Go to Table of Contents

Landslides After Clearcut Logging in a Coast Redwood Forest[1]

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Abstract

Landslides have been mapped at least annually in the 473 ha North Fork Caspar Creek watershed since 1985, allowing evaluation of landslide distribution, characteristics, and rates associated with second-entry partial clearcut logging of 1989 to 1992. Comparison of sliding rates in logged and forested areas shows no appreciable difference for streamside slides (size range: 7.6 to 380 m^3). However, the incidence of large landslides, including both streamside and upslope slides of 98 to 4900 m^3, varied by treatment. Such slides displaced 12 m^3/yr per km^2 of unlogged forest but showed rates one and two orders of magnitude higher in logged areas and along roads, respectively. Moreover, the volume rate of sliding from roads in logged areas was more than three times that from forested roads. The largest slides occurred 9 to 14 years after logging, when root cohesion is expected to be near its minimum value; and within a few years of pre-commercial thinning, when hydrologic changes are again evident. Large slides may strongly influence suspended sediment yields both by increasing yields for several years after the slide and by emplacing temporarily stable channel and floodplain deposits, which then provide a sediment source for future gully and bank erosion.

Key words: cumulative effects, erosion, landslides, logging, roads, sediment budget

Introduction and site description

Associations between logging and increased landslide incidence have long been recognized, and many studies attribute the effect largely to reduced root cohesion (for example, Wu et al. 1979). However, because second-growth coast redwoods (*Sequoia sempervirens*) usually survive logging, altered root cohesion is rarely considered important after redwood logging. Recent studies have identified another influence that may be more relevant in redwood forests: reduced rainfall interception during major storms after logging could increase pore pressures on marginally stable slopes, contributing to their destabilization (Keim and Skaugset 2003, Reid and Lewis 2009). We here evaluate landslide distribution in the 473 ha North Fork Caspar Creek Experimental Watershed (N39°21´ W123°44´), near Fort Bragg, California, to 1) quantify the influence of roads and logging on landsliding in the area; 2) assess interactions between the effects of roads and logging on landslide generation; 3) evaluate storm characteristics associated with landsliding; and 4) assess the contribution of landsliding to the watershed's suspended sediment yield. This study uses a longer record to build on analyses by Cafferata and Spittler (1998).

The North Fork Caspar Creek watershed is underlain by marine sandstones and siltstones of the Coastal Belt of the Franciscan Complex. Soils on ridge-top marine

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terrace deposits are deep, sandy loams, while those lower on the slopes are shallower with higher clay and gravel contents. Many 3rd and 4th order channel segments flow through inner gorges, and drainage density is 4 to 5 km per km^2. Annual precipitation averages 1170 mm and falls mostly as rain; about half runs off as streamflow. The watershed's old-growth redwood forest was logged between 1860 and 1904. Second-growth stands had matured by 1960, when the Caspar Creek watersheds were selected as a location for watershed-scale experiments.

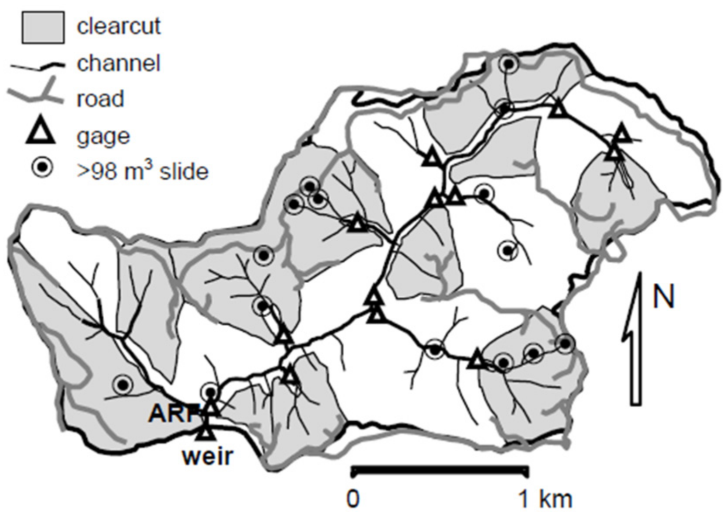

Figure 1—North Fork Caspar Creek watershed.

Stream gaging began in 1962 at the newly constructed North Fork weir (*fig. 1*), and the North Fork watershed remained forested as a control for the next 23 years. Thirteen new gaging stations were installed in 1984 for a study of scale-related hydrologic effects of clearcutting in a second-growth redwood forest. The ungaged XYZ tributary, which enters the head of the weir pond at the basin mouth, was not included in the experiment and was about 64 percent clearcut in 1985 and 1986. Catchments above five gaging stations were then 90 to 100 percent clearcut in 1989 to 1992, while those above three others were left forested; five downstream gages provided information for partially clearcut watersheds of increasing size. Overall, 13 percent of the watershed was logged in 1985 and 1986 and another 37 percent between 1989 and 1992. Logged units were mostly cable-yarded from ridge-top landings. About 18 km of road are present and are located primarily on or near ridge-tops, with 45 percent of the road length constructed immediately prior to logging at each unit. Selectively logged buffer strips were left within 40 to 60 m of channels draining more than about 10 ha.

Methods

Landslide data available for the watershed were grouped into two partially overlapping data sets. First, "streamside slides" consist of landslide events larger than 7.6 m^3 that were observed within 15 m of a gaged tributary channel. These features have been mapped annually since 1985 along 72 percent of the length of 2nd- and higher-order channels in the watershed; observations are also made after major storms. Slide dimensions, associations with treethrow and roads, and the volume of debris still present are noted for each feature. Mapped events in some cases represent progressive enlargements of previously mapped landslides, so the number of landsliding “events” is larger than the number of independent landslides mapped. The second data set consists of “large slides”: those observed anywhere in the North Fork watershed that are 98 m^3 or larger. Many of these were initially observed during the channel-based surveys, but most are located >15 m from a mapped channel. For both data sets, we estimate that volumes are accurate to better than ±25 percent.

Management effects were evaluated separately for each data set using post-1991 data; all land-use categories thus had experienced the same storms. Because buffer zones were selectively logged, they are either evaluated separately or grouped with logged slopes, depending on the analysis. For “streamside slide” data, the inventoried area includes the 15 m strip on either side of each gaged channel, while the entire watershed area above the weir is represented by the “large slide” data set.

A slide is assumed to be associated with a road if it is adjacent to the road or is immediately downslope of a drainage outlet. Areal sliding rates from roads are calculated per unit area of road surface, where road areas are estimated by applying an average width for each road type (mainline or spur road) to the length of that road type present. Only half the road width along North Fork boundary ridges is included because half the drainage from such roads is expected to enter other watersheds. To compare sliding rates on roads in different vegetation types, we calculated rates of volume displacement per unit length of road, and the total “road-km-yr” represented by a road segment in a particular land class is calculated by multiplying the segment’s length by the time it spent in that class. Roads traversing level terrain (gradient <10 percent) are disregarded for this portion of the analysis. These low-gradient surfaces were delineated using aerial photographs and generally correspond to the ridge-top marine terraces. Spur roads on steep ridges often abut a logged slope on one side and a forested slope on the other; in such cases, half the segment length is assigned to each class.

Cafferata and Spittler (1998) identified threshold rainfalls associated with large North Fork slides between 1962 and 1998, and we reevaluate thresholds to account for rainfall interception and transpiration. Rainfall has been monitored since 1962 at the SFC620 gage, located about 3 km downstream of the North Fork weir. Storms are identified as consecutive rain days bounded by days with <2 mm of rain and having a total rainfall >25 mm. The maximum 24-hr rainfall is identified for each storm using consecutive 1 hr rainfalls. The 2nd-growth forest at Caspar Creek intercepts and reevaporates 21 percent of the above-canopy rainfall (Reid and Lewis 2009), so subcanopy rainfall is calculated as 79 percent of the gage rainfall, while that in clearcuts is represented by the gage rainfall. A long-term antecedent precipitation index (API) is assessed for the day preceding each storm by applying a recession coefficient of 0.97 to calendar-day rainfalls. APIs for forested conditions are calculated using subcanopy rainfall, and estimated daily transpiration (Reid and Lewis 2009) is also subtracted. APIs of less than 0 are assigned a value of 0.

Because gaging stations are visited at least daily during storms, failure timing is often known to within days. Most other slides can be attributed to particular sequences of storms occurring over a 2- to 3-week period, and we assume that such landslides occurred during the most severe storm of the sequence.

Suspended sediment loads have been monitored at the North Fork weir since 1962 and at the sub-watershed gages during water years 1986 through 1995;

measurements continue at six of these gages. Loads were originally estimated using sediment rating curves constructed from gravimetrically determined sediment concentrations. Since 1995, load estimates are refined using turbidity readings logged at 10 minute intervals. The potential relative importance of landsliding as a sediment source is evaluated by comparing rates of sediment displacement by landslides with annual suspended sediment loads. An estimated 50 to 75 percent of the sediment displaced by landslides is expected to be of small enough grain size to be carried in suspension, and an additional component would break down to suspendible sizes during transport.

Results and discussion

Between 1985 and 2006, 91 events larger than 7.6 m^3 were observed in the North Fork watershed, and 83 of these occurred after 1991. Of the 65 post-1991 events that were mapped within 15 m of gaged channels (*table 1*), 14 were reactivations of previously mapped slides, so 51 independent slides of 7.6 to 380 m^3 are represented in the streamside slide data set, displacing 2280 m^3 of sediment. "Legacy" slides that originated at an old splash dam or along skid roads built during old-growth logging of the 1800s account for 29 percent of the streamside slide volume.

Table 1—*Landslides in the North Fork Caspar Creek watershed, 1992-2006.*

	Legacy	Forest	Buffer	Logged	Road	Total
Streamside slides > 7.6 m^3						
bank km-yr		140	70.2	34.6		244.8
number of events	7	30	19	9	0	65
volume m^3	670	880	520	210	0	2280
m^3/km-yr		6.3	7.4	6.1	0	9.3
All slides ≥ 98 m^3						
km^2-yr present		34.1	2.9	32.3	1.6	70.9
number of slides	2	3	1	3	4	13
volume m^3	600	420	140	3620	7170	11950
m^3/km^2-yr		12	48	112	4480	169

Between 1992 and 2006, differences in streamside landsliding rates were inconsequential among treatments, with forested, buffered, and clearcut reaches producing averages of 6.3, 7.4 and 6.1 m^3/yr per km of channel bank, respectively (*table 1*). These results may be complicated by influences of logging on adjacent and downstream sites. Two forested slides were associated with blowdown along clearcut margins, for example, and failures along one forested reach began when increased runoff from upstream logging appears to have accelerated headcut retreat at the site, undermining adjacent banks. Events that may have been influenced by nearby logging account for 21 percent of the post-1991 sediment displacement from forested streamside slides. On average, 55 percent of the displaced sediment remained within the landslide scars.

Although rates of sediment displacement from streamside slides are similar among treatment types, associations between streamside events and potential destabilizing features show several differences. In forested areas, 86 percent of the streamside slides are associated with treefalls or undercut banks, while only 70 percent of buffer strip slides and 33 percent of those in clearcuts show such associations. All streamside events at logged sites show evidence of hydrologic influence, either through their association with tunnel erosion or bank erosion, or, in one case, by mobilization of landslide debris into a short debris flow.

Fifteen slides larger than 98 m^3 (including seven also tabulated as streamside slides and three progressive failures) displaced about 13,500 m^3 of sediment in the watershed between 1985 and 2006 (*fig. 1*); 13 of these occurred after 1991 (*table 1*). Debris flows triggered during two events accounted for 2500 m^3 through channel scour and undercutting of banks. In contrast to the smaller streamside slides, the post-1991 rate of sediment displacement from large slides in forested areas (12 m^3/yr per km^2 of unlogged forest) was appreciably less than in treated areas (48 and 112 $m^3km^{-2}yr^{-1}$ in buffer strips and on clearcut slopes, respectively). The four slides associated with roads after 1991 produced about 4500 $m^3yr^{-1}km^{-2}$ of road surface. For large slides, an average of 21 percent of the displaced volume remained on the scars.

Two large slides occurred along forested roads, contributing 16 $m^3km^{-1}yr^{-1}$ for the 97 road-km-yr of forest-lined road present between 1985 and 2006. Both slides occurred before 1992. The four large slides along road segments within logged areas all occurred after 1994 and together displaced an average of 53 $m^3km^{-1}yr^{-1}$ for the 135 road-km-yr of logged road present between 1985 and 2006. The period during which all road types were exposed to the same storms, 1992 through 2006, showed no displacement for the 60 road-km-yr of forested roads present and 61 $m^3km^{-1}yr^{-1}$ for the 118 road-km-yr of logged roads.

Logging roads in steep terrain have long been recognized to be relatively unstable features (for example, Swanson and Dyrness 1975), and Bawcom (2007) notes the prevalence of road-related slides in and near the Caspar Creek watershed. The distribution of slides found by the current study to be associated with North Fork Caspar Creek roads suggests that influences of roading and logging may interact. Piezometric data from North Fork hillslopes (Keppeler and Brown 1998) indicate that such interactions could result from hydrologic change. Measurements in a swale upslope and downslope of a road corridor showed little change during the winter after road construction, though downslope readings showed brief pore pressure spikes that had not been observed previously during similar storms. Piezometers above the road remained dry both before and after roading. However, after the swale was clearcut the following year, positive pressure heads developed upslope of the road and increased as the wet season progressed. The road prism may thus have been retarding subsurface drainage, but changes became apparent only after reduced transpiration and interception increased water inputs to subsurface storage.

The temporal distribution of landslides in the North Fork watershed reflects a strong hydrologic influence. Each of the four storms that generated a total slide volume greater than 100 m^3 in forested areas had a sub-canopy API of >180 mm, a sub-canopy storm rainfall >115 mm, and a maximum 24 hr sub-canopy rainfall >75 mm (*table 2*). These were four of only five storms between 1985 and 2006 that shared these characteristics, and the fifth (December 2005) generated the largest landslide observed in the North Fork watershed between 1985 and 2010.

If these subcanopy rainfall thresholds are applied to the gage record, thus removing the influence of rainfall interception, five additional storms surpass the thresholds, and three of these generated significant landsliding in logged, roaded, or buffered areas. A fourth predated most logging, and the fifth closely followed another slide-generating storm. Three other notable slide-generating storms occurred between

1985 and 2006 (*table 2*), including a major windstorm (December 1995), in which all slides were associated with treefalls, and two storms that strongly exceeded two of the three thresholds. On average, a storm surpassed all thresholds for notable sliding in forests once in 4 years and twice as often for notable sliding on treated slopes.

Table 2—*Storms generating numerous or particularly large landslides, 1985 to 2006.*

Storm	Number of slides	Slide volume (m^3) forest	Slide volume (m^3) treated	Rainfall (mm) storm	Rainfall (mm) 24-hr	Effective API (mm) forest	Effective API (mm) treated
Feb 1986	2	8	1262	310	64	149	212
Jan 1993	8	112	79	146	127	255	345
Jan 1995	9	62	1932	387	107	88	130
Mar 1995	8	67	667	267	97	120	180
Dec 1995	4	55	55	148	69	46	70
Dec 1996	7	154	28	302	104	181	249
Jan 1998	6	37	191	338	85	157	221
Mar 1998	1	103	0	189	124	242	338
Mar 1999	3	0	119	122	95	194	277
Dec 2002	5	102	2035	155	100	230	307
Dec 2005	2	0	4009	266	122	218	291

Landslide risk is likely to be affected by three prominent trends after logging. First, transpiration and interception rates increase once again as regrowth progresses, reducing the likelihood of attaining excessive pore pressures. Second, even though most redwood stumps quickly resprout, a proportion of the original roots die and begin to decay, eventually to be replaced by new roots sustained by the recovering foliage. The minimum root cohesion is expected about 10 to 15 years after logging (J. Lewis, personal communication, March 2011). Third, exposure of trees along clearcut margins initially increases their risk of blowdown, but early post-logging wind storms cull the least stable trees, and regrowth eventually reduces the margins' exposure. Slides associated with blowdown along clearcut margins might thus show reduced frequency with time since logging.

The observed timing of failure events after logging may reflect such trends. All non-road-related slides at either forested or buffer strip sites after 1985 were smaller than 200 m^3. Plots of cumulative landslide volume against years since logging for slides >200 m^3 show slightly different patterns for clearcuts and buffer strips: both show high rates until about 8 years after logging, but slide activity resumes on clearcut slopes at about 13 years, while it does not do so in buffer strips (*fig. 2*). In contrast, all slides larger than 200 m^3 at logged sites occurred 9 to 14 years after logging, when root cohesion on the logged slopes is near its minimum value but regrowing vegetation would ordinarily have ameliorated much of the initial hydrologic change. However, about 70 to 90 percent of the crown area was removed at these sites by pre-commercial thinning 9 to 11 years after logging, and peakflows had again increased to well above those expected for unlogged conditions (Lewis and Keppeler 2007). The largest slides thus occurred at a time when influences of both altered root cohesion and hydrologic change were strong.

The association of landsliding with storms having high 24 hr and storm rainfalls and high APIs demonstrates the dependence of sliding on hydrologic triggers, as does the increased slide frequency for smaller storms after logging. However, the delay in occurrence of the largest slides suggests that while hydrologic influences affect the frequency of sliding, reduced root cohesion may provide an important influence on the size of the slides triggered.

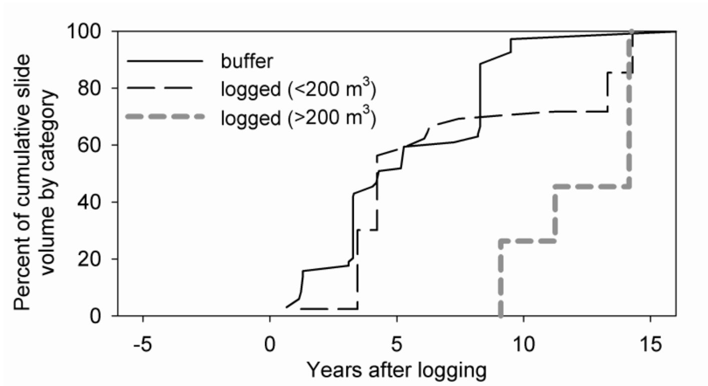

Figure 2—Cumulative landslide volume on treated sites as a function of time after logging.

Annual suspended sediment yield is not significantly correlated with the volume of landslide sediment displaced along gaged channels between 1986 and 1995, the period during which all gages were operating (Reid et al. 2010). All slides that occurred in these sub-watersheds during the period analyzed were < 280 m^3. Although the average sediment displacement rate for streamside slides of 6 to 7 m^3/km of channel bank for 2nd-order and larger channels (*table 1*) would amount to about 20 $m^3km^2yr^{-1}$, more than half of the sediment remains in storage on or near the slide scars and does not consistently contribute to the suspended sediment load.

The largest slides, in contrast, can strongly influence short-term suspended sediment yields. The "Z" slide occurred in 1995 in the ungaged XYZ tributary on a slope logged in 1986 and thinned in 1994. Debris from the 1750 m^3 failure flowed 200 m downstream, scouring sediment from channel banks and triggering streamside failures to mobilize an additional 1000 m^3. Because only XYZ tributary enters the North Fork between the ARF gage and the North Fork weir, excess XYZ inputs can be estimated by comparing measured suspended sediment loads at the weir with those predicted using pre-slide correlations between loads at ARF and at the weir. Results show that the weir station recorded 1300 kg/ha (610 t) more than expected during 1995 to 2000 (*fig. 3*), and that loads had once again stabilized by 2000. The excess suspended sediment accounted for about 14 percent of the sediment displaced by the slide and debris flow, and 55 percent of the slide debris was redeposited near the slide scar, so about 30 percent of the displaced sediment remained within the channel and weir pond. The annual pre-treatment suspended sediment load averaged 68 ± 39 t $km^{-2}yr^{-1}$ at the weir between 1963 and 1985 (incorporating a bias correction suggested by J. Lewis, personal communication, 2007, to adjust for the pre-1976 sediment sampling protocol), so the slide produced the equivalent of about 2 years of suspended sediment yield for the 4.7 km^2 watershed above the weir.

During the 23 years that North Fork sediment loads had been monitored before logging began, only a 3300 m^3 landslide was large enough to increase sediment markedly at the North Fork gage. The 1974 failure occurred on a forested inner-gorge slope about 2 km upstream of the weir (Rice and others 1979). Considering now only the extremely large slides (>2500 m^3) expected to be recognizable from suspended sediment records at the weir, those in the 40 km^2yr of logged area present between

1963 and 2006 displaced an average of 190 $m^3km^{-2}yr^{-1}$, while that in the 173 km^2yr of forest displaced 19 $m^3km^{-2}yr^{-1}$. About 25 to 50 percent of the displaced material is expected to be too coarse to be carried in suspension.

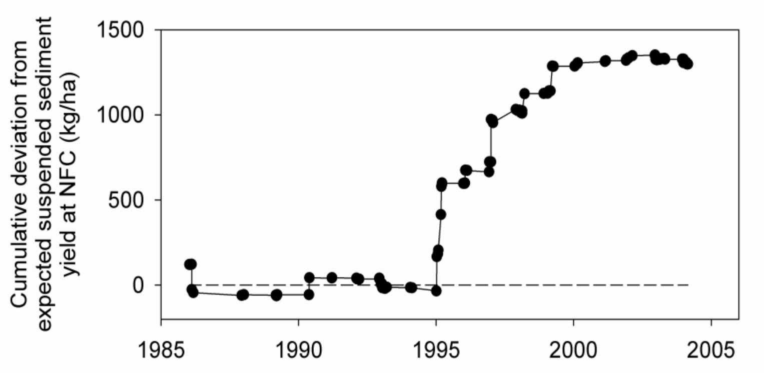

Figure 3—Cumulative deviation in storm suspended sediment yields from expected values at the North Fork weir. The Z slide occurred in January 1995.

The mean pre-logging suspended sediment load of 68 t $km^{-2}yr^{-1}$ at the North Fork weir is equivalent to a volume rate of 52 $m^3km^{-2}yr^{-1}$ if a bulk density of 1.3 g cm^{-3} is assumed. The single extreme slide on undisturbed land thus could have increased the long-term mean suspended yield from forest lands by as much as 20 percent if 75 percent of the displaced sediment eventually becomes suspended load. If the same assumptions are made for extreme landslides associated with disturbed sites, these slides could increase the long-term suspended sediment yield for logged areas by a factor of about 3.1 relative to that expected for pre-treatment conditions. In either case, much of the displaced sediment would be stored along downstream channels and become susceptible to later remobilization by bank erosion and gullying.

Conclusions

Clearcut logging appears to have influenced landsliding in the North Fork watershed primarily through the increased incidence of large landslides and by destabilization of logged slopes adjacent to roads. Clearcutting also appears to have reduced the storm magnitudes required to generate landsliding.

Logging can affect landslide incidence by decreasing transpiration and rainfall interception and by reducing root strength. Hydrologic conditions appear to be the primary influence on the generation of small to medium landslides at Caspar Creek, while root strength may be an important influence on landslide size. Notably, all slides >200 m^3 that occurred between 1986 and 2006 were associated either with roads, buffer strips, or clearcut slopes, and all slides >200 m^3 on logged lands occurred 9 to 14 years after clearcutting and within 5 years of pre-commercial thinning. Three destabilizing conditions were present at that time: 1) root cohesion would have been near its minimum value after logging as roots killed by clearcutting had decayed while regrowing roots were not fully developed, 2) new roots killed by thinning would have begun to decay, further reducing root cohesion, and 3) thinning would have again reduced interception and transpiration, again increasing the hydrologic response to storms. At sites where slope stability is of particular concern, it may be useful to delay thinning to a time when root cohesion has recovered more fully from logging so that the ensuing increase in hydrologic response does not coincide with the period of minimum root cohesion.

An interaction between the topographically destabilizing presence of roads and hydrologic changes induced by clearcutting may be responsible for the higher frequency of road-related landsliding in clearcuts than in forest. In many areas, rates of landsliding along roads have been contrasted to rates on logged slopes, producing the conclusion that logging has a relatively insignificant influence on sliding. However, in areas where road-related instability is expressed primarily after adjacent slopes are logged, the distinction between "logging-related" and "road-related" landslides may not be particularly useful: the cumulative effect of roads and logging may be synergistic rather than additive. The number of slides associated with roads was relatively small in the North Fork Caspar Creek watershed, however, and it would be useful to test for interactions of roads and logging at additional sites.

Comparison of landslide incidence with suspended sediment yields in North Fork Caspar Creek tributaries demonstrates that small to medium landslides have little short-term effect on suspended sediment yields (Reid et al. 2010), while a few extremely large slides can strongly influence the suspended sediment yield for the entire watershed. Much of the sediment generated by landsliding remains stored in and adjacent to channels, making it susceptible to later entrainment through bank erosion and gullying. Sediment inputs during small to moderate storms might thus be influenced by the history of past landsliding.

Acknowledgments

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