Post-Landslide Recovery Patterns in a Coast Redwood Forest[1]

Leslie M. Reid,[2] Elizabeth Keppeler,[3] and Sue Hilton[2]

Abstract

Large landslides can exert a lasting influence on hillslope and channel form and can continue to contribute to high in-stream sediment loads long after the event. We used discharge and suspended sediment concentration data from the Caspar Creek Experimental Watersheds to evaluate the temporal distribution of sediment inputs from 11 landslides of 100 to 5500 m^3. Slide-related suspended sediment loads were estimated as deviations from expected loads referenced to nearby control watersheds. For the two largest slides, suspended sediment export during the year of the slide accounted for 5 and 15 percent of the initial slide volumes, while subsequent export accounted for an additional 8 and 2 percent over the period for which export has been tracked (8 and 10 years). Regressions of excess sediment against time and storm size indicate that suspended sediment loads are likely to recover more quickly for small storms than large ones. Measurements of sediment storage along channels affected by the slides generally showed aggradation for 1 to 2 years. For the largest slide, however, downstream accumulation has now continued for at least 8 years. Nearly half of the sediment initially displaced by that slide remains in storage adjacent to channels and so may be subject to re-mobilization during future storms. In addition, in-channel deposits have triggered bank erosion and diverted the channel in places; much of the downstream increase in suspended sediment load during the post-slide years is derived from these secondary sources rather than directly from the slide debris.

Key words: channel condition, cumulative impacts, landslides, sediment yields, watershed recovery

Introduction

Large landslides can be an important source of excess sediment in the redwood region. Sediment from new landslides increases turbidity and may lead to channel blockages and aggradation, but influences can also persist long after a slide occurs. Slide scars can require decades to revegetate and far longer to redevelop forest soils, and slide debris can exert a lasting effect on channel form. In addition, slide deposits may contribute to pervasive increases in stream sediment loads as they succumb to bank erosion, and slow-moving coarse sediment inputs may take decades to reach the mouth of a watershed.

The cumulative impact analyses required for many planned land-use activities need to evaluate potential interactions between the effects of past and planned activities, so the persistent influences of past landslides need to be considered where activities have been associated with increased landsliding. Several studies have described long-term influences of major slide-generating storms on the migration of coarse sediments through the Redwood Creek watershed (Madej and Ozaki 1996, Nolan et al. 1995). In that case, slides were distributed widely across the basin, so the effects of individual slides could not be distinguished. An understanding of long-term effects at the scale of individual slides would also be useful. Records of suspended sediment loads at the Caspar Creek Experimental Watersheds in coastal Mendocino County allow evaluation of the temporal distribution of sediment inputs during and for up to a decade after major landslide-generating storms, and repeated channel surveys allow analysis of changes in storage of landslide-generated sediment after the slides occurred.

[1] A version of this paper was presented at the Coast Redwood Science Symposium, September 13-15, 2016, Eureka, California.

[2] USDA Forest Service, Pacific Southwest Research Station, 1700 Bayview Drive, Arcata, CA 95521.
[3] USDA Forest Service, Pacific Southwest Research Station, 802 N. Main St., Fort Bragg, CA 95437.
Corresponding author: ekeppeler@fs.fed.us.

Study Site

Watershed research has been carried out since 1961 in the North Fork (473 ha) and South Fork (424 ha) Caspar Creek Experimental Watersheds (fig. 1) (Cafferata and Reid 2013). The watersheds are underlain by sandstones and shales of the Coastal Belt of the Franciscan Complex. Most soils developed on slide-prone slopes are relatively shallow (50 to 150 cm) loams (North Fork) to very gravelly loams (South Fork). About 15 to 20 percent (North Fork) and 20 to 65 percent (South Fork) of the surficial soil horizons are composed of clasts >2 mm. Clay-rich subsoils are cohesive, compactable, and can impede drainage. Mean hillslope gradient is about 25^o, and channels of third order or larger often flow through inner gorges with side-wall gradients of up to 60^o. Drainage density in the area is about 4.6 km/km^2. Evidence of ancient deep-seated landslides is common (Spittler and McKittrick 1995).

Annual precipitation averaged 1160 mm (standard deviation 339 mm, range 400 to 2200 mm) at the mouth of the South Fork between 1962 and 2015. About 95 percent of the precipitation falls as rain between October and May; snowfall is not important. The watersheds currently support second- and third-growth forests dominated by coast redwood (*Sequoia sempervirens* (D.Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco); old-growth was logged between 1860 and 1904.

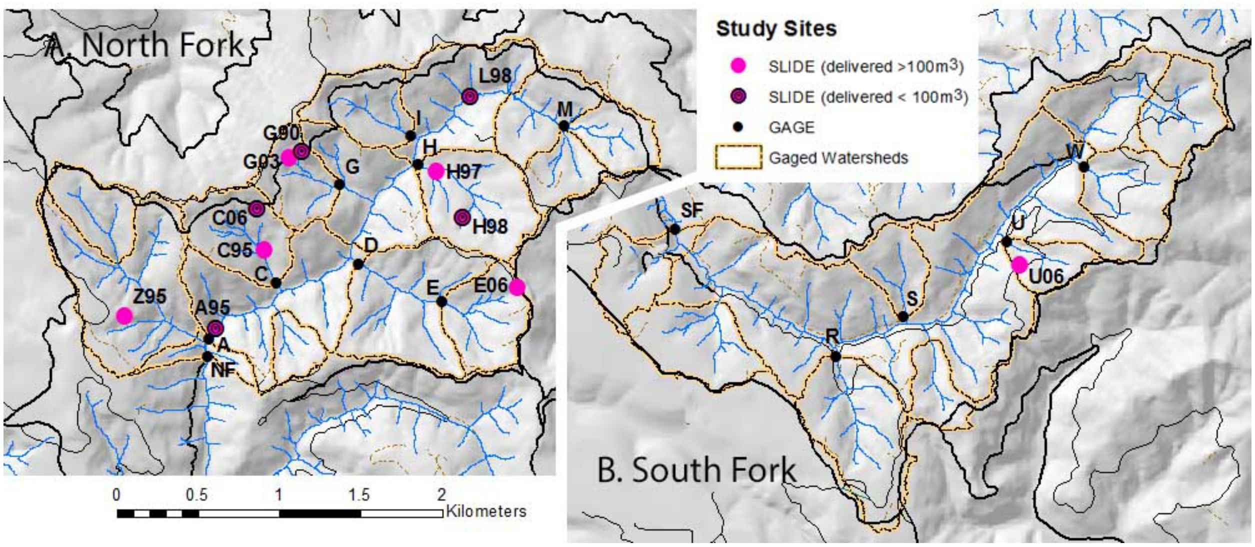


Figure 1—Post-1985 landslides of >100 m^3 in the A. North and B. South Fork Caspar Creek Watersheds. Single and double letters—initials of the gage names—indicate locations of the gages analyzed.

The Experimental Watersheds have hosted two major experiments, and a third is now beginning. The South Fork was selection logged and tractor-yarded between 1971 and 1973, while the North Fork was left as a control to permit detection of the effects of South Fork logging on sediment and flow. Portions of the North Fork were then clearcut logged and primarily cable-yarded between 1985 and 1992, with three sub-watersheds left as controls. Papers included in Ziemer (1998) describe the experimental designs and results of both experiments. Annual suspended sediment yield at the North Fork before experimental treatment was 68 t km^{-2}yr^{-1} (95 percent CI: ± 39 t km^{-2}yr^{-1}; Reid and Keppeler 2012).

Reid and Keppeler (2012) examined conditions contributing to landsliding at Caspar Creek and found an increased incidence of large landslides after clearcutting, particularly in logged areas adjacent to roads. Results suggested that infrequent slides larger than 2500 m^3 may contribute more than 20 percent of the suspended sediment load over the long term. Large post-logging slides were found to occur preferentially during the period when small roots have decomposed and foliar interception of rainfall has not yet recovered; the largest slides occurred 10 to 15 years after logging, soon after pre-commercial thinning had again reduced rainfall interception (Reid and Keppeler 2012). Although rotational slides and earthflows also occur, most recent slides—including those >100 m^3—are planar failures.

Methods

Three kinds of data were used for the analysis: stream-gaging records, landslide inventories, and channel surveys. Gaging stations were installed at the mouths of the North and South Fork watersheds in 1962, at 13 new sites in the North Fork watershed in 1984-1985, at two more North Fork sites in 1999 and 2001, and at 10 South Fork sites in 2000 (fig. 1); six of the North Fork gages were decommissioned in 1995. The two downstream gages are located at sharp-crested weirs with inset 120° V-notches, while gaging along the main channels is carried out at rated sections. Tributary gages originally employed Parshall flumes, and these were replaced by Montana flumes in the early 2000s. Henry (1998) describes the monitoring network and protocols in use until 1995. Since then, suspended sediment loads have been calculated from continuous turbidity records calibrated for each storm at each station using suspended sediment samples (Lewis and Eads 2009). Because >90 percent of the suspended sediment is carried during storms, storm sediment loads were used for this analysis. Coarse sediment deposition in the weir ponds is surveyed each year. Lewis (1998) reports that the weirs trap about 40 percent of the suspended load entering the ponds.

The entire gaged channel network is walked at least once a year to map the distribution of new slides capable of contributing sediment to the channels; non-contributing slides are also mapped whenever they are observed. Scar dimensions are measured and the volume of displaced material is estimated, as is the volume of sediment still in storage at the site. In some cases, sediment deposition downstream of major slides is described or mapped. Slides can usually be associated with particular storms on the basis of survey timing, field evidence, and gaging station records.

The 124 cross sections established in the 1980s along the main North and South Fork channels are resurveyed biennially using a rod and level; scour and fill calculations at the cross sections define changes in sediment storage and document channel incision and widening. Following the E06 slide (notation: watershed EAG, hydrologic year hy2006), areas of slide-related deposition were mapped and six cross sections were established and then resurveyed in 2007, 2008, 2015, and 2016 to track deposition and scour along the downstream channel. North Fork channel profiles were surveyed in 1992, and selected reaches were resurveyed using a total station between 2000 and 2006. Along the reach downstream of the E06 slide, measured changes in cross-sectional area were used in conjunction with the deposit maps to determine scour and fill volumes between surveys. In addition, periodic inventories of sediment storage along gaged channels were made annually between 1985 and 1996, and again along selected reaches (including those affected by the E06 slide) in 2006 and 2016. These inventories provide estimates of sediment volumes trapped by debris dams (steps associated with wood or roots) taller than 0.3 m which store >0.14 m^3 of sediment.

Suspended sediment inputs during and after the slide-generating storms were estimated as the deviations from expected sediment loads at a gaging station downstream of each slide. Most analyses used data from the nearest downstream gage and from the North or South Fork control gages (North Fork: HEN, IVE, MUN; South Fork: RIC, SEQ, WIL). Pre-slide relations between loads at treatment and control gages (e.g., fig. 2a) were used to estimate the expected load for each post-slide storm, and the deviation from the expected load was estimated as the mean of the differences between expected and observed loads as calculated using each of the three controls' records (e.g., fig. 2b). The Z95 slide occurred before the XYZ gage was installed, so a relation was developed between storm loads measured at ARF gage, immediately upstream of the XYZ confluence, and at NFC gage, located 120 m downstream. Sediment from Z95 was then estimated as deviations from the pre-slide relation between the ARF and NFC loads. Two slides triggered debris flows that damaged the downstream gage. In the case of E06, data from a station located farther downstream were employed to m downstream. Sediment from Z95 was then estimated as deviations from the pre-slide relation between the ARF and NFC loads. Two slides triggered debris flows that damaged the downstream gage. In the case of E06, data from a station located farther downstream were employed to characterize the slide. At the UQL gage, sampling resumed 24 hours after the U06 slide occurred, and loads were estimated from a hydrograph and turbidity record reconstructed using data from nearby gages. In several cases, slide effects were superimposed on logging-related sediment inputs, complicating the analysis of slide-related inputs.

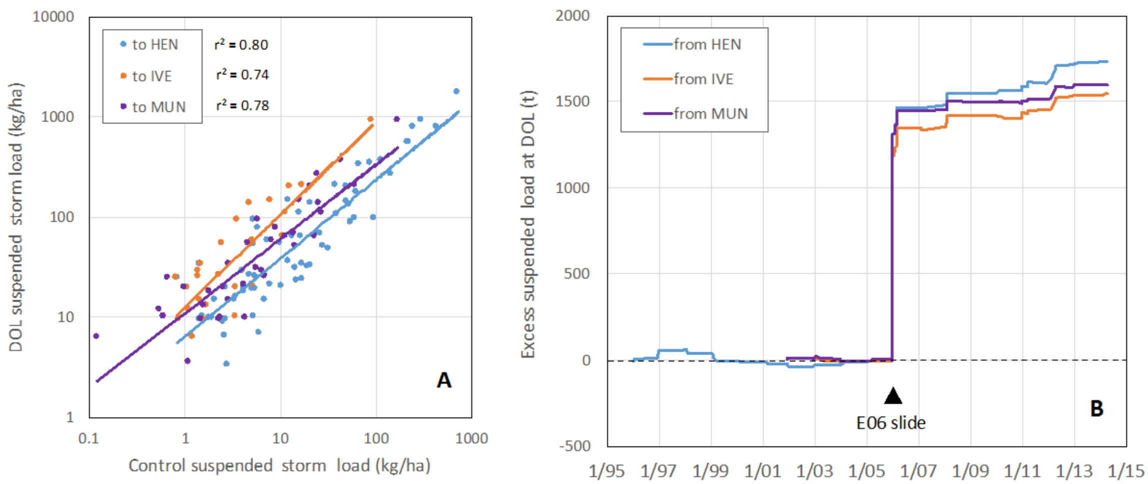


Figure 2—A. Pre-slide relations between storm suspended sediment loads at DOL and at controls HEN, IVE, and MUN; and B. cumulative excess suspended sediment at DOL between 1/1/1995 and 8/1/2014.

The initial phase of suspended sediment export was considered to end at the conclusion of the wet season during which the slide occurred. Revegetation before the onset of the following winter is expected to partially stabilize slide deposits. Delayed sediment export is calculated for the period between the hydrologic year following slide occurrence and the time that the record is either terminated, impacted by the occurrence of another slide upstream of the gage, or reattains its pre-slide characteristics. Storm suspended loads are calculated as kg/ha or tons. For comparison, slide and deposit volumes are converted to estimated mass by assuming an original average bulk density of 1.8 t/m^3 for the combination of soil mantle and weathered bedrock displaced by large landslides, 1.5 t/m^3 for valley-bottom regolith, 1.8 t/m^3 for slide deposits, 2.0 t/m^3 for debris flow deposits, and 2.1 t/m^3 for poorly sorted channel gravels.

Results

Landslide inventories carried out in the North and South Fork watersheds since 1987 and 2000, respectively, have identified 11 landslides or landslide complexes with volumes >100 m^3 (fig. 1, table 1). An average of 47 percent of the sediment originally displaced by 10 of the slides remained on site at the time of the first post-slide inventory, with values ranging from 3 to 97 percent.

Suspended sediment export during the year of the slide accounted for 0 to 15 percent of the initial slide mass (mean: 4 percent), while export following the first year accounted for an additional 0 to 8 percent (mean: 3 percent). For the two largest slides, 5 and 15 percent of the slide mass was removed as suspended load during the first year, and 8 and 2 percent in following years. Most records were terminated by decommissioning of a gage or occurrence of another slide. Only the C06 slide appeared to stabilize within the analysis period, and it was notable for having retained a high proportion of the slide material on the scar; outputs from the E06 and U06 slides continue to be tracked. No signal was detected in two cases (A95 and L98) for which the nearest downstream gage at the time of the slide

ARF load for the year of the slide, so any response is expected to be below the detection limit at this downstream gage.

Channel response to slides delivering >100 m^3 of sediment (n = 6) was evaluated using cross-section data to calculate scour and fill along the mainstem reach downstream of the point of entry for slide sediment (table 1). Four of these slides were associated with positive accumulations the first post-slide year of measurement, which, depending on whether or not the slide occurred during a survey year, was either the summer after the slide or the following summer. Deposits associated with most slides continued to aggrade for only 1 or 2 years, but E06 had a more enduring impact on the mainstem channel. The cross-sectional area at the nearest mainstem cross-section changed by more than 3 m^2 due to deposition after the slide, and this reach showed continued aggradation as recently as 2015. On the South Fork, U06 did not produce identifiable aggradation in the main channel, which for several years had already been responding to sediment inputs from a reactivated 1974 failure and from channel incision associated with road decommissioning. Deposition was evident in UQL tributary itself.

Table 1—Slides of >100 m^3 in the Caspar Creek Experimental Watersheds after 1986, and disposition of slide debris in the year of the slide (“initial”) and following years (“delayed”)

		Scar (m^3)		Tributary (m^3)		Mainstem (m^3)		Suspended load (t)		Period
Slide	Date	Total	On-site	Initial	Delayed	Initial[a]	Delayed	Initial	Delayed	(yr)[b]
G90	5/90	280	280	--	--			0	19	5
Z95	1/95	3600	1600	--	--			340	490	10
A95	3/95	370	280	NA	NA	32	-6	nd	nd	2
C95	3/95	130	120	--	--			4	--	0
H97	12/96	120	4	--	--	28	-15	11	1	1
L98	<2/98	180	90	NA	NA	-9	6	nd	nd	2
H98	3/98	100	70	--	--			2	6	1
G03	12/02	2000	760	--	--	14	-69	48	--	3
E06	12/05	5500	--[c]	1853	-18	115	47	1410	210	>8
C06	12/05	210	200	--	--			11	2	>8
U06	3/06	250	20	--	15	-35	-10	16[d]	6	>8

Tributary and mainstem values represent deposition or erosion; “nd” indicates that a suspended sediment response was not detected; and dashes indicate that measurements were not made at the site or, for suspended sediment measurements, ongoing changes in logging-related inputs prevented interpretation of results. Slides are designated by sub-watershed initial and hydrologic year (e.g., G90 occurred in GIB during hy1990).

[a] For mainstem deposition, “initial” may include the first 1 or 2 years of aggradation.

[b] Period: duration over which post-slide analysis is possible; analysis may be terminated due to decommissioning of a gage or occurrence of a new slide in the watershed upstream of the gage

[c] Estimated to be <10 percent of the slide volume.

[d] A minimum value for suspended sediment as the period of hyperconcentrated flow was not sampled.

The three large slides for which nearby downstream gaging records are available (Z95, E06, U06) were evaluated in more detail. The 5500 m^3 E06 slide complex (approximately 9500 t of displaced material, 3000 t from the debris flow track) occurred upstream of four gages, one of which (EAG) was located 150 m downstream of the toe of a debris flow triggered by the slide; a portion of the flow travelled on and damaged the gaging flume. Consequently, neither the initial sediment pulse nor the next storm were recorded at EAG (drainage area: 27 ha). Downstream 560 m, the DOL gage (77 ha) recorded a suspended sediment load of 1260 t for the pulse (fig. 3a), equivalent to about 13 percent of the sediment displaced by the slide. The ARF gage (384 ha), another 1100 m downstream of the EAG gage, recorded 1390 t for the initial pulse, with the difference likely to be attributable to a combination of estimate uncertainty, breakdown of clasts, and the greater capacity of North Fork flow to carry sediment in suspension. The EAG gage was repaired within 17 days, and subsequent measurements showed that the primary source of slide-related sediment to downstream reaches had shifted from above the EAG gage to the reach between the EAG and DOL gages (fig. 3b).

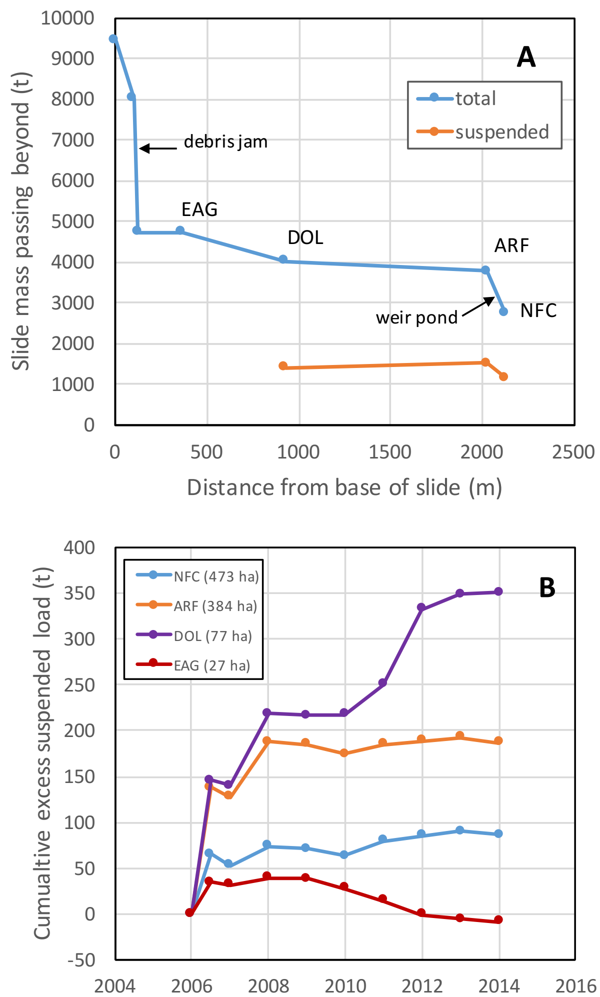


Figure 3—A. Initial distribution of sediment from E06 (through hy2006), and B. E06 excess suspended sediment loads during subsequent storm events at four downstream gages for hy2006 through hy2014.

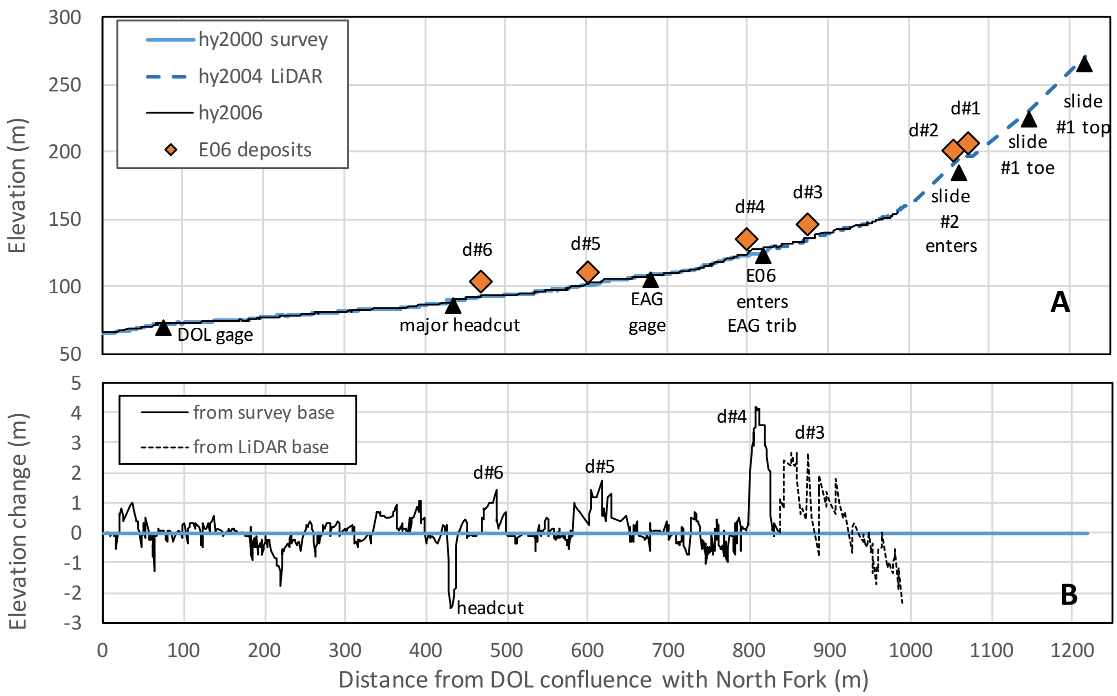
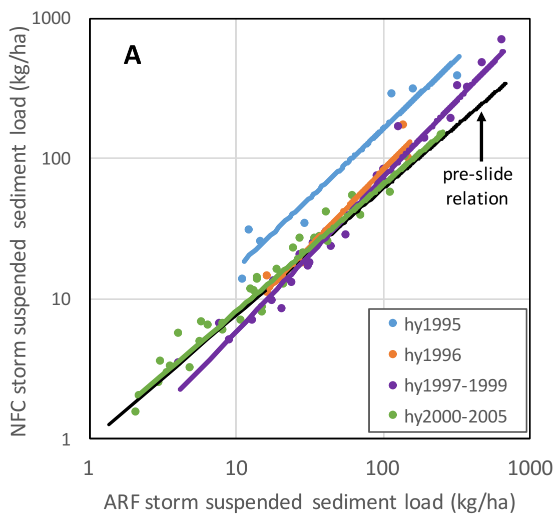


Figure 4—A. hy2000 or hy2004 (pre-slide) and hy2006 (post-slide) channel profiles in DE tributary, and B. elevation change between surveys (survey precision: ±1 cm).

Aggradation from E06 is evident along a 400-m reach where thalweg profiles were surveyed in 2000 and 2006 (fig. 4a). Following the slide, mean thalweg elevation increased 0.33 m along the reach, with a maximum increase of 4 m (fig. 4b). Most of the aggradation occurred in three 30- to 70-m segments with a total estimated deposit volume of 1090 m^3 (d#4, d#5, d#6). These depositional features were not contained within the pre-existing banks, and an entirely new channel was created at the d#5 site. Additional deposits along the unsurveyed slide track above this reach were estimated on the basis of field measurements of deposit dimensions to contain 1660 m^3 of slide material for a total of 2750 m^3—about 68 percent of the volume of the slide complex.

Channel deposits from E06 showed substantial reworking in the months following the slide, and cross-sections established in February 2006 document later changes (table 1). Material accumulated during the first two post-slide winters at d#3, but scour prevailed by year 9. Just downstream, a 2-m debris step storing most of the new d#4 deposit had begun to incise by 2008 and retreated about 5 m by 2016. At d#5, the channel was stable after hy2006, having established a 3-m-wide U-shaped channel with a maximum depth of 0.5 m. This channel occupies about one-fourth of the deposit area, and the pre-slide channel remains buried. Channels through the upstream deposits are similarly confined to only 6 to 30 percent of the deposit width. Channel depths at these cross-sections range from about 0.5 to 1.75 m.

Step inventories describe in-channel sediment storage at a finer scale. Along the 400-m surveyed reach below the slide track confluence, 33 organic steps were present in 1995 and in 2006, after E06 occurred; 3 had disappeared by 2016. However, overall in-channel storage behind debris steps increased from 52 m^3 to 740 m^3 between 1995 and 2006, mostly due to wood associated deposits d#5 and d#4, behind which most of the over-bank deposition occurred. The in-channel step deposition component at d#5 (110 m^3 of the total d#5 deposit of 225 m^3) was deemed stable in 2016 because the post-slide channel was no longer in contact with the sediment. Of the original 572 m^3 of step deposition at d#4, an estimated 10 m^3 had been excavated by 2016 and about 16 m^3 remains within the active channel, while the remainder has revegetated and appears stable. One-third of the other steps along the EAG-DOL channel were relatively stable, showing increased volumes of 20 to 34 percent (mean: 24) between the pre-slide (1995) and post-slide (2006) inventories and returning to approximate pre-slide totals by 2016. In 2006, 21 steps showed signs of accretion, and only one showed erosion. A decade later, the numbers of eroded and aggraded steps were nearly equal. Two of the 11 steps initially buried by slide debris were re-exposed by 2016, while two others had washed away. Gravel and cobbles dominated the deposits at all but a few steps. Although most of the sediment storage within the active channel is associated with organic steps, the volume of slide-derived sediment stored in these steps (160 m^3) is small compared to the amount stored outside of the active channel above the major debris jam (d#3, d#4: 1630 m^3) and on the valley bottom (d#5, d#6: 400 m^3).



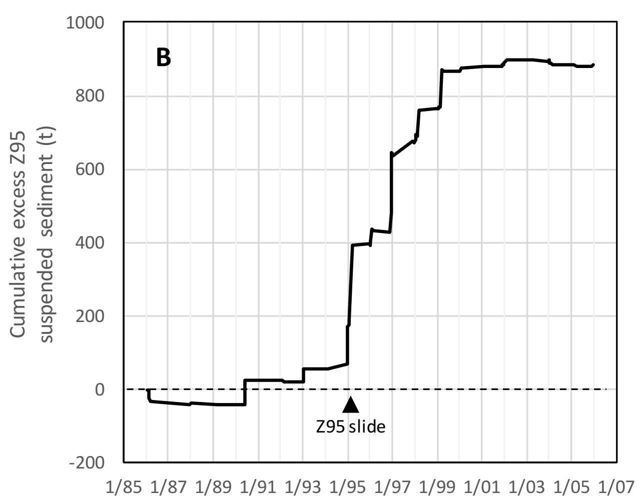


Figure 5—A. Relations between storm suspended sediment loads at ARF and NFC before and after the Z95 slide; and B. excess storm loads from XYZ tributary (draining the Z95 slide) through time.

Sediment data for the Z95 slide are more limited. Because only the tributary affected by Z95 (XYZ tributary, 77 ha) enters the North Fork channel between gaging stations ARF and NFC, change in output through time from Z95 is evident as a shift in the relationship between storm suspended sediment loads at stations ARF and NFC (fig. 5a). The cumulative sediment deviation through time shows most of the slide effect to have dissipated by 5 years after the slide (fig. 5b). Analysis ends at the time of the E06 slide, which is expected to have changed the relation between loads at ARF and NFC due to the unusually large influx of slide-derived sediment during that event. Deposition was not surveyed for Z95.

The 250 m^3 U06 slide appears to have occurred in two phases, with a preliminary slide releasing about 4 t of suspended sediment in late December, followed 74 days later by second failure which triggered a debris flow that destroyed the UQL gage (drainage area: 13 ha). Although neighboring gage records and a reinstalled sampler allowed estimation of the storm load at the site, the reported value represents an underestimate because hyper-concentrated flows associated with the event were not sampled. A minimum of 16 t was exported in suspension after the slide, along with a large volume of debris flow sediment; and an additional 6 t was exported over the following 8 years (fig. 6).

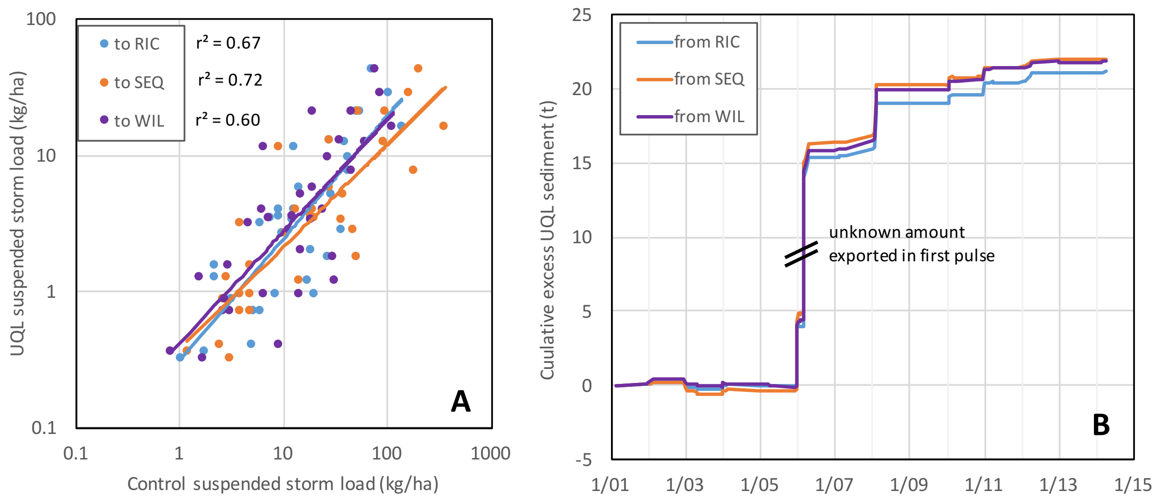


Figure 6—A. Pre-slide relations between storm suspended sediment loads at UQL and at controls RIC, SEQ, and WIL; and B. cumulative excess storm suspended load at UQL between 1/1/2001 and 1/1/2015.

Discussion

Although large landslides mobilize considerable volumes of sediment over a short period, much of that sediment is quickly redeposited on or immediately below the landslide scar. At Caspar Creek, about half the displaced sediment remained on-site for the 10 major slides for which on-site measurements were made. During the slide, the rest of the sediment may be deposited lower on the slope, in the channel below, or along downstream channels. Landslide debris in contact with flow becomes subject to further erosion and contributes to suspended sediment loads downstream. Because most Caspar Creek landslides are associated with major rainstorms, the slide scar and proximal deposits often also contribute fine sediment to downstream loads. Some slides incorporate enough water to move down-channel as debris flows. During and immediately after such flows, downstream suspended sediment concentrations can be extremely high. Concentrations at the DOL gage reached 94 g/l during the E06 event and remained above 20 g/l for more than 4 hours.

Fluvial erosion of landslide and debris flow deposits can become a persistent source of suspended sediment. However, only a portion of the deposited sediments are fine enough to be transported in suspension. At Caspar Creek, about 50 to 80 percent of the mass of landslide-prone soils is of sand size and smaller, and large slides also incorporate weathered bedrock with a much lower proportion of suspendible sediment. Weathering and abrasion of larger clasts will make additional sediment susceptible to suspension through time. However, revegetation of the deposits increases the stability of even fine-grained deposits, and winnowing of fine sediments from around large clasts leaves an armor layer that progressively reduces surficial erosion rates on the slide scar and deposits.

For the two largest slides at Caspar Creek (table 1), 5 and 15 percent of the debris contributed to the suspended load during the slide-generating storm and during later storms of the same wet season.

Subsequent erosion of the slide scar, deposits, and disturbed downstream channels accounted for increased suspended sediment loads for several years after the initial slides, with the effect dwindling with time after the event. Overall, suspended sediment contributions after the initial year accounted for an additional 8 percent of the total slide mass from Z95 and 2 percent from E06.

Opportunities for sediment storage are limited in the high-gradient, incised channels typical of 1^{st}-order streams at Caspar Creek. Organic debris dams common in headwater channels provide a finite storage capacity that may be orders of magnitude less than the volume of sediment mobilized by a major slide. Two debris jams emplaced by the E06 debris flow provided key obstacles that accounted for about one-third of the deposition along the first 500 m of channel below the slide (d#4 and d#5, fig. 4); another is where the flow had to negotiate an abrupt turn to continue down-valley (d#3). These jams impounded sediments across the valley bottom, spanning widths more than four times that of the active channel. In contrast, U06 travelled straight down an abandoned skid trail and continued its path directly down the channel; any obstacles present were insufficient to trap the debris. Where deposits overwhelm the transport capacity in an existing channel, flow may be diverted to carve a new channel through valley-bottom deposits, as occurred at d#5 during the E06 event. In larger, low-gradient channels such as the North Fork, storage is largely controlled by woody debris loading and floodplain or terrace connectivity.

The amount of excess sediment transported in years following a slide depends in part on the progress of stabilizing influences, but it also depends strongly on the size and timing of the subsequent storms; during a drought year, not much sediment moves. Calculated excess suspended sediment loads for 2006 to 2014 from the UQL (*U*, t/ha) were evaluated in a multiple regression against the average of storm sediment loads at nearby control watersheds RIC, SEQ, and WIL (*RSW*, t/ha) and time after the U06 slide (*t*, yr). The resulting relation shows significant ($p < 0.001$) dependence on both influences:

$$U = 10.5 + 0.81\ RSW - 4.3\ t \qquad n = 41 \qquad r^2 = 0.$$
(1)

This relation suggests that recovery for small storms occurs more quickly than for larger storms, with the 0.5-yr return-interval events (averaging 34 kg/ha at the control watersheds) showing recovery in 8 years, while recovery for the 2-yr event (146 kg/ha at the controls) is expected to require several decades. A 1.62-yr event (as evaluated from flow records at NFC) did occur in December 2015, 10 years after the U06 event. Equation 1 predicts an excess load of 64 kg/ha for the event at the UQL gage, and the preliminary data for the storm indicate that the observed excess load was 62 kg/ha. Predicted excess load for the same storm would have been 103 kg/ha had it occurred during the year following the slide.

Six of the 8 years following the U06 slide had below average rainfall, and the largest storm during this 8-yr analysis period (hy2006 to hy2014) had a return interval of about 1.7 yr at the NFC gage. The net post-slide suspended sediment export for the period is thus expected to be substantially lower than it would have been for a more typical 8-yr sequence of storms. We thus applied Equation 1 to an average distribution of storms of 10-yr return interval or less for an 8-yr period. Results suggest that the excess suspended load observed during the first 8 years after U06 is about a third of that expected for the hypothetical average storm distribution. However, weather conditions also affect rates of stabilization of the slide scar and deposits. Drought years may hinder revegetation, for example, while wet years may trigger new failures on exposed scarps.

Although Z95 and U06 slides and their watershed conditions differ in character, excess loads associated with Z95 show a similar pattern:

$$Z = 6.3 + 0.42\ A - 2.8\ t \qquad n = 80 \qquad r^2 = 0.66 \qquad (2)$$

where *Z* is the excess storm sediment from XYZ tributary (kg/ha), *A* is the storm suspended sediment load at ARF (kg/ha), *t* is years after the slide occurred, and $p < 0.05$ for each variable.

The U06 slide is notable in that most of the slide debris left the watershed as a debris flow, leaving few deposits on the slide scar or in the channel above the UQL gage. The Z95 slide was similar in that it also did not leave a persistent channel-blocking deposit in the main XYZ channel. At E06, in contrast, much of the debris flow that mobilized the slide debris came to rest upstream of the EAG gage at d#3 and d#4 (fig. 4), blocking the EAG channel with a deposit as much as 4 m thick, and a tongue of the flow moved beyond the gage to deposit 390 m^3 of sediment (d#5 and d#6) in the channel between the EAG and DOL gages. Probably in part because of this difference, the post-slide sediment patterns at the EAG and DOL gages are quite different from those produced by the Z95 and U06 slides. After E06, storm sediment loads increased by nearly an order of magnitude over expected values at the EAG gage, but dropped the following year and have remained significantly lower than pre-slide levels since 2010 (fig. 7A, $p < 0.001$). The large debris jam may have impeded sediment transport from about 52 percent of the watershed, and erosion of revegetating slide deposits in and downstream of the jam evidently do not make up for the reduction in sediment from upstream. The decline in sediment production at EAG also reflects a general reduction in sediment inputs from slopes not affected by the slide as they recover from 1990-1991 logging and from 2001 pre-commercial thinning. A similar decreasing trend in non-slide-related inputs would also have been present during recovery from Z95. Logging in that area occurred in 1985-1986, with pre-commercial thinning carried out in 1993.

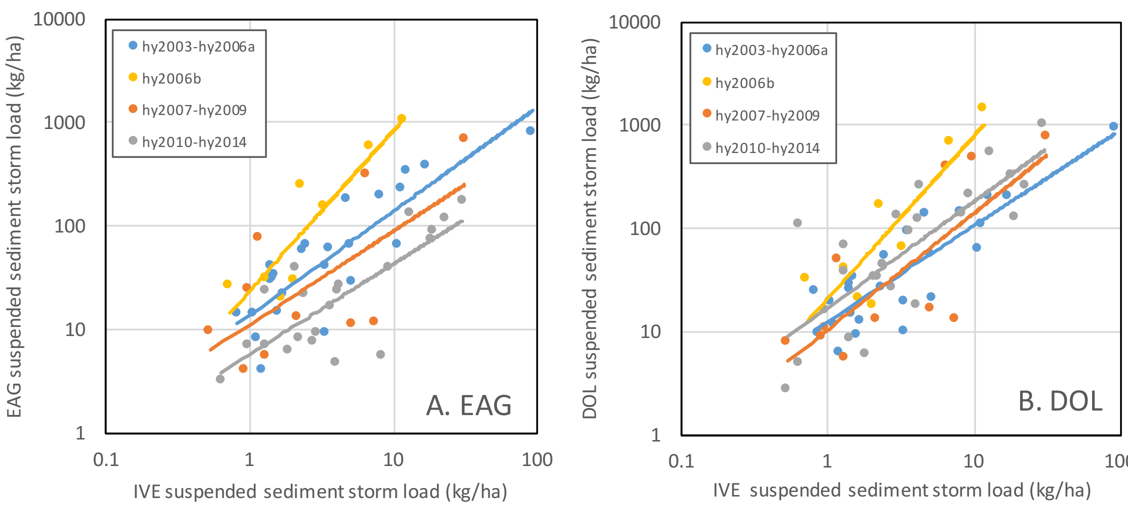


Figure 7—Relations between storm suspended sediment loads at A. EAG gage (drainage area: 27 ha) and B. DOL gage (77 ha) and those at control watershed IVE (21 ha) for periods before (hy2003-hy2006a) and after (hy2006b-hy20014) the 0.13 ha E06 slide.

In contrast, sediment loads at DOL (fig. 7B) were high during the remainder of the hy2006 wet season, then significantly decreased the following season ($p < 0.05$) but showed no further systematic decline after that. Although some of the excess sediment load at DOL is likely to be from remobilization of landslide sediments, a major portion represents 1) adjustment of the DOL channel to accommodate the new deposits and 2) accelerated headcut retreat through valley-fill deposits that date from old-growth logging and earlier. The DOL channel has widened about 20 percent since 2006, and a major headcut (fig. 4) activated soon after logging accelerated its retreat after the slide and is now located 50 m upstream of its initial 1993 location; this headcut has now excavated about 300 m^3 of sediment.

The spatial and temporal patterns of sediment production from major Caspar Creek landslides have several implications for cumulative impact analysis. First, there can be a lengthy period over which new activities may superimpose impacts on those persisting from earlier activities. Deposits from large slides can trigger secondary erosion in downstream channels, and these secondary in-channel sources may require longer recovery periods than erosion of the slide scar and primary slide deposits; this is the case along the DOL-EAG channel, where much of the post-E06 sediment production is from old deposits destabilized by flow and deposition associated with the slide. Some of those old deposits appear to themselves have resulted from debris flows and landslides, and it is likely that E06 deposits will play a similar role in the future. In addition, differences in sediment load recovery rates for large and small storms may lead to an erroneous assumption—after several years without major storms—that sediment production has recovered following a slide, when, in reality, future large storms may continue to produce excess loads even after those from smaller storms have returned to pre-slide levels.

Second, long-term influences from major slides may make it difficult to assess “background” sediment input rates where initial land-use impacts occurred long ago. Field evidence suggests that some of the valley fill deposits along the North and South Forks and their tributaries date from the period of old-growth logging, and valley-fill deposits are the source of a major portion of today’s sediment yield at Caspar Creek (Reid et al. 2010), which increased markedly after recent logging (Lewis et al. 2001). To the extent that erosion processes associated with old-growth logging contributed to valley-fill deposits, such processes would be influencing the expression of today’s land-use impacts, and so would be contributing to an on-going cumulative impact.

Third, downstream changes in the expression of effects associated with large landslides means that different resources will be affected in different ways at different locations along the channel system. Currently, the first-order channel draining E06 continues to sustain perennial flow during the dry season because fill in the swale and channel were scoured out by the E06 debris flow; this represents a major change in dry-season access to surface water in the headwater catchment. In contrast, aggradation at downstream sites may have reduced the annual duration of surface flow and increased fine sediments in pools. Channel response along the mainstem of North Fork is of particular concern because the stream provides habitat for threatened and endangered coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*), and aggradation reduces both the amount and quality of summer habitat.

The current study has focused on aspects of deposition and suspended sediment transport after large slides. However, a large quantity of landslide-derived sediment is transported as bedload, and bedload can itself be transformed to suspended load as clasts weather or as tributaries contribute bedload to streams with higher transport capacities. Future work is planned at Caspar Creek to evaluate patterns of coarse sediment transport after major landslide generating storms.

Conclusions

Landslides are an important source of suspended sediment at Caspar Creek, and a single large slide may influence channel form and sediment production and transport for many years. However, the observed short-term and long-term effects differ between slides, reflecting the particular setting and characteristics of each slide. For example, sediment loads decreased to significantly below pre-slide levels at the EAG gage by 4 years after the E06 event, probably due both to the emplacement of a debris flow deposit that may partially restrict sediment transport from half of the EAG watershed and to the on-going recovery trend from logging and pre-commercial thinning. Downstream, loads again increased, but along this reach the increase is due primarily to slide-related destabilization of the channel rather than to direct erosion of deposited slide debris. In order to evaluate potential cumulative watershed effects, it would be useful for resource planners to consider both landslide history and the vulnerability of legacy sediment storage features to re-mobilization.

Acknowledgments

Research at the Caspar Creek Experimental Watersheds is carried out through a long-term partnership between the USDA Forest Service Pacific Southwest Research Station and the California Department of Forestry and

Fire Protection. The manuscript benefited considerably from Peter Cafferata's review of an early draft and from the detailed comments by two anonymous reviewers on a later draft.

Literature Cited

Cafferata, P.; Reid, L. 2013. Applications of long-term watershed research to forest management in California: 50 years of learning from the Caspar Creek Watershed study. California Forestry Report No. 5. Sacramento, CA: The Natural Resources Agency, Department of Forestry and Fire Protection. 114 p.

Henry, N. 1998. Overview of the Caspar Creek watershed study. In: Ziemer, R.R., tech. coord. Proceedings of the conference on coastal watersheds: the Caspar Creek story. Gen. Tech. Rep. PSW-GTR-168. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 1–9.

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds. In: Ziemer, R.R., tech. coord. Proceedings of the conference on coastal watersheds: the Caspar Creek story. Gen. Tech. Rep. PSW-GTR-168. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 55–69.

Lewis, J.; Eads, R. 2009. Implementation guide for turbidity threshold sampling: principles, procedures, and analysis. Gen. Tech. Rep. PSW-GTR-212. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 87 p.

Lewis, J.; Mori, S.R.; Keppeler, E.T.; Ziemer, R.R. 2001. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. In: Wigmosta, M.S.; Burges, S.J, eds. Land use and watersheds: human influence on hydrology and geomorphology in urban and forest areas. Water Science and Application. Vol. 2. Washington, DC: American Geophysical Union: 85–125.

Madej, M.A.; Ozaki, V. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms. 21(10): 911–927.

Nolan, K.M.; Kelsey, H.M.; Marron, D.C., eds. 1995. Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. Professional Paper 1454. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

Reid, L.M.; Dewey, N.J.; Lisle, T.E.; Hilton, S. 2010. The incidence and role of gullies after logging in a coastal redwood forest. Geomorphology. 117(1): 155–169.

Reid, L.M.; Keppeler, E.T. 2012. Landslides after clearcut logging in a coast redwood forest. In: Standiford, R.B.; Weller, T.J.; Piirto, D.D.; Stuart, J.D., tech. coords. Proceedings of coast redwood forests in a changing California: a symposium for scientists and managers. Gen. Tech. Rep. PSW-GTR-238. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 163–172.

Spittler, T.E.; McKittrick, M.A. 1995. Geologic and geomorphic features related to landsliding, North and South Forks of Caspar Creek, Mendocino County, California. Plate 1, North Fork and Plate 2, South Fork. Scale 1:12,000. DMG Open File Report 95-08. Sacramento, CA: California Department of Conservation, Division of Mines and Geology.

Ziemer, R.R., tech. coord. 1998. Proceedings of the conference on coastal watersheds: the Caspar Creek story. Gen. Tech. Rep. PSW-GTR-168. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 149 p.