

Logging Impacts of the 1970's vs. the 1990's in the Caspar Creek Watershed¹

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Abstract: *The Caspar Creek watershed study provides resource professionals with information regarding the impacts of timber operations conducted under varying forest practices on sensitive aquatic habitats. In the South Fork watershed, roads were constructed near watercourse channels in the 1960's, and the watershed was selectively logged using tractors during the early 1970's. Subwatersheds in the North Fork were clearcut from 1985 to 1991 using predominantly cable yarding and roads located high on ridges. Numerous landslides were documented after road construction and logging in the South Fork owing to inadequate road, skid trail, and landing design, placement, and construction. In contrast, the size and number of landslides after timber operations in the North Fork to date have been similar in logged and unlogged units. Considerably more hillslope erosion and sediment yield have also been documented after logging operations in the South Fork, when compared to the North Fork. An analysis of the storm events associated with documented landslides showed that high 3-day or 10-day precipitation totals in combination with moderately high 1-day amounts have been more important than very high 1-day totals alone in triggering debris sliding at Caspar Creek. Storm sequences meeting the criteria required for causing documented landslides were found to have occurred in all phases of the 36-year study, with the greatest number occurring in water year 1998. Numerous large landslides associated with the road system in the South Fork occurred in early 1998, indicating that "legacy" roads continue to be significant sources of sediment decades after they were constructed.*

The impacts of harvesting and road construction in a second-growth redwood/Douglas-fir forest have been studied for 36 years in the Caspar Creek watershed. This allows us to compare the impacts from the first phase of the project, completed before the implementation of the modern Forest Practice Rules in California, with those associated with considerably improved forestry practices. Specifically, in the South Fork, roads were constructed in 1967, and the entire basin was selectively harvested from 1971 to 1973, before the enactment of the Z'berg Nejedly Forest Practice Act of 1973. Approximately 6.8 km (4.2 mi) of road were built low on the slopes in the watershed, much of it adjacent to the South Fork channel, and tractors were used to skid logs to low-slope landings. Some of the skid trails were built in small stream channels. In contrast, 47.8 percent of the North Fork, within 10 nested subwatersheds, was clearcut from 1985 to 1992 using 11.4 km (7.1 mi) of existing roads and 8.4 km (5.2 mi) of new roads located high

on the ridges (Preface, fig. 2, these proceedings). The steeper slopes were cable yarded. This long-term instream monitoring study provides resource professionals in California with information regarding the impacts of timber operations with varying forest practices on sensitive aquatic habitats.

In this paper, we present a discussion of the geology and geomorphology present in the Caspar Creek drainage, as well as a summary of the major erosional sources which have followed logging in the gaged portions of each tributary. Additionally, we compare and contrast rainfall and runoff events that occurred during both phases of the study. A summary of the sediment yields documented during the life of the study is presented, and changes in sediment generation attributable to improved forest practices are discussed. Finally, recommendations are offered to forest managers regarding the applicability of Caspar Creek results to other California watersheds.

Geology and Geomorphology Physiography

The North Fork of Caspar Creek above its weir drains a watershed of 473 ha (1,169 ac), in northern California, whereas the area above the South Fork weir is approximately 424 ha (1,047 ac). These small watersheds, located inland from the central Mendocino County coast, are about 11 km (7 mi) southeast of Fort Bragg. The low point of each experimental watershed is at its weir, 85 m (275 ft) for the North Fork and 50 m (160 ft) for the South Fork, with the high points 310 m (1,020 ft) and 320 m (1,057 ft), respectively.

Geology

Both watersheds are underlain by the Coastal Belt of the Franciscan Complex (Kilbourne 1982, 1983; Kilbourne and Mata-Sol 1983). Well-consolidated marine sedimentary sandstone with intergranular clay and silt (graywacke) and feldspathic sandstone, with lesser amounts of siltstone, mudstone, and conglomerate, are the dominant rock types. The sandstones are poorly bedded to massive, and moderately well consolidated. Individual exposures range from coarsely jointed sandstone that is moderately hard and strong to highly fractured to sheared rock that exhibits low strength.

Alluvium of Holocene age is locally present in both watersheds. A significant accumulation of this material is present in the upper portion of the North Fork watershed. The alluvium consists of loose to somewhat indurated, poorly sorted sands, gravels, and silts that were deposited behind barriers or locally along low-gradient segments of the stream channels. An extensive area of alluvium was deposited behind an ancient landslide dam in the North Fork. The

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remnant of the landslide dam is an inclined (depositional inclination) deposit of poorly sorted sand, silt, and gravel that forms a perched bench on the north bank. The geometry of the remaining sediment indicates that this old landslide transported on the order of 1 to 5 million cubic meters of material.

Geomorphology

Both the North Fork and South Fork of Caspar Creek flow in relatively narrow, bedrock-controlled stream channels. The upper portion of the North Fork of Caspar Creek flows in a narrow gully through Holocene alluvium that was deposited behind the landslide dam. Carbon-14 (^{14}C) dating of carbonaceous material, found by Dr. Stephen Reneau (1989) in the alluvium upstream from the landslide dam, indicates that this material slowly filled the valley beginning about 7,000 years before present (BP) through at least the late Holocene. Deposition stopped only recently, after which renewed downcutting occurred. This indicates to us that the broad (approximately 100 m [330 ft] wide) debris flow deposits formed a long-lasting dam that resisted downcutting for thousands of years.

Logging of the old-growth forest in the Caspar Creek watershed occurred between the 1860's and 1904. All large, accessible trees that would generate high-quality forest products were felled, topped, and limbed on the slopes. Included in the harvest were the trees that lined the stream channels and all partially buried logs and other structural features that could impede the transport of logs down the main channels during future floods. After the limbs and tops had dried (and the logs had lost a great deal of water weight), the watersheds were burned to clear away the logging slash. The resistance to fire of the old-growth redwood protected the logs from immolation. Fire scars are still visible on old-growth trees that were not harvested. After burning, the bucked logs were skidded to the main stream channels by oxen (a small percentage of the North Fork watershed was logged later starting about 1900 with steam donkeys). Small stream channels were used as skid roads, with corduroy logs half buried, heavily greased, and evenly spaced at intervals equal to the stride of the oxen that were teamed to pull the log trains.

During this time dams were constructed across steep, narrow reaches in the headwaters of the two forks of Caspar Creek. Remnants of the splash dam in the North Fork are visible along the steep, narrow channel at the old landslide dam. During the winter, when the streams were at flood stage and the reservoirs behind the dams were full, the gates would be opened and the resulting flood would raft the accumulated logs to the mill at the mouth of Caspar Creek. The transport of logs down the streams continued for roughly 25 years until most of the watershed had been logged (Wurm 1986).

It is clear that the artificial floods and the removal of the riparian vegetation and in-channel large woody debris had a profound impact on channel geometry, stream bank stability, and sediment discharge. Napolitano (1996) documents that the depletion of large woody debris from the stream channel, caused by the clearing and flooding, was so severe that the streams have not yet recovered. However, the consequences of the logging on the hillslopes did not persist. Other than a few remnants of corduroy

skid roads in small channels, little evidence of the original logging is still present. In fact, in the North Fork watershed, the majority of which was never logged with tractors, the well-preserved details of the surface morphology allow the geomorphic mapping of debris slides, debris flows, rotational landslides, disrupted, hummocky ground, and inner gorges.

The geomorphic mapping of the North Fork took place at intervals between 1986 and 1994. The upper portion of the watershed was field mapped using the published topographic map that was photographically enlarged to a scale of 1:6,000. The remainder of the North Fork was mapped using aerial photographs and limited field reconnaissance on a 1:12,000-scale, photographically enlarged topographic base. The quality of ground surface exposure in the North Fork allowed the landslides to be subdivided into five relative age classes (Spittler and McKittrick 1995): (1) fresh-appearing landslides that were most recently active within the past 20 years; (2) landslides that have affected the second-growth trees but have recovered to some degree—estimated to be from 20 to 120 years old; (3) landslides that have affected the old-growth trees or stumps, but have not affected the second-growth trees—estimated to be from 100 to 1,000 years old; (4) landslides that have not affected the old-growth trees or stumps but have well-defined surficial morphologies—estimated to be from 500 to several thousands of years old; and (5) geomorphic features with morphologies suggestive of landsliding but that are highly modified. These last features may be related to differential erosion of inhomogeneous bedrock, perched ancient erosional surfaces, or ancient landsliding.

In contrast to the logging history of the North Fork, the logging history of the South Fork of Caspar Creek has resulted in a significant impairment in our ability to map geomorphic features. Mapping was conducted by using aerial photographs taken for this project, and photos taken in 1975 after the more recent logging was completed. Field work was impeded by ground surface modifications and dense regeneration. The South Fork watershed was affected by a high degree of ground disturbance that occurred as a result of road construction in 1967 and tractor logging between 1971 and 1973, before the implementation of modern forest practices. This disturbance has modified surface features to the extent that only larger landslides, and those that occurred following the timber harvesting, are well defined. The landslide incidence and sediment yield data suggest that the ground disturbances affected more than our ability to map landslides. Although the South Fork was selectively logged, the persistence of the surface disruption during the 25 years since the logging was completed suggests to us that the recovery is very slow.

Within the North Fork watershed, only one small landslide⁴ was observed in the clearcut units of the North Fork of Caspar Creek between the beginning of logging in 1985 and the end of the geologic study in late 1994. This was a failure from a yarder landing in

⁴ Landslides are defined here as those greater than or equal to 76 m³ (100 yd³). Additional smaller features were also recorded.

subwatershed G that occurred during an unseasonable storm event in late May 1990. Of the 15 other landslides in the watershed that were fresh appearing, seven are associated with the existing roads across the upper slopes and eight occurred in areas not adjacent to roads. Other than the subwatershed G feature, landslides in the harvested blocks appear to predate the timber harvesting on the basis of the age of vegetation growing on the scars. Eight of the fresh-appearing landslides are larger than 0.2 ha (0.5 ac) (*fig. 1*). Of these, all but one are associated with the older roads. After the completion of the geologic study, a debris flow in the YZ subwatershed transported about 3,600 m³ (4,700 yd³) in January 1995. Seven other small failures have been documented in the North Fork since the start of 1995. Three small failures occurred in both clearcut blocks and areas outside of harvest units.⁵ In addition, one fill failure occurred that was associated with an existing road in a clearcut subwatershed.

Unlike the North Fork watershed, where only one small landslide was related to roads, skid trails, or landings constructed for the recent predominantly cable clearcut logging, almost all of the smaller, more recent landslides in the selectively cut South Fork watershed are associated with these types of disturbance features. Interpretation of aerial photographs of the South Fork of Caspar Creek from 1975 revealed 66 recently active landslides, all of which appear to be debris slides or debris flows. Of these, 35 are associated with roads, 12 with landings, and 16 with skid trails, with three not associated with ground disturbances and not within the area that was selectively logged. Seventeen of the post-logging landslides were larger than 0.2 ha (0.5 ac). Of these larger landslides, six are associated with roads, seven with landings, and three with skid trails; one is not associated with the timber operations (*figs. 2, 3*).

The number and relative sizes of post-harvesting landslides differ substantially between the North Fork and South Fork of Caspar Creek. Within the North Fork, 10 landslides have been reported to have occurred since the beginning of operations in 1985, including two in 1998. Of these, six are associated with logged units and four are in unlogged portions of the watershed. Only one landslide failed in the North Fork that exceeded 0.2 ha (0.5 ac). In contrast, during the first 8 years after the initiation of road construction within the South Fork watershed, 66 landslides, 17 of which are larger than 0.2 ha, failed.

During the El Niño storm year of 1997-1998, which is the winter of record for precipitation during the life of the Caspar Creek watershed study (greater than 2,030 mm [80 in.] total precipitation), only one small landslide was reported for recently logged or roaded units in the North Fork watershed. This slide feature is approximately 76 m³ (100 yd³) and occurred along the North Fork in a unit clearcut in 1990; it is located immediately above the streambank and is actually a reactivated slide mapped earlier in the study. Another slide of similar size took place in uncut tributary H (*table 1*). In contrast, landslides of 1376, 149, 68, 57, and 25 m³ (1800, 195, 89, 74, and 33 yd³) have been documented in

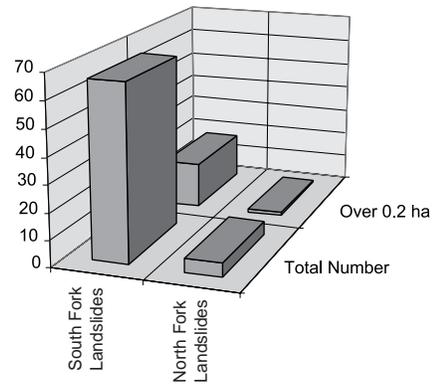


Figure 1—Comparison of the total number of landslides and number of landslides over 0.2 ha after timber harvesting activities in the North Fork (until 1996) and South Fork (until 1975) of Caspar Creek.

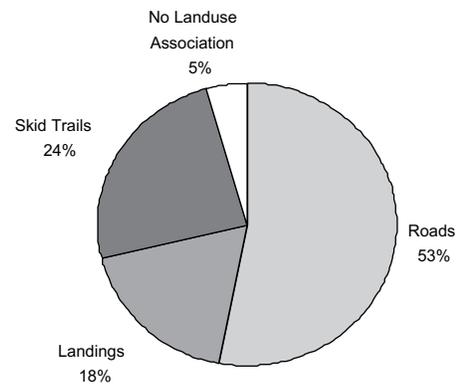


Figure 2—Distribution of all landslides after 1967 road construction and 1971-1973 logging as interpreted from 1975 aerial photographs, South Fork Caspar Creek.

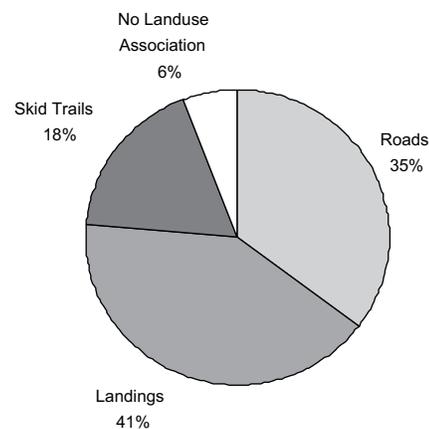


Figure 3—Distribution of landslides over 0.2 ha after 1967 road construction and 1971-1973 logging as interpreted from 1975 aerial photographs, South Fork Caspar Creek.

⁵ Data from North Fork Caspar Creek Large Event Inventory, supplied by Elizabeth Keppeler, USDA Forest Service, Pacific Southwest Research Station, Fort Bragg, California.

the South Fork watershed that were related to the old road system and have discharged substantial amounts of sediment into the stream. In addition, a 420-m³ (550-yd³) feature associated with the old skid trail network and an inner gorge slide of 168 m³ (220 yd³) not related to old roads or skid trails occurred (Keppeler 1998).

Hydrologic Considerations

Rainfall and Hillslope Failures

Rainfall characteristics are well-correlated with landslide initiation. Deep-seated failures are heavily influenced by seasonal precipitation amounts (Sidle and others 1985). In contrast, shallow rapid failures, such as the debris avalanches and debris slides that have occurred in the Caspar Creek watershed, are generally triggered by a critical combination of rainfall intensity and duration (Cannon and Ellen 1985). Intense rainfall can exceed the rate of hillslope drainage, causing the piezometric surface to rise and generating positive pore water pressures within the soil that can ultimately cause slope failure (Campbell 1975).

Timber operations can alter hillslope drainage patterns. Harvesting timber in a small swale in the North Fork of Caspar Creek elevated pore water pressures from 9 to 35 percent above background levels during the first 4 years after logging, but did not initiate slope failure. On slopes with known or suspected stability problems, however, additional pore water pressure generated by timber harvest may increase the risk of landsliding (Keppeler and others 1994). Mid-swale road construction along with timber harvest in the North Fork produced dramatic increases in pore water pressures in and up-slope of the road prism (Keppeler and Brown, these proceedings). LaHusen (1984) reported similar results in Redwood National Park. He documented greatly increased pore water pressures within roadfill

material, with a corresponding two- to five-fold decrease in hydraulic conductivity, and concluded that intense rainfall events can create pronounced "groundwater mounds" in road prisms that eventually culminate in debris flow initiation.

Campbell (1975) and Wieczorek and Sarmiento (1983) found that 25 to 38 cm (10 to 15 in.) of antecedent seasonal precipitation can ready a hillslope for debris slides. Once field capacity of the soil mantle has been reached, a storm with extreme 12- to 24-hour precipitation can cause shallow debris avalanche failure. For 24-hour storm duration, a failure threshold has been shown to occur at a rainfall intensity of 0.7 cm hr⁻¹ (0.3 in. hr⁻¹) in the part of the San Francisco Bay area with mean annual precipitation of more than 66 cm (26 in.) (Cannon and Ellen 1985), and a failure threshold of 0.43 cm hr⁻¹ (0.17 in. hr⁻¹) has been reported by Caine (1980) using data in the worldwide literature. Caine (1980) used published records of rainfall intensities and durations associated with shallow landsliding to develop a rainfall-debris flow threshold equation for durations from 10 minutes to 10 days.

Rainfall Records for Caspar Creek

Before we can draw valid conclusions regarding the relationship between landsliding and sediment generation with forestry practices, we must assess the number and relative sizes of stressing storms that occurred throughout the calibration period for both watersheds (water years 1963-1967), the South Fork road construction, logging, and recovery period (1968-1978), and the North Fork road construction, logging, and recovery period (1986-1998).

Daily precipitation values are available for the South Fork of Caspar Creek for hydrologic years 1963 through 1998.⁶ Goodridge (1997) provides rainfall depth duration frequency data for the South Fork Caspar Creek 620 station.⁷ From this information, we plotted

Table 1—Precipitation amounts from storm periods associated with known landslides greater than 76 m³ (100 yd³) in the North Fork of Caspar Creek (exact dates of landslides during storm events are assumed in some cases).

Slide date	Subwatershed	Slide Vol (m ³)	Slide Vol (yd ³)	1-Day Total (cm)	3-Day Total (cm)	5-Day Total (cm)	10-Day Total (cm)	API (cm)
March 31, 1974 ¹	L-not logged	3306	4324	6.17	11.79	17.63	20.09	17.30
Feb 16, 1986	L-not logged	1262	1650	4.95	11.94	15.95	16.13	16.92
May 27, 1990	G-logged	283	370	4.88	12.40	12.40	23.77	17.81
Jan 9, 1995	YZ-logged	3606	4715	5.97	15.62	19.71	23.67	20.80
March 14, 1995	A-not logged	306	400	5.11	11.38	15.98	25.58	20.07
March 14, 1995	G-logged	76	100	5.11	11.38	15.98	25.58	20.07
March 14, 1995	C-logged	130	170	5.11	11.38	15.98	25.58	20.07
Jan 24, 1996	E-logged	84	110	5.13	7.42	10.85	23.37	16.56
Dec 31, 1996	H-not logged	122	160	8.59	17.60	19.18	23.90	23.55
February 1998 ²	L-logged	76	100	—	—	—	—	—
March 22, 1998	H-not logged	103	135	5.08	12.57	12.57	12.62	15.16
Mean				5.74	12.59	15.53	21.14	18.52

¹The date of this slide feature was assumed based on large amounts of precipitation at the end of the month. Slide volume is from Rice and others (1979).

²The date of this feature is unknown, preventing the association of rainfall amounts with the landslide feature.

⁶ The hydrologic year is defined as beginning on August 1st for the Caspar Creek watershed. Daily precipitation values are determined from midnight to midnight.

⁷ Data missing from Goodridge (1997) were obtained from the USDA Forest Service's Pacific Southwest Research Station's Internet site (<http://www.rsl.psw.fs.fed.us/projects/water/caspar.html>).

the 1-, 3-, 5-, and 10-day annual maximum rainfall totals to determine the frequency and size of stressing storm events over the life of the study. For example, the 1-day annual maximums are displayed in *figure 4*.

In Goodridge's (1997) analysis, 11.07 cm (4.36 in.) of precipitation over a 1-day period constitutes a 5-year return period event, 12.88 cm (5.07 in.) represents a 10-year 1-day event, and 16.59 cm (6.53 in.) is the 50-year 1-day event. Before any modern disturbances in either the South Fork or the North Fork, 5-year rainfall events occurred in water years 1964, 1965, and 1966. After road construction in the South Fork, another 5-year stressing storm occurred in 1969. An event of approximately this magnitude occurred in 1985, before the start of logging in the North Fork. The highest 1-day precipitation total during the period of the study is 12.75 cm (5.02 in.) and occurred in water year 1998, approximately 7 years after completion of logging in the North Fork. This is only slightly less than a 10-year event. Therefore, it appears that only one 1-day duration storm total approached the 10-year recurrence interval during the 36-year study record. Five-year return period rainfall events occurred in all phases of the study except the period immediately after logging in the South Fork, but were most frequent before road construction or logging occurred in either watershed.

The 10-day precipitation totals for the South Fork Caspar Creek station tell a similar story (*fig. 5*). Goodridge (1997) reported the 5-year return interval for this duration as 28.42 cm (11.19 in.). Storms in hydrologic years 1965, 1966, 1969, 1988, 1995, and 1998 exceeded this amount. The 1995 10-day total of 33.25 cm (13.09 in.) is second only to that of 1965, with 34.26 cm (13.49 in.), and

both of these exceed the 10-day, 10-year return interval storm of 32.56 cm (12.82 in.) reported by Goodridge (1997). Therefore, these longer-duration storms are distributed more evenly throughout the 36-year rainfall record than the 1-day storm events, and have occurred in all phases of the study except the period immediately after logging in the South Fork.

Durgin and others (1989) state that Caine's (1980) data are most relevant to harvest area related landslides, but a similar threshold may apply to road-related failures. Rice and others (1985) reported that Caine's 1-day threshold has about a 4-year return period on the North Coast of California. In Caspar Creek, Goodridge (1997) reported the 5-year 1-day storm as 11.07 cm (4.36 in.), which is slightly above Caine's 24-hour threshold of 10.4 cm (4.1 in.). Therefore, to determine whether forest practices are sufficient to prevent landsliding above background rates with Caine's threshold, it is necessary for logging units and new roads to be tested by a 4-year return interval storm event after seasonal precipitation amounts that produce saturated mantle conditions. Events of this magnitude occurred after logging impacts in the South Fork in water years 1969, 1985, and 1998, and in the North Fork in 1998.

Caine's index includes durations up to 10 days. Using his equation, minimum landslide-triggering rainfall amounts for 3-, 5-, and 10-day durations are 20.12 cm (7.92 in.), 27.50 cm (10.83 in.), and 41.95 cm (16.52 in.), respectively. These 3- and 5-day totals are between 10- and 25-year return interval events, and the 10-day total is between a 50- and 100-year event for Caspar Creek, based on Goodridge's (1997) data. Highest recorded totals for these durations at Caspar Creek are all less than Caine's thresholds.

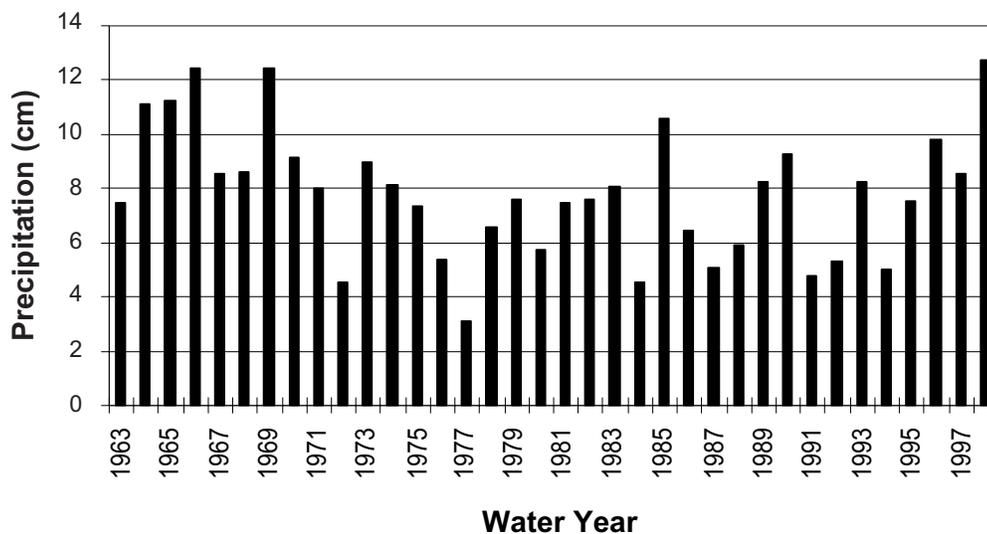


Figure 4—Annual maximum 1-day rainfall totals for the South Fork Caspar Creek 620 raingage.

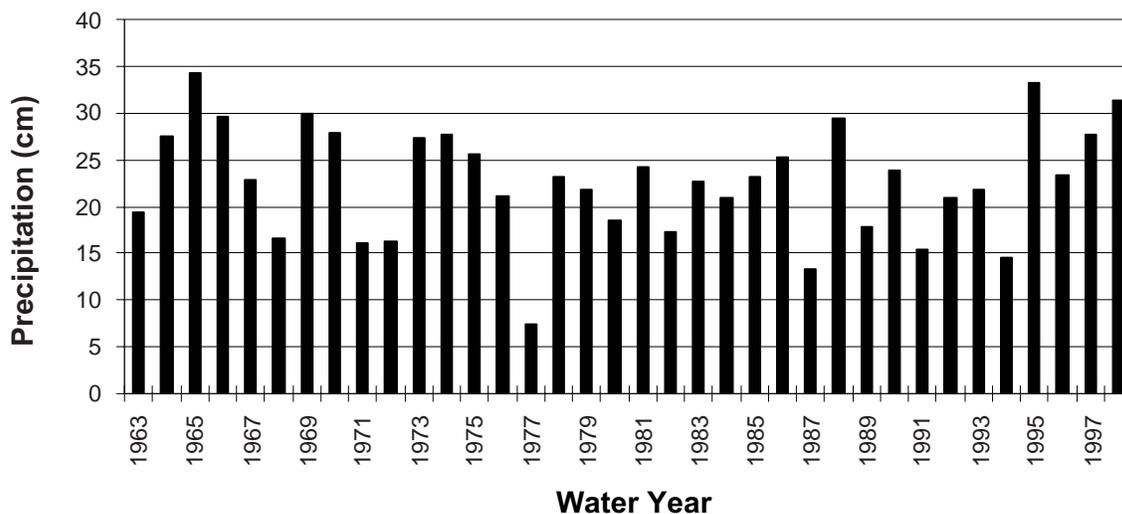


Figure 5—Annual maximum 10-day rainfall totals for the South Fork Caspar Creek 620 raingage.

Rainfall Records and Large Landslides in the North Fork

Eleven large (i.e., greater than or equal to 76.5 m³ or 100 yd³) landslides have been documented in the North Fork watershed during the life of the study⁸ (table 1). Five features are located in unharvested areas (i.e., mature second-growth forest), and six are in clearcut blocks. Three of these landslides were much larger than the others, exceeding 1,000 m³ (1,308 yd³). The first of these features occurred during March 1974 and was a shallow debris slide of approximately 3,306 m³ (4,324 yd³) that directly entered the North Fork of Caspar Creek (Rice and others 1979). The second recorded large feature was a shallow debris slide that occurred during February 1986, near the old splash dam site. Both of these landslides occurred before the most recent logging and were not associated with the clearcut logging or new road construction. The largest landslide in the study period was a 3,606-m³ (4,715-yd³) debris flow that came from a steep hollow high on a hillslope in a clearcut unit in January 1995.

The rainfall amounts for storm periods associated with the landslides larger than 76 m³ are displayed in table 1. The totals for 1-, 3-, 5-, and 10-day period preceding the event are generally similar for logged area and uncut area landslides. The mean precipitation totals for 1-, 3-, 5-, and 10-day durations are all below 5-year recurrence interval amounts. For individual storms, rainfall amounts for either 3-day or 10-day durations were at or over 2-year return intervals, whereas all but one of the 1-day totals were under this return frequency. This suggests that it is critical to have significant amounts of precipitation for long durations to generate

large landslides in Caspar Creek.

On the basis of the largest landslides documented in the North Fork during the life of the study, it appears that Caine's (1980) 1-day threshold of 10.4 cm (4.1 in.) is less important for slide initiation than 3-, 5-, or 10-day totals below Caine's thresholds. None of the recorded large landslides in the North Fork occurred when 1-day precipitation totals exceeded Caine's threshold, and all of the landslides occurred with precipitation totals that were less than Caine's thresholds for 3-, 5-, and 10-day totals.

Therefore, we defined a potential minimum threshold for stressing storm events on the basis of the rainfall amounts associated with known landslides in the North Fork. We screened the entire rainfall data set from August 1962 to April 1998 and determined the storm events that met minimum standards of 4.88 cm (1.92 in.) of precipitation in 1 day and either 11.94 cm (4.70 in.) in 3 days or 20.09 cm (7.91 in.) in 10 days. These rainfall amounts were based on the values triggering the landslides shown in table 1. Additionally, an antecedent precipitation index (API) was calculated for all daily rainfall totals in the life of the study.⁹ We found that 41 days and 34 unique storm sequences met the screening criteria (fig. 6 and appendix 1). Three storm events occurred during the calibration period for both watersheds, five events took place after road construction in the South Fork, five events occurred during logging and recovery in the South Fork, six events occurred during the early 1980's before logging the North Fork, and 15 events occurred during the logging, road construction, and recovery period in the North Fork. These data suggest that storm events of magnitude similar to those known to have created landslides in the North Fork were reasonably well distributed over

⁸ The Critical Sites Erosion Study (Rice and Lewis 1991) used 189 m³ha⁻¹ (100 yd³ac⁻¹) as the definition of a large erosion site (either landslide or large gully). An inventory of erosion events greater than 7.6 m³ (10 yd³) was begun in 1986 for the North Fork.

⁹ API = Ppt_t + 0.9(API)_{t-1}

all phases of the study. The greatest number of storm events occurred during hydrologic year 1998.

Based on this interpretation of the landslide data and the rainfall record for the basin, we conclude that: (1) Caine's thresholds did not predict the conditions leading to landslides at Caspar Creek, (2) the approximate magnitude of stressing storms that have triggered failures in the North Fork watershed are equal to or greater than 4.88 cm (1.92 in.) of precipitation in 1 day and either 11.94 cm (4.70 in.) in 3 days or 20.09 cm (7.91 in.) in 10 days, (3) sufficient numbers of stressing rainstorms or combinations of storm events have tested the practices implemented on the landscape in both the South and North Fork, and (4) an extreme precipitation event, such as a 50-year return period storm of any duration, has not occurred in either watershed. When such an event occurs, we will be able to further evaluate the impacts of logging and road construction in Caspar Creek.

Streamflow Discharge Records

Streamflow has been measured at both the South Fork and North Fork weirs since hydrologic year 1963.¹⁰ Instantaneous annual peak discharges for the North Fork are displayed in *figure 7*. Peak discharges for 240 separate storm events were used for a partial duration flood series to plot a flood frequency analysis for both

watersheds (R. Ziemer, USFS-PSW, written communication).¹¹ Flood events with return periods of 5 or more years are shown in *table 2*. These data illustrate that for discharge, flood events with 5-year or greater return frequency occurred before and after logging for the South Fork phase, as well as before and after logging in the North Fork phase. The primary difference, however, is that the largest flood events for the South Fork phase had return frequencies of approximately 20 years, whereas the return frequencies for the North Fork phase were between 5 and 10 years.

Estimates of historic flooding can also be made for the Caspar Creek watershed. The December 1955 discharge measured at the USGS's Noyo River gaging station¹² was similar in size to that measured for the January 1993 storm. It is likely that this was also the case at Caspar Creek, because the distribution of major flood peaks is similar in both basins from 1963 to the present. This flood event was likely to have been about a 10-year return interval event at Caspar Creek. According to regional records, the only other large flood that is likely to have taken place in the 1900's may have occurred in 1937 (Janda and others 1975).

One possible reason why the return frequencies for rainfall and runoff differ relates to antecedent moisture conditions. If a watershed is fairly dry before a large precipitation event, considerably less runoff will occur when compared to a fully

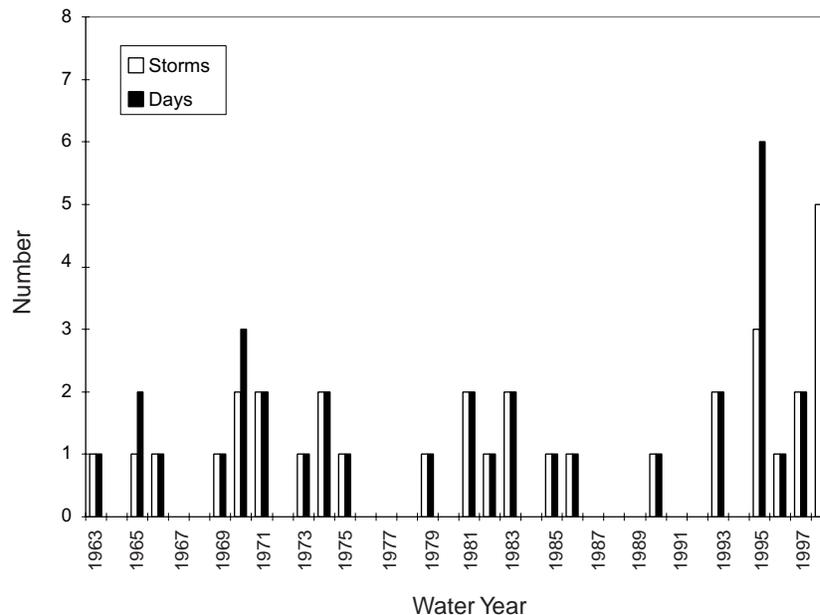


Figure 6—Number of days and unique storm sequences above the minimum threshold estimated to have the potential to produce landslides in the Caspar Creek watershed for the study period.

¹⁰ Data for hydrologic year 1977 is missing, but this was the driest year of record and no large peaks occurred that winter.

¹¹ A storm for this analysis was defined as having a stage of at least 0.6 m (2 ft) at the South Fork weir (or a discharge of $0.7 \text{ m}^3\text{s}^{-1}$ [$24.5 \text{ ft}^3\text{s}^{-1}$]).

¹² USGS No. 11468500; records at this station began in 1952. The station is located approximately 6.4 km (4 mi) to the north of the Caspar Creek watershed.

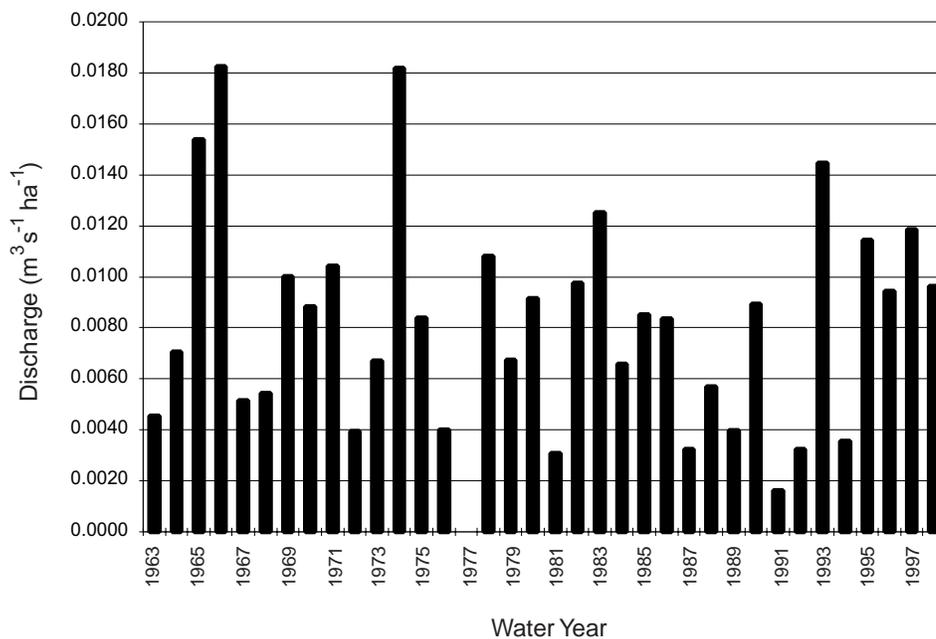


Figure 7—Maximum annual instantaneous peak discharges for the North Fork of Caspar Creek.

Table 2—North Fork Caspar Creek peak discharges with return intervals of 5 years or more.

Date	Discharge (m³ s⁻¹)	Discharge (m³ s⁻¹ ha⁻¹)	Discharge (ft³ s⁻¹)	Return Interval (yr)
01-04-1966	8.6	0.0182	304.9	21
01-16-1974	8.6	0.0182	304.3	21
03-29-1974	7.5	0.0159	263.8	12
12-21-1964	7.3	0.0154	257.5	10
01-20-1993	6.8	0.0145	241.6	8
12-21-1982	5.9	0.0125	209.6	6
12-09-1997	5.6	0.0118	198.0	5
03-14-1995	5.4	0.0115	191.5	5

saturated wet mantle condition. Antecedent wetness has been shown to be an important variable explaining runoff differences at Caspar Creek (Ziemer, these proceedings). Additionally, instantaneous peak discharges vary considerably depending on storm intensity and duration. Long-duration, low-intensity storm events can generate high rainfall amounts and high total storm flow volumes, but relatively low instantaneous peak discharges at Caspar Creek, when compared to shorter-duration storms with higher intensities.

Most sediment movement during an average hydrologic year occurs during a few, very large runoff events. Rice and others (1979) reported that about 80 percent of suspended sediment measured during the South Fork phase was transported by flows exceeding

1.13 m³ s⁻¹ (40 ft³ s⁻¹). Discharges of this magnitude occur about one percent of the time as shown by flow duration curves developed for both the North and South Forks of Caspar Creek.

Hillslope Erosion and Sediment Delivery Data

Hillslope erosion was measured for both the North and South Fork phases of the study. In the South Fork, estimates were obtained from seven plots distributed throughout the watershed. Plots were rectangular, approximately 200 m (656 ft) wide and 200 m to 320 m (1,050 ft) long. Gullies greater than 0.09 m² (1 ft²) in cross section and mass movements displacing more than 0.76 m³ (1 yd³) were

measured. Rice and others (1979) concluded that logging resulted in $81.1 \text{ m}^3 \text{ ha}^{-1}$ ($42.9 \text{ yd}^3 \text{ ac}^{-1}$) of hillslope erosion above background rates. Only 3 percent of the total erosion was rill erosion; the remainder occurred as landslides or large gullies (Rice and others 1979). Sheet erosion was not included in the erosion estimate.

Rice (1996) also completed a sediment delivery study in the North Fork of Caspar Creek. Comparable types of hillslope erosion measurements were made, but the sampling scheme differed considerably, with measurements made on smaller randomly located plots. Circular 0.08-ha (0.20-ac) plots were installed on harvested or forested areas, and road plots consisted of 1.5-m (5-ft) segments of road prism normal to the road centerline (plus erosion to the nearest drainage structure). Rice (1996) concluded that the average hillslope erosion rate above background levels for the North Fork was $45.5 \text{ m}^3 \text{ ha}^{-1}$ ($24.1 \text{ yd}^3 \text{ ac}^{-1}$), or roughly half that measured in the earlier South Fork study. We updated Rice's (1996) estimate with data through water year 1998 and revised Rice's earlier estimate to $47.6 \text{ m}^3 \text{ ha}^{-1}$ ($25.2 \text{ yd}^3 \text{ ac}^{-1}$).

These erosion rates are generally similar to those reported earlier in the literature. For example, Dodge and others (1976) found hillslope erosion rates on California's North Coast of 106, 77, 195, and $346 \text{ m}^3 \text{ ha}^{-1}$ (56, 41, 103, and $183 \text{ yd}^3 \text{ ac}^{-1}$) on slopes of 0-30, 31-50, 51-70, and > 70 percent, respectively, from timber harvesting conducted before the implementation of the modern forest practice rules. The Critical Sites Erosion Study (Rice and Lewis 1991) compared hillslope erosion on 0.81-ha (2-ac) sites having large erosion events greater than $189 \text{ m}^3 \text{ ha}^{-1}$ ($100 \text{ yd}^3 \text{ ac}^{-1}$) to randomly selected control sites and found an average of $19.1 \text{ m}^3 \text{ ha}^{-1}$ ($10.1 \text{ yd}^3 \text{ ac}^{-1}$) for roads and harvest areas with logging that was completed under the modern Forest Practice Rules (1978-1979). In the North Fork of Caspar Creek, using the landslides in the harvested units listed in *table 1*, we found that the comparable amount is $18.8 \text{ m}^3 \text{ ha}^{-1}$ ($10.0 \text{ yd}^3 \text{ ac}^{-1}$).

Rice and others (1979) reported that 22.4 percent of the measured hillslope erosion was delivered as sediment at the South Fork weir during the South Fork phase of the study. In contrast, for the North Fork logging, Rice (1996) calculated a sediment delivery of 11.3 percent at the North Fork weir. Therefore, Rice (1996) concluded that the North Fork logging resulted in approximately half as much erosion and a sediment delivery ratio that was similarly about half of the estimate for the South Fork logging. This indicates that the volume of sediment delivered to the stream channel in the North Fork was approximately one-quarter of that delivered to the South Fork.

Sediment Yields

Sediment sampling at Caspar Creek has been accomplished with several different techniques, reflecting changing technology and attempts to improve data quality. For most of the initial South Fork phase, suspended sediment yield was estimated with rising stage samplers mounted on the weirs. These devices, used from 1962 to 1975, are mounted at a specified stage and collect a sample only when the streamflow is rising. Some measurements were made with DH-48 depth-integrated hand-held samplers, but the majority of

the data was from the mounted bottles. In 1975, PS-69 automatic pumping samplers were installed at both the North and South Forks. During spring 1976, frequency-controlling devices were added to these pumping stations, which provided for more intensive sampling during higher flows. This, however, was at the very end of the South Fork phase and, for all practical purposes, did not heavily influence the study results. Suspended sediment yields collected during the South Fork phase were generated from sediment rating curves. Thomas (1990) reported that rating curve estimates of sediment yields are biased and depend systematically on sampling protocols.

Sediment measurement methods were substantially improved for the entire North Fork phase (1985-1995), which used SALT (Selection At List Time) sampling at both the North and South Fork weirs and also at 13 gaging stations located above the North Fork weir. This newer suspended sediment sampling technique yields unbiased estimates of sediment discharge. At Caspar Creek, the probability of taking a sample is based on stage height. This provides unbiased estimates of total suspended sediment yield while causing more sampling to occur at higher flows (Thomas 1985).

Bedload transport has been estimated with annual surveys of weir pond sedimentation. Sediment samples analyzed to determine the percentage of particles $\geq 2 \text{ mm}$ have been used to estimate the percentage of the material that settled behind the weirs and that can be considered bedload (material $\geq 1.4 \text{ mm}$), using a correction factor to account for the percentage of material from 1.4 mm to 2 mm (Napolitano 1996). Napolitano (1996) found that approximately 85 percent of the sediment produced at Caspar Creek can be considered suspended sediment. Material surveyed in the weir ponds averages about 35 percent of the total sediment load, which indicates that about 20 percent of the fine sediment ($< 1.4 \text{ mm}$) settles out in the ponds (Napolitano 1996). Lewis (these proceedings) has completed a similar data analysis and concluded that approximately 40 percent of the suspended sediment yield settles out in the weir ponds. With this analysis, approximately 30 percent of the total sediment yield can be considered bedload and 70 percent suspended sediment. This latter estimate is likely to be more accurate, since Napolitano (1996) used annual loads based on the fixed-stage samplers.

Annual sediment totals for suspended sediment and bedload measured at the weir ponds and estimated from samples taken at the weir outlets are shown in *figure 8* for both the North and South Forks of Caspar Creek. Mean sediment yields in the North and South Forks from 1963 to 1995 are $1,895$ and $2,018 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (465 and $495 \text{ yd}^3 \text{ mi}^{-2} \text{ yr}^{-1}$), respectively.¹³

Lewis (these proceedings) has used a log-log model to compare suspended sediment and total sediment yields for both the North and South Forks for the before and after road construction and logging periods. For the South Fork, an increase of approximately 212 percent

¹³ Note that the sediment estimates made from 1963 to 1975 were made without SALT sampling and are likely to overestimate true suspended sediment loads, since rating curves were generally based on rising limb sediment collection.

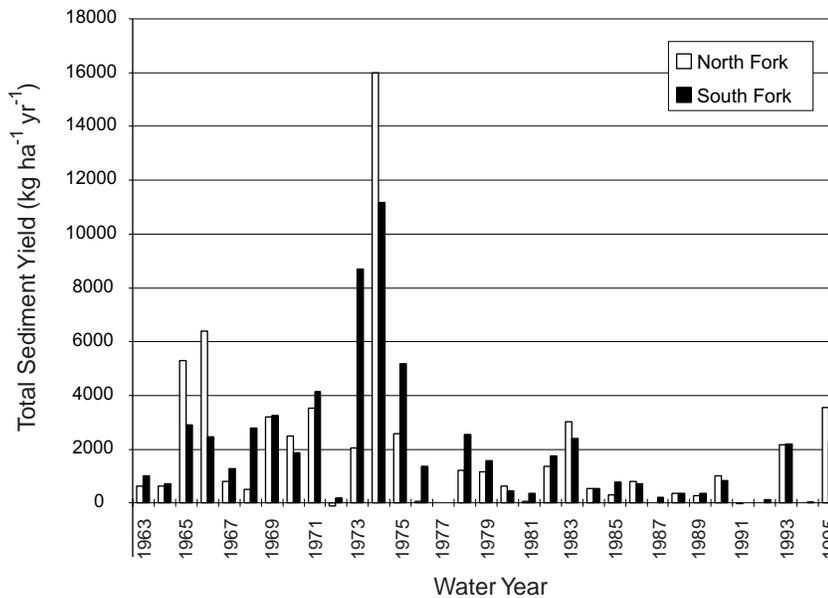


Figure 8—Total annual sediment yield for both the North and South Forks of Caspar Creek.

(2,510 kg ha⁻¹ yr⁻¹) over background levels has been calculated for suspended sediment loads for the first 6 years after the start of logging.¹⁴ Total sediment load was 184 percent (2,763 kg ha⁻¹ yr⁻¹) above expected levels. Lewis (these proceedings) has determined that because of the data collection techniques used for the South Fork phase, the original sediment volume estimate may be too high by a factor of 2 or 3 for suspended sediment measured in outflow from the weir, which would be approximately 1.7 to 2.4 times for the total volume of suspended sediment and bedload material. Sediment loads appeared to have returned to pre-logging levels in the 6th or 7th winter after the completion of logging (Thomas 1990). However, on the basis of widespread failures noted along South Fork roads during winter 1998, this conclusion may have been premature.

Lewis similarly calculated suspended sediment and total sediment yield increases above expected levels at the North Fork weir for logging and road construction during hydrologic years 1990 through 1995 and found no significant increase over background levels for either parameter. Lewis (these proceedings) then used a more sensitive analysis based on sediment measured at the North Fork weir for individual storm events compared to uncut tributaries upstream in the North Fork. This analysis indicated a significant, estimated increase of 89 percent (188 kg ha⁻¹ yr⁻¹) in suspended sediment over that predicted for undisturbed conditions.

Lewis (personal communication) has concluded that percent increase is a more accurate representation of increased sediment yields than sediment volume, because of the problems associated

with measurement techniques used in the South Fork phase of the study. Comparing the 89 percent increase for the North Fork with the 212 percent South Fork increase suggests that suspended sediment yields were 2.4 times greater following logging in the South Fork. This estimate is based on the unadjusted sediment measured in the North Fork during 1974, when a large landslide (see *table 1*) in the uncut basin produced more sediment than any of the post-disturbance years documented during the life of the study through water year 1995 (*fig. 8*).

Conclusions

After timber harvesting activities, both the North Fork and the South Fork of Caspar Creek were subjected to stressing storms that triggered landslide activity. The data indicate that high 3-day or 10-day precipitation totals in combination with moderately high 1-day amounts have been more important for initiating shallow landsliding than very high 1-day totals alone. Storm events with the potential to produce landslides, based on the minimum threshold we defined in this paper, have occurred at least 13 times since the completion of logging and road construction in the North Fork (*appendix 1*). Therefore, we conclude that stressing storm events with return intervals of up to 10 years have adequately tested the forestry practices implemented in the North Fork.

The frequency of landslides greater than 76 m³ (100 yd³) to date has not been substantially different between the clearcut units and the uncut control subwatersheds for the North Fork of Caspar Creek. Additionally, the volume of sediment discharged by landslides from the uncut and cut units to date has been

¹⁴ Data for hydrologic year 1977 is missing.

approximately the same: $21 \text{ m}^3 \text{ ha}^{-1}$ ($11 \text{ yd}^3 \text{ ac}^{-1}$) from the uncut units and $19 \text{ m}^3 \text{ ha}^{-1}$ ($10 \text{ yd}^3 \text{ ac}^{-1}$) from the harvested areas. Long-term monitoring will inform us if these trends continue with much larger stressing storm events. For perspective on the magnitude of past events, the largest landslide mapped in the North Fork watershed, the debris flow that dammed the creek for thousands of years, was on the order of 1,000,000 to 5,000,000 m^3 . This is more than three orders of magnitude larger than the largest landslide observed during the study.

Road, landing, and skid trail design, placement, and construction are the dominant controls on the number and locations of shallow landslides. As observed in the monitored part of the South Fork of Caspar Creek, land use practices, specifically tractor operations on steep slopes, can obscure and overwhelm intrinsic properties for shallow landslides. In contrast, in the watershed of the North Fork of Caspar Creek, where cable yarding was conducted on steeper slopes, the rate of landsliding is substantially lower, and there does not appear to be a significant increase in post-logging landsliding. Roads, landings, and skid trails that were constructed prior to the implementation of the Forest Practice Act have resulted in a legacy that continues to affect the watershed of the South Fork of Caspar Creek 30 years after operations began.

Results similar to those reported in this paper have been found elsewhere in northwestern California. Rice (1998) compared logging-related road erosion on industrial timberland in the middle portion of the Redwood Creek watershed before the implementation of the modern Forest Practice Rules with erosion rates associated with roads used in the 1990's. The estimated erosion rate under the modern Forest Practice Rules was about one-tenth of that estimated for an adjacent tributary of Redwood Creek as a result of timber operations utilized before 1976 (Best and others 1995).

Recommendations for Forest Managers Based on Caspar Creek Results

The lessons that have been learned at the Caspar Creek watershed may be applied to many North Coast watersheds. Numerous issues on Timber Harvesting Plans, such as hillslope erosion rates, sediment yields, and changes in peak flows, have already been addressed with data generated from this study.¹⁵ The value of having research-level, long-term monitoring data from various types of logging operations is significant in today's arena of listed species, Total Maximum Daily Load (TMDL) allocations, and Habitat Conservation Plans. The data provided by this project has, and will continue to be, used to estimate the true impacts of modern logging operations. Long-term monitoring should continue at Caspar Creek as further operations are completed in the basin in the future decades, and as the watersheds are subjected to large, long-return frequency storms and floods.

Clearly, forest managers in other North Coast watersheds

should take home the message that old roads built with practices prevalent in the 1950's, 1960's, and early to mid-1970's are still significant sources of erosion. Dr. William Weaver, Pacific Watershed Associates, has often referred to perched fill and poor watercourse crossings associated with old roads as "loaded guns" waiting to fail with strong stressing storm events. It is imperative that forest managers develop long-term *road management plans* that inventory these source areas and quickly reduce their numbers with an organized schedule based on watershed sensitivity and vulnerability of downstream beneficial uses.

One of the most important components of a comprehensive road management plan is the determination of which high-risk roads should be properly abandoned. Under the current California Forest Practice Rules, this means leaving a logging road in a condition that provides for long-term functioning of erosion controls with little or no continuing maintenance. Proper road abandonment usually involves removing watercourse crossing fills, removing unstable road and landing fills, and providing for erosion-resistant drainage (Weaver and Hagans 1994). During summer 1998, most of the old road system built in the South Fork watershed in 1967 will be properly abandoned. Proper abandonment of old roads and removal of high-risk sites on roads which will be part of the permanent transportation network are examples of the level of commitment from resource managers that is needed to substantially reduce the impacts from practices that were implemented on the landscape before the mid-1970's. Continued monitoring of the effects of various road abandonment techniques in Caspar Creek will aid forest managers elsewhere in developing proper abandonment practices.

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¹⁵ Permits issued by the California Department of Forestry and Fire Protection to log more than 1.2 ha (3 ac) on non-federal lands in California.

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Appendix 1—Dates and amounts of precipitation (cm) above the defined threshold based on actual landslides and associated Antecedent Precipitation Index (API) levels for the entire study period. Abbreviations under Study Period are South Fork (SF), North Fork (NF), and Subwatershed YZ (YZ).

Date	Study Period	Hydrologic Yr	1-day	3-day	10-day	API
10-11-62	Calibration	1963	7.49	12.80	14.38	13.36
12-21-64	Calibration	1965	11.28	17.78	19.58	20.09
12-22-64	Calibration	1965	5.41	18.06	24.99	23.50
01-04-66	Calibration	1966	11.89	18.39	26.97	23.29
01-11-69	Post SF road	1969	12.42	12.65	12.78	16.38
12-12-69	Post SF road	1970	9.14	13.97	15.88	14.76
01-23-70	Post SF road	1970	6.10	13.72	27.79	24.36
01-26-70	Post SF road	1970	5.08	6.40	27.84	23.93
12-03-70	Post SF road	1971	7.29	11.68	22.94	17.70
01-16-71	Post SF road	1971	5.84	13.77	20.90	19.02
01-11-73	Logging SF	1973	8.97	14.66	17.60	17.40
01-15-74	Post SF log, road	1974	6.10	15.11	16.43	17.45
03-31-74	Post SF log, road	1974	6.17	11.79	20.09	17.30
03-21-75	Post SF log, road	1975	7.11	7.37	20.75	18.64
02-13-79	Post SF log, road	1979	5.72	12.22	13.23	13.08
12-03-80	Pre NF log, road	1981	7.52	13.23	14.63	14.35
01-27-81	Pre NF log, road	1981	6.73	8.64	20.98	16.18
02-15-82	Pre NF log, road	1982	7.62	14.48	14.48	14.61
12-21-82	Pre NF log, road	1983	8.00	10.92	20.14	17.93
01-26-83	Pre NF log, road	1983	8.08	12.14	23.44	18.47
11-11-84	Pre NF log, road	1985	10.62	14.81	18.77	18.97
02-16-86	Log, road NF (YZ)	1986	4.95	11.94	16.13	16.92
05-27-90	Log, road main NF	1990	4.88	12.40	23.77	17.81
12-31-92	Post NF log, road	1993	8.28	16.74	12.65	17.42
01-20-93	Post NF log, road	1993	6.05	10.90	20.98	20.17
01-08-95	Post NF log, road	1995	7.54	12.42	17.86	16.48
01-09-95	Post NF log, road	1995	5.97	15.62	23.67	20.80
01-13-95	Post NF log, road	1995	6.40	11.35	33.25	25.17
03-13-95	Post NF log, road	1995	5.44	8.10	20.47	16.61
03-14-95	Post NF log, road	1995	5.11	11.38	25.58	20.07
03-20-95	Post NF log, road	1995	5.23	7.54	21.11	18.08
01-24-96	Post NF log, road	1996	5.13	7.42	23.37	16.56
12-09-96	Post NF log, road	1997	8.31	12.52	25.12	20.60
12-31-96	Post NF log, road	1997	8.59	17.60	23.90	23.55
11-26-97	Post NF log, road	1998	12.75	13.54	19.02	19.15
01-12-98	Post NF log, road	1998	5.00	11.94	17.48	15.65
01-14-98	Post NF log, road	1998	5.00	11.56	20.17	19.08
01-18-98	Post NF log, road	1998	5.00	9.68	30.43	22.96
01-26-98	Post NF log, road	1998	7.67	11.15	21.26	22.40
02-21-98	Post NF log, road	1998	4.98	11.73	22.83	22.89
03-22-98	Post NF log, road	1998	5.08	12.57	12.62	15.16