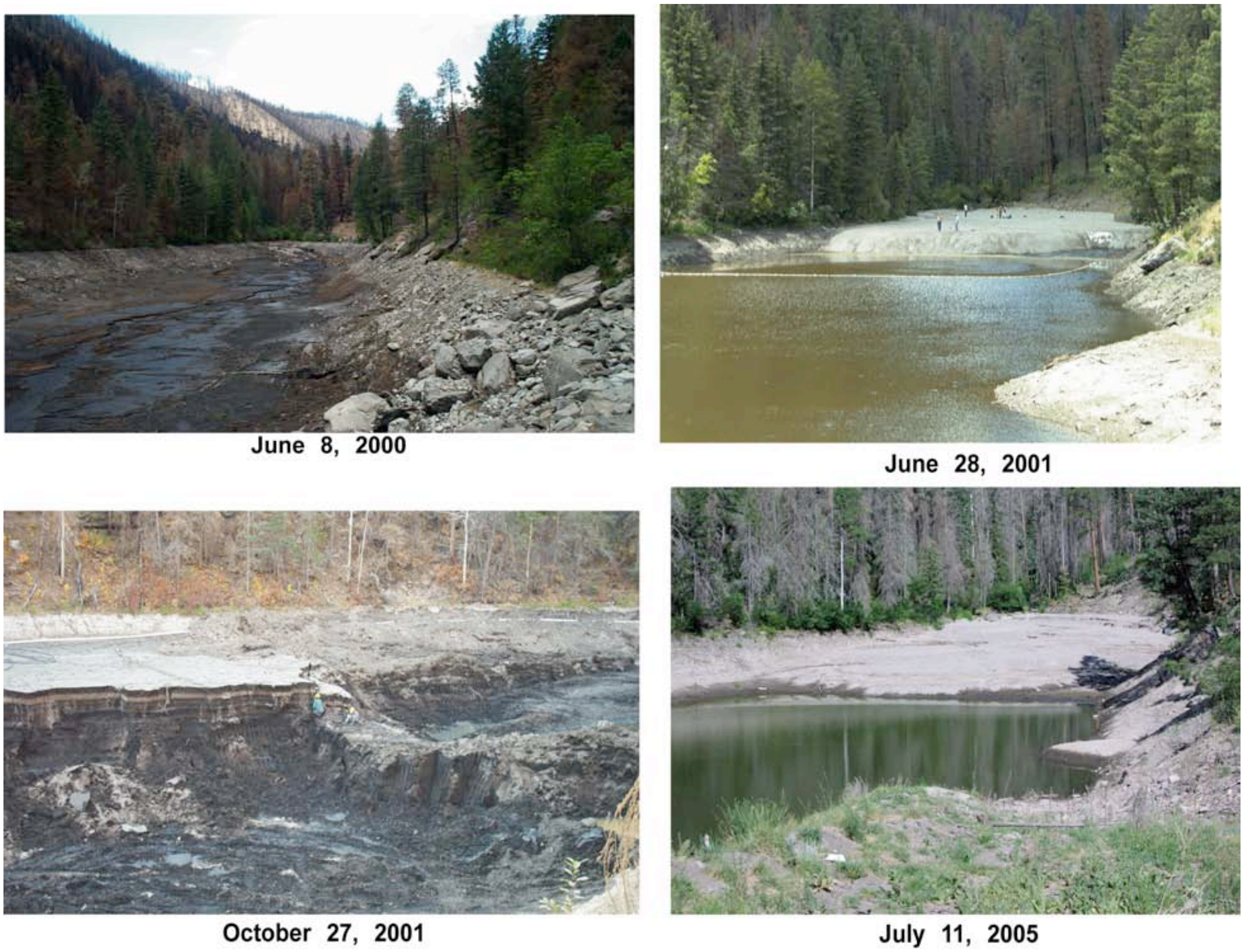

Figure 3. Photographs of the Los Alamos Reservoir. June 8, 2000, drained, after a single post-fire flood. June 28, 2001, showing a large coarse-grained delta that was formed during snowmelt runoff in spring 2001. October 27, 2001, partially excavated, showing fine-grained post-fire sediment deposits; people in center are describing stratigraphic section shown in Figure 4. July 11, 2005, showing delta formed during snowmelt runoff in spring 2005.

RESULTS

The initial total station survey of the Los Alamos Reservoir on June 8, 2000, in combination with the as-built drawings from 1943, indicated that approximately 10,200 m^3 of sediment had been deposited since construction of the reservoir (Table 2). The initial survey occurred after a single post-fire flood, on June 2, 2002, that deposited ~1,600 m^3 of sediment, with an average thickness of less than 0.3 m. This yields an estimate of ~8,600 m^3 of sediment accumulation in 57 years (Table 2), or an average of ~150 m^3/yr prior to the fire, equivalent to an average basin-wide denudation rate of ~0.009 mm/yr (assuming similar densities for reservoir sediments and hillslope soils). Observations in the drained reservoir indicated that the pre-fire sediment was dominated by fine-grained sediment that would have been carried in suspension. The sediment deposited during the June 2, 2000 event was predominantly silt and very fine sand with a large component of ash.

When total station surveys were repeated in June 2001, a large volume (5,300 m^3, Table 2) of medium to very coarse sand and gravel had formed a subaerial delta at the head of the reservoir (Figure 3). The distal subaqueous portion of the delta and deeper-water sediments were composed of finer sand, silt, and reworked ash (muck). Field observations document that the delta was formed during snowmelt runoff in early spring of 2001, which followed a winter with above average precipitation (Table 1). The coarse-grained delta and fine-grained distal sediments together comprised approximately 21,800 m^3 of sediment accumulated in one year, of which about 75% consisted of fine-grained sediment. Excavation of reservoir fill began in August 2001, exposing a stratigraphic record of the first

15 months of sedimentation (Figure 3). Detailed stratigraphic studies and surveys completed in the excavation between October 2001 and January 2002 allowed for basin-scale correlation of discrete strata and identification of the dates of specific layers (Figure 4). A series of rainstorms recorded at the RAWS sites, with about 0.5 to 3 cm of

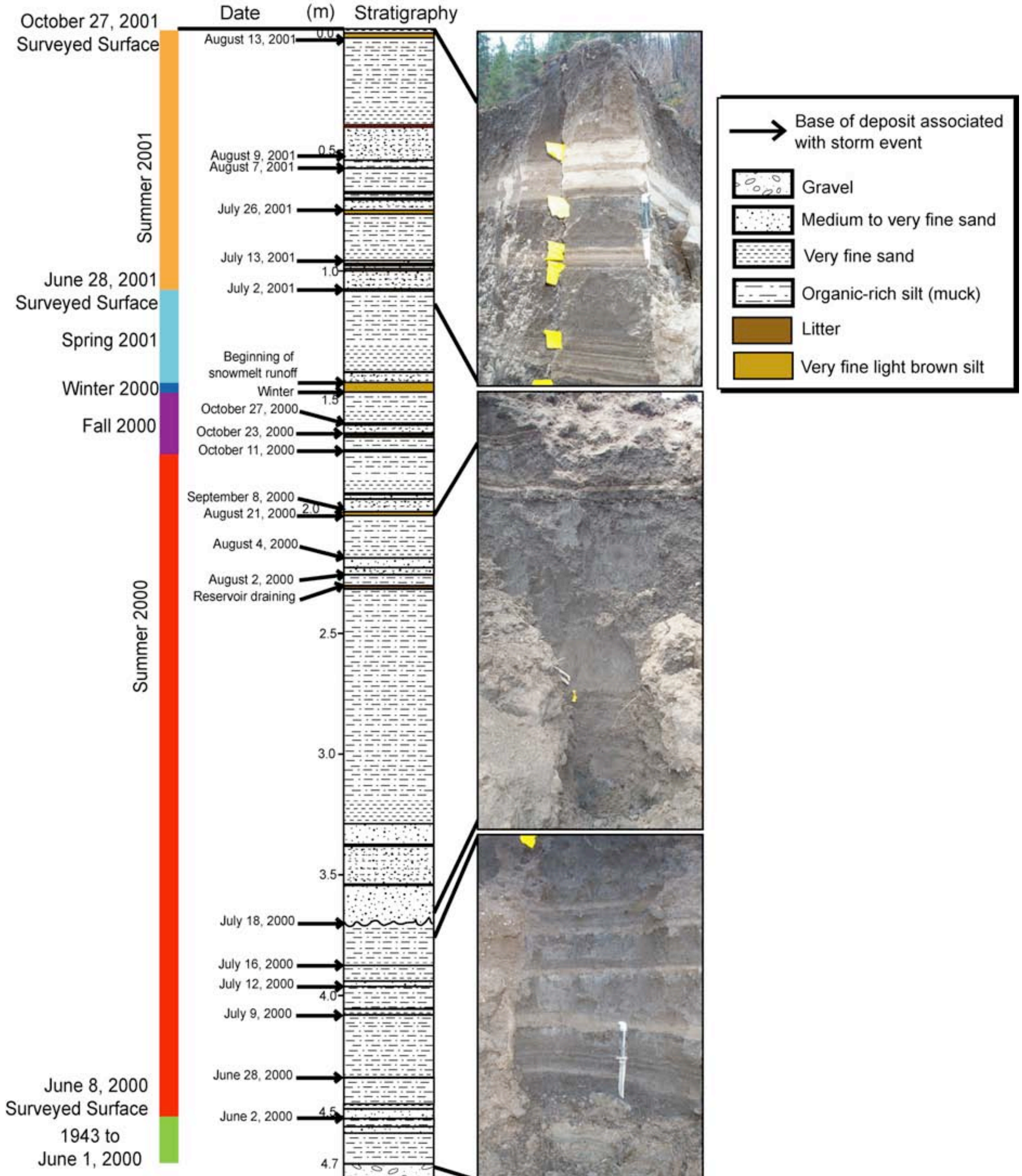

Figure 4. Stratigraphy exposed in excavation at the reservoir on October 27, 2001. Surveyed elevations, precipitation data, and field observations allowed correlation of individual layers to specific storms. More than 3 m of sediment were deposited during the first year following the fire, close to half of this following the July 18, 2000 storm, compared with ~0.2 m in the prior 57 years.

Table 1. Precipitation data.

Water Year	Precipitation at Quemazon SNOTEL		
Oct – Sept	Oct – Apr (cm)	May–Sept (cm)	Total (cm)
2000	21.59	24.13	45.72
2001	49.78	37.85	87.63
2002	12.70*	19.56	32.26
2003	30.23	27.94	58.17
2004	35.31	13.71	49.02
2005	49.28	--	--
1981 - 2004	35.86**	36.07**	71.93**

*Lowest in record. **Average values.

Table 2. Sediment data.

Sediment Volume in Reservoir		
Period	Total (m^3)	Delta (m^3)
1943 – 6/8/00	10,200*	0
6/8/00 – 6/28/01	20,200	5,300
6/28/01 – 4/2/02	8,000	0
4/2/02 – 7/23/03	4,000	900
7/23/03 – 6/30/04	4,800	3,700
6/30/04 – 7/11/05	4,500	3,500

* Includes 1,600 m^3 from 1 post-fire event.

rain falling in periods of no longer than 2 hours, could be correlated to specific strata exposed in the reservoir. The thickest sediment deposit in the center of the reservoir, ~1.4 m thick, resulted from a storm on July 18, 2000, that had an estimated average 2-hour rainfall on the burn area of 1.73 cm (an event with a return period of less than 1 year). This deposit fined upwards from fine to medium sand at the base to silty muck, a sequence typical of deposits from individual post-fire events. Overall, post-fire sediment in the center of the reservoir was about 1/3 very fine to fine sand (with minor medium sand), and about 2/3 silt and muck. Bulk density of the sand layers averaged 1.25 g/cm^3 and the silt and muck layers averaged 1.06 g/cm^3, similar to densities of surface soils on the Pajarito Plateau. It was not determined how much of the finer layers were ash versus mineral grains from the soil, although the muck layers were noticeably lighter in color in the upper 1 m of the section, indicating lower ash contents in the deposits from summer 2001 than summer 2000. In the fine-grained reservoir sediments that were exposed in October 2001, about 2/3 had been deposited in 2000 and 1/3 in 2001, despite the summer of 2001 being much wetter. In the first five summer monsoon seasons after the fire, 2001 was the only one with average precipitation totals, with the others being below average (Table 1). In addition, available data indicates the heaviest rainstorm in 2000 in the burn area in the upper Los Alamos Canyon watershed had a return period of less than 1 year, whereas at least two larger storms occurred in 2001 (July 13 and August 9, 2.51 and 2.97 cm in 2 hours, respectively), with estimated return periods of about 1-2 years. About 30% of the fine-grained sediment deposited in 2001 was apparently transported by snowmelt runoff, composing the surface that was surveyed on June 28, 2001, but overlying a distinctive light brown fine silt layer that records a period of minimal sediment input, probably representing deposition during the winter (Figure 4).

In 2002 to 2005, there was less sedimentation from summer precipitation relative to the first two years after the fire, and sedimentation was instead dominated by spring snowmelt runoff that formed coarse-grained deltas at the head of the reservoir (Table 2, Figure 5). Surveys performed in the second year after the fire record over 8,000 m^3 of sedimentation between June 2001 and January 2002, most of which occurred as a result of storms between July 2 and August 15, 2001. Minimal amounts of sediment were deposited in the reservoir between January and April 2002 due to limited snowmelt runoff associated with record low winter precipitation. The reservoir was completely excavated by April 2002, and a new baseline survey was completed. Subsequent surveys document reduced sedimentation as compared with the first two years, associated with intermediate levels of precipitation relative to 2000-2001 (Table 1). Between April 2002 and July 2003, ~4000 m^3 of sediment was deposited in the reservoir, with a small delta accounting for ~900 m^3. Between July 2003 and July 2004, ~4,800 m^3 of sediment was deposited, mostly consisting of a larger coarse-grained delta (~3700 m^3). This period included one of the two most intense storms in the watershed as recorded by the RAWS sites, August 23, 2003, with an estimated average 2-hour rainfall of 2.95 cm on the burn area, yet summer 2003 had relatively small amounts of fine sediment deposition relative to 2000 and 2001 (Figure 5). Between July 2004 and July 2005, ~4500 m^3 of sediment was deposited in the reservoir, with ~3500 m^3 comprising a delta. The 2005 delta, similar in size to the 2004 delta and smaller than the 2001 delta, was associated with the most prolonged snowmelt runoff period and the highest snowmelt peak after the fire.

The total amount of sediment deposited in the reservoir during the 5-year period after the fire was ~43,100m^3, ~70% fine-grained sediment and ~30% coarse-grained sediment. About half of the post-fire sedimentation occurred in the first year, ~21,800 m^3 (Table 2), equivalent to an average basin-wide denudation rate of soil of ~1.3 mm/yr, or ~140 times the average pre-fire rate. Assuming that all of the sediment was derived from high and moderate severity burn areas (5.4 km^2) yields an average denudation rate of ~4.0 mm/yr for those areas, or ~450 times the pre-fire rate.

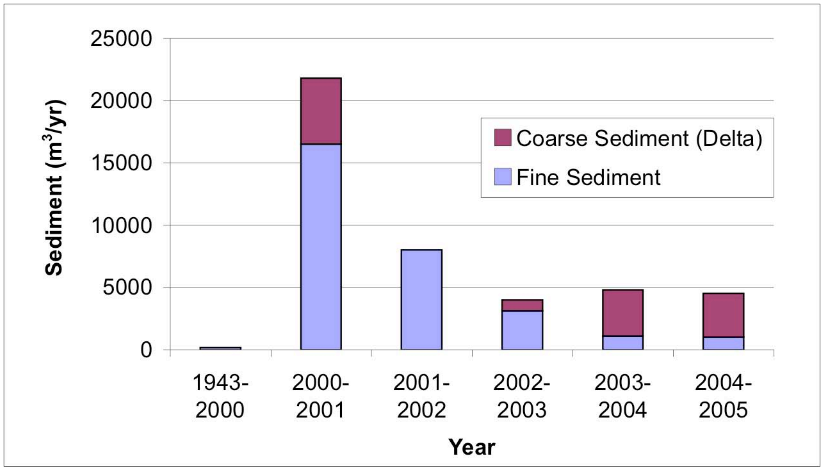

Figure 5. Plot of annual sedimentation in the reservoir, distinguishing coarse-grained sediment in the delta that predominantly reflects snowmelt runoff and fine-grained sediment that predominantly reflects suspended transport in summer floods. Note the overall annual decrease in the amount of fine sediments, and the relative increase in the percentage of coarse-grained to fine-grained sediments. 1943-2000 value is a 57-year average.

Calculated denudation rates using total sediment volumes declined rapidly over time, being about ~0.7-0.9 mm/yr in 2002 to 2004 (assuming a source in the high and moderate burn severity areas), or ~80-100 times the pre-fire rate.

Fine-grained and coarse-grained sediments, supplied largely by summer flash floods and spring snowmelt, respectively, show much different temporal patterns of deposition in the reservoir (Figure 5, Table 2). Fine-grained sediments show the highest depositional rates in the first year after the fire, and decline rapidly in subsequent years. Equivalent denudation rates were ~340 times pre-fire averages in 2000, declining to ~20 times pre-fire levels in 2003 and 2004. This trend is apparently independent of variations in summer precipitation. In contrast, coarse-grained sediment shows variations that relate more to the amount of winter precipitation and resultant snowmelt runoff than to time since the fire.

DISCUSSION AND CONCLUSIONS

The Los Alamos Reservoir has yielded an excellent record of post-fire erosion and sedimentation following a major wildfire. In addition to recording the magnitude of initial changes relative to pre-fire conditions and subsequent changes associated with watershed recovery, the effects of individual storms and variations in seasonal precipitation can be evaluated.

As recorded in the reservoir, erosion rates in the heavily forested watershed were extremely low in the 57 years prior to the Cerro Grande fire, averaging ~0.009 mm/yr. This low rate is consistent with field observations indicating the absence of extensive surface runoff and erosion prior to the fire, and is supported by stream gage records from nearby basins that show monsoon-season floods were rare in the eastern Jemez Mountains before the fire (Gallaher and Koch, 2004).

Erosion and sediment delivery into the reservoir were highest in the first year after the fire, accounting for about half of the total sedimentation in the first five years, despite the occurrence of below-average summer precipitation and relatively low-intensity storms (<1 year return intervals). Adjusted for the area of high and moderate burn severity, equivalent denudation rates increased to ~4.0 mm/yr, ~450 times the pre-fire rate. Actual denudation rates in these areas may have been higher because of reduced sediment yield following treatments soon after the fire (1.5 km^2; e.g., straw mulch shown in Figure 1b). This exceeds an increase of 150-240 times reported by Moody and Martin (2001) for an area with similar vegetation and climate in Colorado. Most of the sediment deposited in the first year was fine-grained and ash-rich, recording rapid stripping of hillslope soils by sheetwash and rill erosion and small debris flows in summer thunderstorms, common processes after fires (e.g., DeBano, 2000; Cannon et al., 2001). Sedimentation in the reservoir decreased by over half the second year after the fire, despite the occurrence of more summer precipitation and higher intensity storms that initiated gullying on the hillslopes. Sediment deposits in the second year were visibly lighter in color, containing lower ash contents, which is consistent with local stormwater analyses indicating lower concentrations of ash-derived constituents by the second year (Johansen et al., 2003; Gallaher and Koch, 2004). Sedimentation further decreased in the subsequent years, although remaining ~80-100 times higher than pre-fire levels in 2002-2005. A very slow return to pre-fire conditions in this region is similarly indicated by data from Frijoles Canyon, 8 km south, where peak stream discharge remained above pre-fire levels 22 years after the La Mesa fire (Veenhuis, 2002).

Significant differences occurred between delivery of fine-grained and coarse-grained sediment to the reservoir that are related to varying transport of these two components. The fine-grained sediment, carried in suspension, was largely transported quickly to the reservoir in flash floods, and deposition rates of fine sediment may closely track erosion rates on hillslopes in the burn area. In contrast, the coarse-grained sediment, transported as bedload, was largely delivered to the reservoir by snowmelt runoff, lagging behind upstream hillslope erosion. Studies downstream in Los Alamos Canyon showed that this seasonal difference in suspended versus bedload transport was also present before the fire (Malmon et al., 2004). Field observations after the fire confirm substantial deposition of coarse sediment along the main channel upstream from the reservoir during summer storms, and subsequent partial remobilization by snowmelt runoff. As inferred in other areas, much of this coarse sediment may remain in long-term storage upstream from the reservoir (e.g., Moody and Martin, 2001), although in the short term it may continue to be a major source of sediment reaching the reservoir.

ACKNOWLEDGMENTS

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