

A Landslide Study in the Redwood Creek Basin, Northwestern California:
Effects of the 1997 Storm

by

Tera L. Curry

A Thesis

Presented to

The Faculty of Humboldt State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

In Environmental Systems: Geology

May, 2007

A Landslide Study in the Redwood Creek Basin, Northwestern California:
Effects of the 1997 Storm

by

Tera L. Curry

Approved by Master's Thesis Committee:

Mary Ann Madej, Major Professor	Date
---------------------------------	------

Andre Lehre, Committee Member	Date
-------------------------------	------

Leslie Reid, Committee Member	Date
-------------------------------	------

Sharon Brown, Graduate Coordinator	Date
------------------------------------	------

Chris Hopper, Interim Dean for Research and Graduate Studies	Date
--	------

ABSTRACT

Analysis of aerial photographs following the January 1997 storm in the Redwood Creek basin, north coastal California, documented 250 fresh landslides greater than 400 m² in area. Data on failure type, hillslope position, hillslope form, hillslope gradient, bedrock type, road association, timber harvest unit association, and percent sediment delivery to stream were collected for each landslide. Storm rainfall was of moderate intensity and the return intervals for the 1-, 6-, and 24-hour rainfall intensities were less than 2 years, except the 24-hour rainfall intensity at the O’Kane gage (upper Redwood Creek) which had a return interval of 8 years. The peak flow recurrence interval was 12 years. The antecedent precipitation index (API) was 188 mm, the second highest API at the Orick gage in the Redwood Creek basin since 1950. This API was higher than that for the 1964 storm, which is the storm of record in the basin. Total landslide material volume was about 570,000 m³, and estimates of delivery of landslide material to Redwood Creek and its tributaries range between 345,000 m³ and 496,000 m³.

The most significant risk factors in the initiation of landslides in the Redwood Creek basin were the inner gorge hillslope position, the Grogan Fault Zone bedrock type, and the ‘very steep’ hillslope gradient categories. These factors are correlated because the Grogan Fault Zone bedrock type lies primarily along Redwood Creek, as does the inner gorge, and, by definition, the inner gorge has hillslope gradients greater than 50%. Preliminary results showed that landslide volume per unit area derived from the Grogan

Fault Zone bedrock type was 100 times greater than the basin average of $930 \text{ m}^3/\text{km}^2$ after separation of hillslope gradient and bedrock type in the inner gorge.

Commercial timber harvesting in the upper basin of Redwood Creek has occurred in the inner gorge since the 1930's and has continued through the present. Sediment input from inner gorge areas containing harvest units was over three times greater on a per unit length basis than in inner gorge areas not containing harvest units. Twenty-nine kilometers of the inner gorge was harvested from 1977 to 1997. If the inner gorge had not been harvested, there could have been a reduction of 11% (or $47,000 \text{ m}^3$) of the sediment that was delivered to the study area.

Sixty-three percent of the total landslides in this study were associated with roads. Landslides associated with roads contributed 2.6 times more sediment to Redwood Creek and its tributaries on a per unit area basis than the basin average.

ACKNOWLEDGEMENTS

I would like to thank Dr. Mary Ann Madej of the United States Geological Survey (USGS), for all her painstaking edits and for always holding me to the highest standards. Dr. Leslie Reid, Pacific Southwest Research Station of the United States Forest Service, was instrumental in the expansion of the concepts and with the overall organization in this work. Leslie spent many hours performing detailed editing. Thank you to the USGS and the Forest Service for funding this thesis.

The staff of Redwood National Park was instrumental in support of this thesis. I thank Greg Bundros, geologist, for all his time reviewing the air photo analysis and for sharing his vast field experience with me. Vick Ozaki and Darci Short, geologists, shared various data and war stories with me which helped to give me the conviction that I might finish the thesis one day. Judy Wartella, Dave Best, and Van Hare gave their time in various ways to perform GIS analyses. Mike Sanders from the Orick office also shared data which was essential in determining the size of landslide that I could correctly map from the aerial photos. Redwood National Park was instrumental in funding this work.

I would also like to thank the United States Forest Service for allowing me to remain employed while finishing this thesis. Mary Beth Marks of the Humboldt-Toiyabe National Forest, Greg Schimke of the Tahoe National Forest, and Dr. Tom Koler of the Eldorado National Forest were all mentors for me and I will never forget the humor, the kindness, and the direction they gave me throughout this process.

I would like to acknowledge Dr. Andre Lehre, Professor of Geology at Humboldt State University. Andre taught some of the most complex classes that were necessary for my degree but managed to make the information accessible by his straightforward teaching methods. Thank you for all your office time throughout my education.

Last, but most important of all, I would like to thank my three sons for their sacrifice in the early years and their support as they became adults. Chris, thank you for diligently serving our country as an active Marine for many years while surviving and saving others' lives through all kinds of altercations. Thank you for the gift of my first grandchild. Jonathan, I thank you for being an excellent roommate and for chasing me through community college. I would have spent even more years in school if you hadn't been coming through the education system right behind me while taking no prisoners. Julian, Junk Food Night was one of the best things that we have ever done together. I will never forget you serenading me with your trombone; sometimes with jazz, sometimes with Jimi Hendrix. You were also really good at ducking my flying physics books. Robin, my outlaw daughter, thank you for the excellent engineer-drawing of the inner gorge. It has withstood many edits and made it into the final product. Thank you for the girl-talk too.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vii
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF MAPS	xii
INTRODUCTION	1
Previous Work	2
DESCRIPTION OF STUDY AREA	8
Field Setting	8
Geology and Structure	8
Geomorphology	14
Vegetation	15
Land Use	15
Basin Conditions Prior to the 1964 and 1997 Storms	21
Climate	23
Storm History	24
Rainfall	27
Antecedent Precipitation Index	30
Comparison of the 1964 Storm to the 1997 Storm	32

METHODS	35
Air Photo Interpretation Methods	35
Estimation of Volume	41
GIS planimetric area/cos 29° = Hillslope area	41
Estimation of Hillslope Gradient	42
Estimation of Sediment Delivered to Redwood Creek and its Tributaries	43
Measuring Inner Gorge Landslide Volume in Association with Timber Harvest Units	45
RESULTS	48
Quantification of Sediment	48
TOTAL LANDSLIDE VOLUME (m ³)	52
LANDSLIDE COUNT	52
Patterns of Landslide Distribution	59
Methods to Decrease the Number of Landslides in Highly Susceptible Areas ...	64
DISCUSSION AND CONCLUSIONS	70
REFERENCES	74
PERSONAL COMMUNICATIONS	79
APPENDIX A DATA SHEETS FOR 1997 LANDSLIDES	80
APPENDIX B RAINFALL DATA	104
APPENDIX C REGRESSION GRAPH	106

LIST OF TABLES

Table	Page
1 Area percentage of bedrock types in the Redwood Creek basin.	13
2 Harvest information for the Redwood Creek basin from 1930's to 1978. Park expansion occurred in 1978. No harvesting was done in the lower basin since 1978 (Best, 1984).	20
3 Comparison of peak discharges in the Redwood Creek basin from 1955 to 1997 (modified from Bloom, 1998, and Harden, 1995; return intervals from Redwood National and State Parks in-house records, 1997).	25
4 Maximum rainfall intensities for Redwood Creek basin for water year 1997 (Redwood National and State Parks, in-house records, 1997, California Department of Water Resources, 2005).	28
5 Redwood Creek rainfall intensities and intensity return intervals for the January 1997 storm (derived from Redwood National and State Parks, in-house records, 1997; California Department of Water Resources, 2005). Return intervals (years) are shown in parentheses and are based on Redwood National and State Parks in-house records, 1997.	29
6 Maximum API for Redwood Creek at Orick at the onset of the large storms in the Redwood Creek basin (modified from Redwood National and State Parks records, 1997).	33
7 Landslide volume statistics.	49
8 Sediment delivered to stream channels in Redwood Creek basin from 1997 landslides.	52
9 Sediment delivered to Redwood Creek and its tributaries from the January 1997 storm.	54
10 Material delivered to streams from a subset of 1997 and 1964 storm streamside landslides.	55
11 Suspended sediment yield from October to April of the 1997 water year and sediment delivered to Redwood Creek and its tributaries from landslides (Redwood National and State Parks in-house records, 2005).	58

12	Sediment volume of landslides per square kilometer categorized by potential controlling variables. (Percentages within each controlling variable classification may not add up to 100% due to the effect of rounding.)	60
13	Evaluation of delivered sediment volume per square kilometer to Redwood Creek and its tributaries categorized by potential controlling factors. Delivered volumes are estimated using the midpoints of the delivery categories. (Percentages within each controlling variable classification may not add up to 100% due to the effect of rounding.)	61
14	Inner gorge landslides and their relation to slope gradient and bedrock type. This table includes information only for inner gorge landslides upstream of Redwood National Park boundaries.....	63
15	Sediment input from 1997 landslides to the inner gorge of Redwood Creek upstream from Redwood National and State Parks lands.	66

LIST OF FIGURES

Figure	Page
1 Land ownership in the Redwood Creek watershed as of 2004 (modified from Bundros, 2004).....	17
2 Annual peak flow at the Orick gage from 1954 to 2005 (modified from Redwood National and State Parks records, 2003).....	26
3 Comparison of Redwood Creek rainfall intensities and durations from the January 1997 storm (red circles) and the December 1964 storm (blue crosses) with those from regions experiencing shallow debris slide activity at reported rainfall intensities and durations. The lower curve is the minimum critical intensity-duration threshold and the upper curve is the maximum critical intensity-duration threshold. (Modified from Caine, 1980; 1997 and 1964 data from California Department of Water Resources (CDWR-California Data Exchange Center), 2005).	31
4 Diagram of channel and inner gorge harvest unit classifications. Case 1, timber harvest unit inside inner gorge: Case 2, timber harvest unit within 200 m upslope of the inner gorge: Case 3, bottom of the timber harvest unit > 200 m from top of inner gorge. L_H = distance from top of inner gorge boundary to bottom of timber harvest unit. L_C = bank segment length.	46
5a Landslide volume distribution from the 1997 storm in Redwood Creek basin. ...	50
5b. Cumulative volume frequency relation for landslides.	51
6. Comparison of peak flows and suspended sediment from 1971 to 2006 at the Orick gage, Redwood Creek.	57
7 Delivered landslide sediment in upper Redwood Creek inner gorge.	68

LIST OF MAPS

Map	Page
1 Location map of study area (Redwood National and State Parks, 2006)	8
2 2 North Half. 1997 landslides with underlying bedrock geology and the Grogan Fault Zone. Geology by Harden et al, 1982. Note: Landslides are not to scale. They are shown larger to be more easily seen	10
2 2 South Half. 1997 landslides with underlying bedrock geology and the Grogan Fault Zone. Geology by Harden et al, 1982. Note: Landslides are shown larger to be more easily seen	11
3 North Half. 1997 landslides with subbasin boundaries (Redwood National and State Parks, 1998).....	36
3 South Half. 1997 landslides with subbasin boundaries (Redwood National and State Parks, 1998).....	37

INTRODUCTION

Redwood Creek is listed as 'sediment impaired' under section 303(d) of the Clean Water Act (U. S. Environmental Protection Agency, 1998). Land managers with Redwood National and State Parks and in the upper Redwood Creek watershed are actively striving to reduce the amount of sediment delivered to Redwood Creek and its tributaries because of the detrimental effects of sediment. Suspended sediment in high concentrations can damage the gills of salmonids and invertebrates; high turbidity can impair the ability of fish to locate food; and fine sediment can reduce oxygen supply to incubating salmon eggs and can reduce the amount of photosynthesis possible at a given water depth. Aggradation of channels heightens the risk of flooding and bank erosion. Increased sediment production can lead to the filling of pools, channel widening, and a loss of flood capacity. As a result, fish habitat can be lost, property damage from floods can occur, and a cycle of increased bank failure can be perpetuated. Landslides are a major source of the sediment that is impairing the Redwood Creek channel (U. S. Environmental Protection Agency, 1998).

The storm of 1964 was the biggest storm in the Redwood Creek basin since the 1890's. There is still sediment from the 1964 flood that contributes to reduced pool depths and an elevated stream bed (Madej and Ozaki, 1996). Pitlick (1995) and Kelsey et al (1995) show that almost 4 million cubic meters of landslide-derived sediment were emplaced in Redwood Creek and its tributaries from the 1964 storm. Since 1964, measures have been implemented to reduce the amount of sediment that is delivered into

stream channels. The Z'berg-Nejedly Forest Practice Act of 1973 was enacted in part to reduce input of excess sediment to stream channels by regulating timber harvest practices.

On December 29, 1996, a 2- to 8-year return period storm set in that eventually resulted in hundreds of landslides in the Redwood Creek basin. This storm continued to January 4, 1997, and will be referred to in this study as the January 1997 storm. This study addresses four questions regarding landslide occurrence: 1) How did the quantity of material from the landslides that occurred from the January 1997 storm compare to the landslide-derived sediment production from the 1964 storm and flood? 2) How much did the 1997-derived sediment contribute to the suspended sediment load of Redwood Creek measured at the Orick gage in Water Year 1997? 3) What do the patterns of landslide distribution in the Redwood Creek basin suggest are the most important risk factors in the initiation of landslides? and, 4) Would the amount of sediment delivered to the Redwood Creek basin have been less if there had been no timber harvest in the landslide-susceptible inner gorge?

Previous Work

Landslide material is a major source of sediment in the Redwood Creek basin. Kelsey et al (1995) measured landslides along the mainstem of Redwood Creek to determine the volume of sediment produced between 1954 and 1980. They estimate that there were almost 4,000,000 m³ of sediment delivered to stream channels in that period.

Pitlick (1995) quantified the amount of sediment delivered to 16 tributaries of Redwood Creek between 1954 and 1981. The average amount of delivered sediment was $415 \text{ m}^3/\text{km}^2$ annually over a 244 km^2 study area, for a total of $101,300 \text{ m}^3$. Colman (1973), in a study of the history of mass movement in the Redwood Creek basin, stated that floods were a major factor in sediment delivery to the Redwood Creek basin. The above studies all agree that timber harvesting and its associated road building are the major human influences on the hillslope failures that contribute sediment to Redwood Creek and its tributaries. Timber harvest took place inside the inner gorge of the upper basin of Redwood Creek through at least 1997. Madej and Ozaki (1996) reported that a sediment wave generated from high sediment inputs during floods in 1964, 1972 and 1975 made its way downstream in the Redwood Creek channel. Channel recovery is slowly following in the wake of the sediment wave in terms of pool spacing, pool depth, and elevated channel beds, but complete removal of excess sediment takes decades.

In the northwestern US, there have been many landslide studies after large storms. Staff of the Siuslaw National Forest (1996) used 1:24,000 air photos to survey 1.4 million acres for landslides after a storm in March, 1996. Their study area includes densely forested National Forest System, Bureau of Land Management, state-owned, and privately owned lands in the low mountains of the central Coast Range in Oregon. Lands with forests older than 20 years (in-forest land) were compared with land in two categories: 1) land that had been clearcut, and 2) land where roads had been built. When compared with in-forest areas, results show that landslide density (slides/acre) is 2.6 times higher in clearcut areas and 5.7 times higher on lands associated with clearcuts plus

roads. They conclude that management changes on the forest over the past 20 years to improve road design and construction and the reduction in annual harvest levels reduce the severity and occurrence of management-associated landslides.

In another study, staff of the Klamath National Forest (KNF), located in the north-central part of California and abutting the Oregon border, used 1:16,000 and 1:40,000 scale air photos to survey lands after the January 1997 storm (de la Fuente and Elder, 1998). They found that the majority of the landslides initiated either from roads, on timber harvest units, on weakened bedrock, or in inner gorges. The KNF study area is located in the central Klamath Mountains and has a terrain that varies from steep mountains to open meadows.

The amount and intensity of rainfall influences the initiation of landslides, especially if previous rainfall is saturating the hillslopes. Crozier (1999) analyzed rainfall and the antecedent precipitation index in Wellington, New Zealand, in order to predict urban landslides. Data from his study enabled the construction of an early warning system that can predict the occurrence of damaging landslides 24 hours in advance with a satisfactory level of confidence. Meyer et al (2001) found that intense rainfall from the January 1997 storm triggered hillslope failures in steep areas underlain by weak bedrock in Idaho. Guthrie and Evans (2004) studied a relatively untouched watershed in coastal British Columbia and propose that landslides are triggered from intense storm cells within large regional events. They find that landslide rates in their unlogged study area are much lower than post-logging landslide rates in nearby areas. A Chi-square analysis showed that the landslide rate on a geologic unit consisting of metamorphosed gabbros,

schists, and amphibolites was 1.4 times the average rate for the area, and that landslides were 1.5 times less likely than average to occur on a granitic bedrock suite.

Besides rainfall, other factors in the initiation of landslides are steep slopes (Kelsey et al, 1995; de la Fuente and Elder, 1998; Crozier, 1999); convergent hillslope form (Dietrich et al, 1995; Jakob, 2000); timber harvest practices; abandoned, rehabilitated, and existing roads and skid-trails (LaHusen, 1984; Best, 1995; Bloom, 1998; Jakob, 2000; Montgomery and et al, 2000; Laird, 2001; Dhakal and Sidle, 2002); and loss of root strength from land clearing (Abe and Ziemer, 1991; Chen et al, 2001). Generally these factors exist together. Baeza and Corominas (2001) used discriminant function analysis to identify the major influences on the distribution of shallow landslides in the Spanish Eastern Pyrennees. Their study area has a Mediterranean climate. They show that the three major influences are slopes with steep angles, large unforested watersheds, and concave hillslopes where colluvium may accumulate. Dhakal and Sidle (2002) found, by using a physically based slope stability model, that leaving understory vegetation, increasing harvest rotation time, and partial cutting reduces the volume of landslide-derived sediment by about five times relative to clearcutting.

Models have been tested (Dietrich et al, 1995; Hare, 2003) that predict areas prone to shallow debris slides fairly well. The models are based on the assumption that landslides occur on steep convergent hillslopes. Hare found that the SHALSTAB model flags 13% of the Redwood Creek watershed as having a high potential for landsliding. Slopes within this category, including inner gorge slopes, are shown to generate 75% of the shallow landslides mapped within the watershed. Maps of the landslide-prone areas

of the Redwood Creek basin have been constructed using the SHALSTAB model for field personnel, but Hare warns that field experience is imperative to put the model to use appropriately.

Large areas are difficult to survey in the field, so air photo surveys are commonly used to map landslide occurrence after storms (Siuslaw National Forest, 1996; de la Fuente and Elder, 1998; Robison et al, 1999; Brardinoni et al, 2002). Robison et al (1999) determine that from 42% to 55% of the landslide-related sediment volume is missed when slides are identified using 1:6,000 scale air photos at their field sites. Results of the Robison et al (1999) study show that about 50% of landslides actually present can be detected using air photos in the recently harvested areas that they studied, but only 5% of landslides can be detected in mature timber stands. They state that using only air photos results in biased and incomplete landslide inventories. The study was conducted on steep forested slopes in western Oregon. There is no minimum size for detectable landslides reported by Robison et al. Brardinoni et al (2002) studied landslides in steep, forested mountains of southwest British Columbia using air photos having a scale of 1:6,000. They found that up to 85% of the total number of landslides, accounting for about 30% of the total landslide volume, are not visible. The minimum landslide sizes that could regularly be detected by air photos are 650 m² in forests older than 50 years and 150 m² on recently harvested land in their field area. The Brardinoni study found that in both harvested and older stands, gullies are commonly not visible and contribute a significant amount of sediment to streams.

Riparian buffer zones are used extensively to protect aquatic environments and to reduce sediment delivery to streams (Lee et al, 2003). Tang and Montgomery (1995) found that riparian buffers are generally not wide enough to protect potentially unstable ground from failure. They tested various buffer widths required to effectively buffer potentially unstable ground and found that a 100-m-wide buffer strip would include 75 to 90% of the potentially unstable areas in their study area on the Olympic Peninsula in Washington. Their results show that riparian buffers are not efficient mechanisms for protecting potentially unstable ground and they suggest that potentially unstable ground be identified using a physically-based model rather than relying on extensive buffer zones.

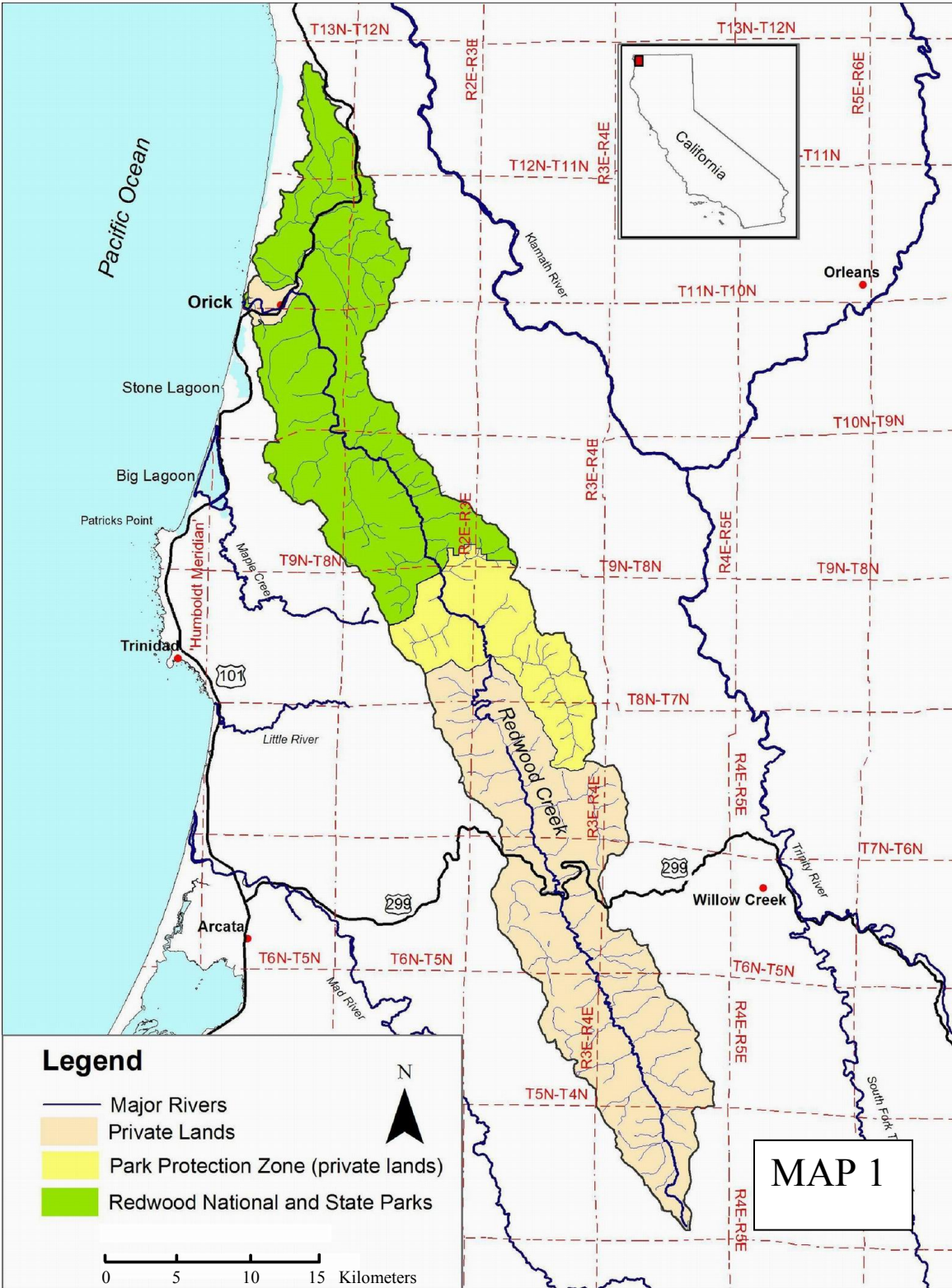
DESCRIPTION OF STUDY AREA

Field Setting

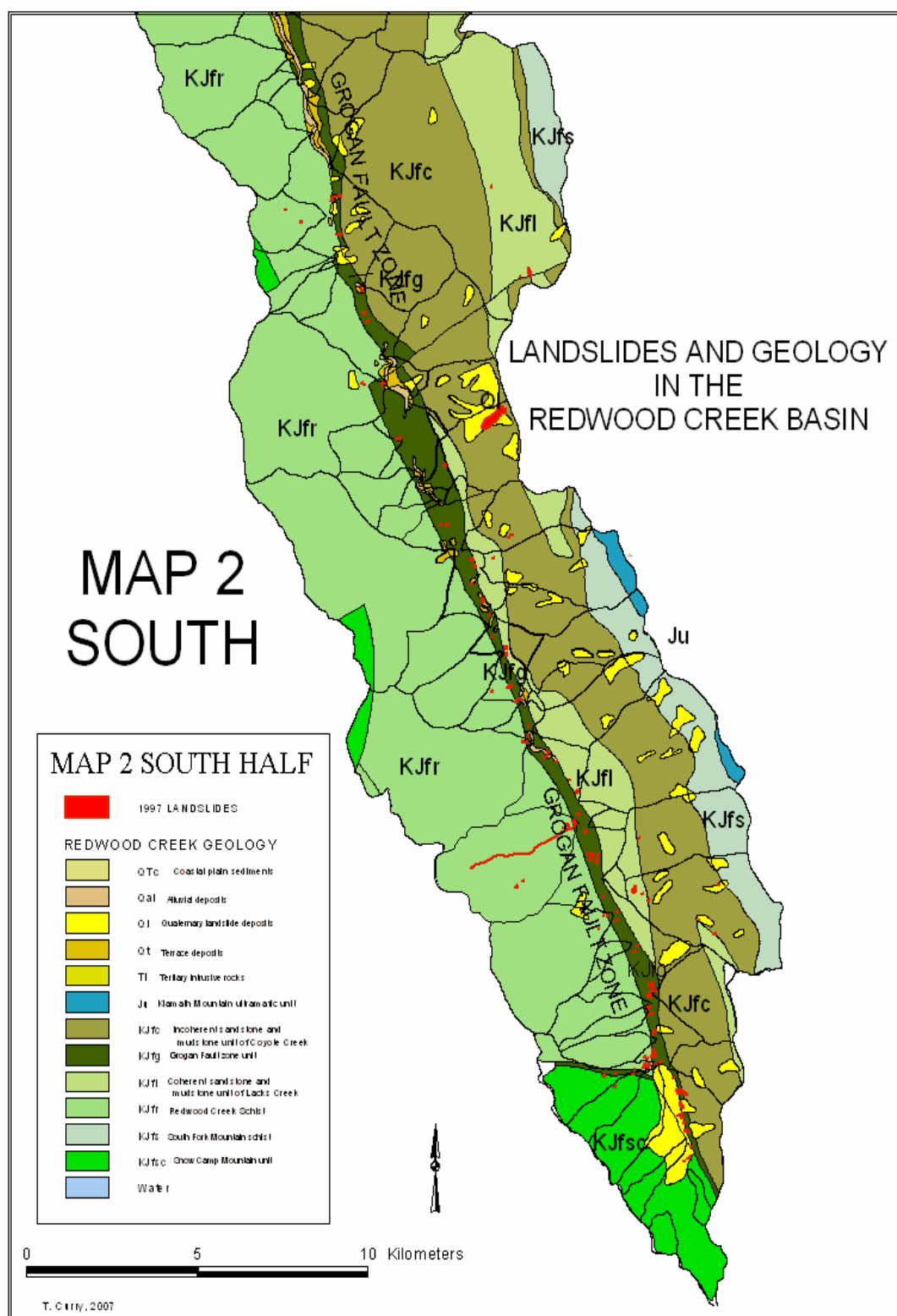
Redwood Creek is located in northwestern California (Map 1) with its headwaters near Board Camp Mountain and its mouth draining into the Pacific Ocean approximately 3 km west of Orick, California. The Redwood Creek basin is strongly elongated, with an average width of 9 km and a length of 90 km. The course of Redwood Creek follows the north-northwest trend of the Grogan Fault through most of its length, and it is the structural control of this fault that gives the basin its elongate shape (Cashman et al, 1995). The study area encompasses 616 km² and excludes the Prairie Creek drainage at the north end of the Redwood Creek basin. Hereafter, 'Redwood Creek basin' will refer to the 616 km² of the study area.

Geology and Structure

The Redwood Creek basin is underlain mostly by the Franciscan assemblage of metamorphic and sedimentary Cretaceous and Late Jurassic lithologic units, most of which are sheared and fractured (Harden et al, 1982), and a small area of alluvium. There are two sandstone and mudstone units, the incoherent unit of Coyote Creek (KJfc) (Map 2) and the coherent unit of Lacks Creek (KJfl); both are on the east side of



Map 1. Location map of study area (Redwood National and State Parks, 2006).



Map 3 South Half. 1997 landslides with underlying bedrock geology and the Grogan Fault Zone. Geology by Harden et al, 1982. Note: Landslides are not to scale. They are shown larger to be more easily seen.

Redwood Creek. The Coyote Creek unit is composed of massive sandstone and interbedded sandstone and mudstone. Characteristics of turbidites are evident in locations where this unit is not heavily disturbed by faulting and folding. The Lacks Creek unit is also composed of massive sandstone and interbedded sandstone and mudstone, but has a higher ratio of sandstone to mudstone than the Coyote Creek unit.

The Grogan Fault Zone unit (KJfg) is generally located in the lower hillslope and inner gorge areas along Redwood Creek. It is a narrow unit of metamorphosed sandstone and mudstone with conglomerate and greenstone also present. It crops out along much of the Grogan Fault and along the Snow Camp Creek fault. The structure and composition of the Grogan Fault Zone unit suggest that it was derived from parts of both the Coyote Creek and the Lacks Creek units, although it is more metamorphosed. Outcrops of siltstone and mudstone have a phyllitic sheen due to the presence of white mica and metamorphic chlorite (Harden et al, 1982).

There are two belts of quartz-mica schist in the Redwood Creek basin, the Redwood Creek schist (KJfr) and the South Fork Mountain schist (KJfs). The Redwood Creek schist, located mostly on the west side of the Redwood Creek basin, is a fine-grained, light green to dark gray phyllite. The South Fork Mountain schist occurs on the southeast edge of Redwood Creek basin. Crenulation cleavage and crenulation fracture are pervasive throughout these two units. Only six percent of the study area is underlain by the South Fork Mountain schist and alluvial deposits (Table 1).

Table 1 Area percentage of bedrock types in the Redwood Creek basin.

BEDROCK TYPE	AREA (km ²)	PERCENT OF AREA
Redwood Creek Schist	310	50
Lacks Creek	70	11
Coyote Creek	178	29
Grogan Fault Zone	19	3
South Fork Mountain schist and Alluvium	39	6

Geomorphology

The Redwood Creek basin runs from southeast to northwest from Board Camp Mountain to the Pacific Ocean. The Redwood Creek mainstem channel has an elevation rise of about 670 m from its outlet to its headwaters.

The topography of the Redwood Creek basin varies by bedrock unit. The Redwood Creek schist unit generally has gently convex profiles and broad, flat ridges. The Coyote Creek unit is subdued and rolling with a few high points and knobs formed by some of the more resistant rocks. Its drainage networks are not very deeply incised especially compared with the coherent Lacks Creek unit. The Lacks Creek unit has distinctive geomorphic expressions of sharp ridge crests, steep slopes, and narrow V-shaped tributary valleys. Where the Grogan Fault Zone bedrock follows Redwood Creek, there are usually steep cliffs, but where the Grogan Fault Zone rocks deviate from the Redwood Creek channel, the Grogan Fault Zone rocks are geomorphically similar to the Coyote Creek bedrock type (Cashman et al, 1995).

The inner gorge is defined as a geomorphic feature that consists of steep streamside slopes below a defined break-in-slope (Kelsey, 1988). It is shaped primarily by debris slides and its break-in-slope occupies a low hillslope position. Slope steepness below the break-in-slope is at least 50% and commonly exceeds 60%. The inner gorge designation in this study is taken from Redwood National and State Park's mapping (Bundros and Andras, 2001)

Vegetation

The Redwood Creek basin is dominated by Douglas-fir except in the coastal-influenced lower basin, where redwoods and Douglas-fir dominate (Best, 1984). The Redwood Creek basin has a mixture of 82% conifer forests, 9% grasslands (prairies), and 9% oak woodlands. The prairies are usually bounded by oak woodlands (Best, 1984).

Before 1940, except for timber harvest in the headwaters of Devils and Panther Creeks, the Redwood Creek basin was mostly uncut and conifer-dominated with a dense cover. By 1948, 7% of the conifers along Redwood Creek channel and its tributaries upstream of the current Redwood National and State Parks were cut (Best, 1995). Hardwoods, especially alder, replaced the conifers after timber harvest. By 1997, one-half of the riparian zone along the Redwood Creek channel was dominated by hardwoods, mostly alder, instead of conifers. Based on the analysis of sequential aerial photographs, the riparian zone of Redwood Creek basin is deemed most sparse after the 1955 and the 1964 floods (Urner and Madej, 1998).

Land Use

In 1950 the Redwood Creek basin was 95% privately owned by timber companies and large family ranches. The remaining 5% was in public ownership, primarily by the United States Forest Service (USFS), and in individual private ownership primarily for vacation home purposes. The USFS exchanged some land with timber companies to

consolidate National Forest land boundaries (Best, 1984). Both the ranchers and the timber companies logged their land.

In 1968, about 124 km² of the lower Redwood Creek basin were designated as Redwood National Park. The expansion of the park in 1978 added about 150 km² of recently harvested land to Redwood National Park (Madej, 2001). Since 1994, three state parks and Redwood National Park have been jointly managed as Redwood National and State Parks, and the combination of state and federal park lands within the Redwood Creek basin encompasses 41% of the watershed (Figure 1). By 1980 virtually all the uncut timber was in Redwood National and State Parks ownership.

Abutting the southern boundary of Redwood National and State Parks is a Park Protection Zone (PPZ) that encompasses about 120 km². This PPZ is privately owned by timber companies but is subject to Redwood National Park review for all timber harvest plans.

Redwood Creek basin land use has been regulated since 1945 with the advent of the Forest Practices Act (FPA). At first, timber harvest practice rules were set by regional Forest Practices committees. In 1971 the FPA was declared unconstitutional because it was a case of industry regulating itself. The Z'berg-Nejedly FPA was adopted in 1973, and authorized the California Department of Forestry to regulate timber harvest practices. This FPA is still in use.

Timber harvest practices have changed in the Redwood Creek basin in the last century. Prior to 1936 the Redwood Creek basin was mostly clearcut logged and cable yarded by using Dolbeer steam donkeys. A steam donkey was the first

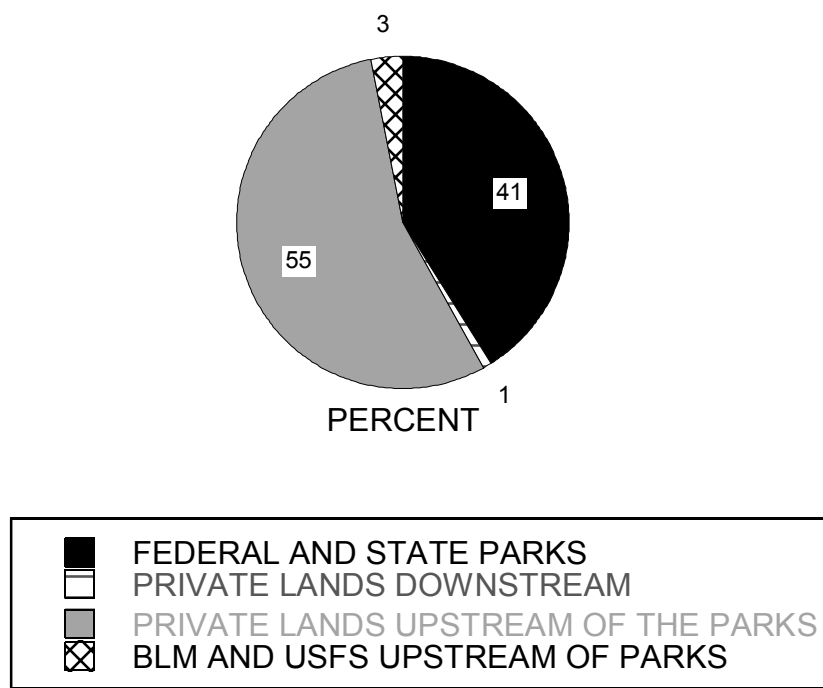


Figure 1. Land ownership in the Redwood Creek watershed as of 2004 (modified from Bundros, 2004).

mechanized form of timber harvest in the Pacific Northwest. The steam donkey was an upright wood-burning boiler attached to a one-cylinder engine. The engine turned a drive shaft that had a rope pulley which 'yarded' logs upslope. The timber operations were primarily on the west side of the watershed in the middle third of the basin.

Between 1936 and 1948 the logging was mostly confined to the broad ridges on both sides of Redwood Creek. Forests were harvested by many methods, including tractor operations with clearcuts and steam-donkey yarding with selective cuts in which more than 60% of the stand was left. In the period between 1949 and 1954 timber harvesting was most intense, with tractor yarding replacing steam-donkey yarding. Harvest took place mainly in the middle and upper thirds of Redwood Creek. Between 1955 and 1962 operations were mainly done by tractor-yarded clearcutting. Most of the more accessible harvest tracts had been entered by 1963. The period between 1963 and 1966 was an intensive period of road and skid road building to access all parts of the Redwood Creek basin. The upper third of the Redwood Creek basin was the primary target during this period, but roads were built along Redwood Creek and its tributaries and down into the inner gorge areas throughout the basin. Tractor-yarded clearcutting still dominated the mode of harvest. Between 1967 and 1970 the harvesting mainly took place in the upper third of the basin. The period between 1971 and 1978 is best described as a period of reentry into previously harvested areas. More new roads were built as the

easily accessible timber was depleted, especially in the upper and middle thirds of Redwood Creek. The lower third of Redwood Creek basin was intensively harvested at that time. FPA rules regulated by the state began in 1973, so timber harvest practices transitioned from large tractor clearcuts to smaller tracts with better constructed roads and fewer stream crossings (Best, 1984).

In 1978 the Redwood National Park expansion resulted in the termination of timber harvest in about 40% of the Redwood Creek basin. Timber harvest still continued in the upstream 60% of the Redwood Creek basin. Table 2 shows the percentage of area harvested up to and including 1978.

From 1978 to 1982, 48 km² of the upper two-thirds of the Redwood Creek basin was harvested and from 1983 to 2006, 152 km² of the upper two-thirds of the basin was harvested. The dominant harvest method between 1983 and 2006 was clearcutting with tractor yarding.

In 1992 the Redwood Creek basin was listed as ‘sediment impaired’ under the Clean Water Act, Section 303(d). Water quality was deemed limited due to sedimentation. At that time, Redwood Creek did not meet water quality objectives necessary to protect beneficial uses of the basin, particularly the cold water fishery. Accelerated erosion from land use activities and other causes impacted migration, spawning, reproduction, and early development of cold water fish, including Coho and Chinook salmon and steelhead trout (U. S. Environmental Protection Agency, 1998). In October, 1997, the Environmental Protection Agency (EPA) entered into a consent decree to develop total maximum daily loads (TMDL) for sediment in the Redwood

Table 2 Harvest information for the Redwood Creek basin from 1930's to 1978. Park expansion occurred in 1978. No harvesting was done in the lower basin since 1978 (Best, 1984).

TIME PERIOD (years)	CUMULATIVE CONIFEROUS FOREST HARVESTED (%) *	BASIN AREA HARVESTED (%) *
1936 to 1948	5.6	4.6
1949 to 1954	25.1	16.0
1955 to 1962	43.0	14.6
1963 to 1966	52.8	8.0
1967 to 1970	62.8	8.2
1971 to 1978	75.8	10.8

*Area excludes the Prairie Creek subbasin of the Redwood Creek basin.

Creek basin. The EPA developed the TMDL's because the state did not complete and submit the TMDL's and by law the EPA had to meet the December 31, 1998, deadline (U. S. Environmental Protection Agency, 1998).

There is a high density of roads in the Redwood Creek basin. The upper portion of the Redwood Creek basin (outside of Redwood National and State Parks) contains 1,840 km of road with a density 4.4 km/km^2 (Redwood National and State Parks in-house records, 2001). There are 650 kilometers of roads in the Redwood National and State Parks area, with a density of about 3.3 km/km^2 . Most of the roads that are now in Redwood National and State Parks have been rehabilitated by various methods (Bloom, 1998, Madej, 2001) but are included in this study because they are still a potential factor in landslide initiation.

Basin Conditions Prior to the 1964 and 1997 Storms

The 1964 flood was the biggest flood in the Redwood Creek basin since the 1890's (Harden, 1995). The effects of the sediment wave that was produced by the mass movements and other erosion processes are still being experienced in the basin. Neither pool depth nor the elevation of the channel bed has yet recovered in several reaches (Madej, 1999). A comparison of the amount of sediment delivered to Redwood Creek and its tributaries from the January 1997 storm and the sediment delivered from the 1964 storm will be discussed later in this study. What follows is a comparison of basin conditions prior to the two storms to set the stage for that discussion.

In 1949, 15 years prior to the 1964 storm, the most intense timber harvesting in Redwood Creek basin's history was occurring. The upper third of the Redwood Creek basin was the focus of most of the timber operations. Sixteen percent of the basin had been harvested by 1954.

Five years prior to the 1964 storm the upper third of the basin was intensely harvested and much of the logging occurred in narrow inner canyons along Redwood Creek and its tributaries (Best, 1984). The period around 1959 saw intense road-building to enable access to all possible parts of the basin. By 1966, 43% of Redwood Creek basin had been harvested. The biggest storm after intensive logging began and prior to 1964 occurred in 1955 and had a recurrence interval of about 10 years.

By 1982, at least 66% of the basin had been harvested. Intense road-building and road-rebuilding was underway to regain access into previously harvested areas on private lands (approximately the upper two-thirds of Redwood Creek basin). Harvest was most intense in the middle third of Redwood Creek basin. The main types of operations were clearcuts and tractor logging on small timber harvest units. The period of time between 1982 and 1997 was a relatively light storm period. The biggest flood in the 15 years prior to 1997 was the 1996 flood, which had a peak flow of 31,800 cubic feet per second (900 cubic meters per second) with a recurrence interval of 6.4 years at the Orick gage.

Five years before the January 1997 storm, timber harvest was occurring mostly in the headwaters of Redwood Creek. Road construction methods had greatly improved by this time. The main types of operations were clearcuts and tractor logging on small timber harvest units on private land. The abandoned timber harvest units from the late

1970's on Redwood National and State Parks lands had at least 15 years' vegetation growth, much of which was alder.

Climate

The climate of the Redwood Creek basin is Mediterranean, characterized by mild, wet winters and warm, dry summers. May through September is usually dry with 90% of the annual precipitation falling between October and April (Ziemer, 1984). The annual rainfall varies throughout the basin from 2,500 mm at the headwaters to 1,520 mm near the mouth (Iwatsubo et al, 1975).

There are two patterns of storm tracks that are typical of northwest California. The first type of storm track is centered to the north of the Redwood Creek basin and produces heavy rainfall in the lower basin and in coastal areas north of Patrick's Point, California. The second type of storm passes directly over or to the south of the inland portion of the Redwood Creek basin (Harden, 1995). The 1997 storm was the second type of storm. The storm produced heavier rainfall in the upper Redwood Creek basin than in the lower basin (P. Nordquist, National Weather Service, personal communication, 2000).

I used data gathered from four rainfall gages and two stream gages in the Redwood Creek basin area. Three of the rain gages were in the Redwood Creek basin. One gage is at Kneeland, about 13 km to the west of the upper Redwood Creek basin. The gages in the Redwood Creek basin are O'Kane (sometimes referred to elsewhere as the Redwood Creek near Blue Lake gage), Lacks Creek, and Orick. The Orick gage is

located near the mouth of Redwood Creek, the Lacks Creek gage and the O’Kane gage are located in the middle of the basin, and the Kneeland gage is close to the upper Redwood Creek basin. The data from the O’Kane gage included hourly and daily precipitation and stream flow information for 1997. The Lacks Creek gage provided rainfall data (see Table 5). The Orick gage supplied hourly and daily rainfall data and stream flow information for both the 1997 and the 1964 storms. The Kneeland gage supplied daily rainfall data.

Storm History

There were six major storm events in the Redwood Creek basin between 1954 and 1998. These storms took place in 1955, 1964, January 1972, March 1972, 1975 (Harden, 1995), and 1997 (Table 3). The largest flood occurred in 1964, with the flood producing effects compounded by warm rain falling on snow (Bloom, 1998). The January 1997 storm was also a rain-on-snow event (T. Nicolini, National Weather Service, personal communication, 2006). The 1964 storm resulted in the most erosion in the 1955 to 1975 period (Harden, 1995; Kelsey et al, 1995; Pitlick, 1995). Slope destabilization from previous storms, extensive timber harvesting and road building may have contributed to the extensive erosion from the 1964 storm (Harden, 1995). Figure 2 shows the annual peak flows recorded at the Orick gage from 1954 to 2005 by water year. Water year begins October 1st of every year. Storms that occur from October to December of 1964, for example, are considered to have occurred in water year 1965. This explains the discrepancy between the years in Table 3 and the water years in Figure 2.

Table 3 Comparison of peak discharges in the Redwood Creek basin from 1955 to 1997 (modified from Bloom, 1998, and Harden, 1995; return intervals from Redwood National and State Parks in-house records, 1997).

YEAR	PEAK DISCHARGE AT REDWOOD CREEK, ORICK (cfs)	RECURRENCE INTERVAL OF PEAK FLOW
December 1955	50,000	17
December 1964	50,500	50
January 1972	45,300	13
March 1972	49,700	14
March 1975	50,200	25
January 1997	40,300	12

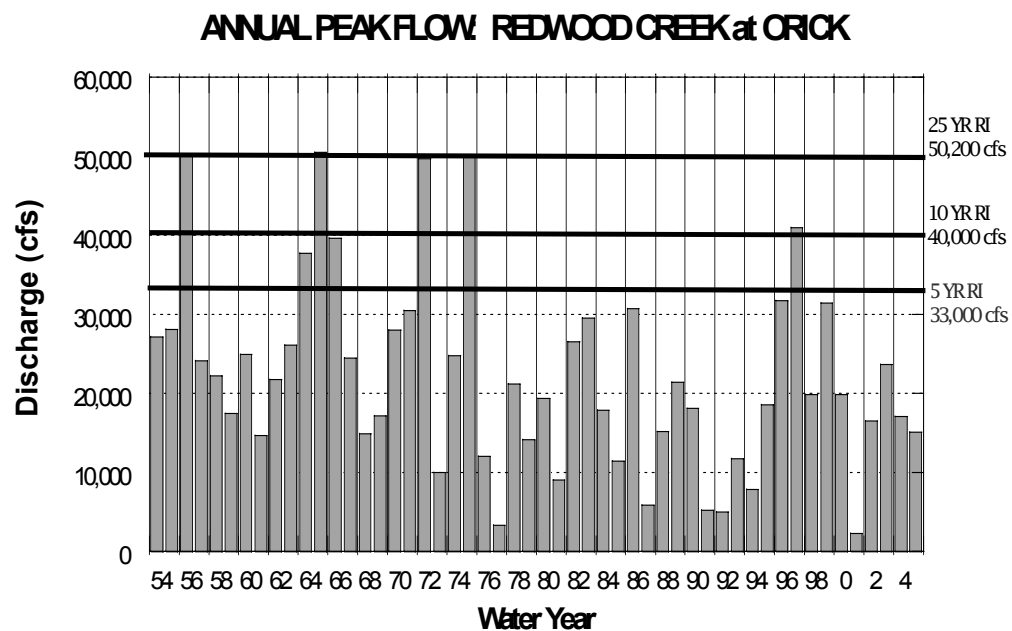


Figure 2. Annual peak flow at the Orick gage from 1954 to 2005 (modified from Redwood National and State Parks records, 2003).

Rainfall

Landslide initiation tends to be well-correlated with rainfall (Cafferata and Spittler, 1998). Deep-seated failures are heavily influenced by seasonal precipitation amounts. In contrast, shallow rapid failures, such as debris avalanches, are usually triggered by high rainfall intensities. A storm with extreme 12- to 24-hour rainfall can cause shallow debris avalanche failures once the soil has reached field capacity.

Hourly precipitation gage measurements from the Orick gage, the O’Kane gage, and the Lacks Creek gage were used to determine rainfall intensity in the Redwood Creek basin during the January 1997 storm. Daily rainfall data from the Orick, O’Kane, and Kneeland gages were used to determine 2-, 3-, 5-, 10-, 20-, and 60-day maximum rainfall that occurred prior to this storm. Data were not available from the Lacks Creek gage for any maximum rainfall above 24 consecutive hours (Table 4). Maximum rainfall for some of the duration categories in Table 4 occurred before the January 1997 storm. Late November and early December, 1996, were very wet.

The rainfall intensity of the January 1997 storm was moderate. The return intervals for the 1-, 6-, and 24-hour rainfall intensities were less than 2 years, except the 24 hour rainfall intensity at the O’Kane gage, which had a return interval of 8 years (Table 5) (Appendix B – Redwood National and State Parks in-house records, 1997). A return interval is the average interval between events equaling or exceeding a given magnitude (Dunne and Leopold, 1998).

Table 4 Maximum rainfall intensities for Redwood Creek basin for water year 1997
(Redwood National and State Parks, in-house records, 1997, California Department
of Water Resources, 2005)

GAGE				
RAINFALL (mm)	ORICK	O’KANE	LACKS	KNEELAND*
1 Hour	15	10	11	n/a
6 Hour	51	43	48	n/a
24 Hour	137	114	160	136
48 Hour	162	160	n/a	163
96 Hour	218	170	n/a	189
5 Day	259	252	n/a	277
10 Day	344	386	n/a	352
20 Day	440	594	n/a	446
30 Day	753	749	n/a	762

* Kneeland gage is 13 km to the west of upper Redwood Creek

Table 5 Redwood Creek rainfall intensities and intensity return intervals for the January 1997 storm (derived from Redwood National and State Parks, in-house records, 1997; California Department of Water Resources, 2005). Return intervals (years) are shown in parentheses and are based on Redwood National and State Parks in-house records, 1997.

GAGE	TOTAL RAINFALL (mm)	1-HOUR INTENSITY (mm) (Return Interval, yr)	6-HOUR INTENSITY (mm) (Return Interval, yr)	24-HOUR INTENSITY (mm) (Return Interval, yr)
<u>DECEMBER 1964</u>				
ORICK	264	n/a	n/a	n/a
PRAIRIE CREEK	267	n/a	n/a	n/a
KNEELAND*	498	n/a	n/a	295
<u>JANUARY 1997</u>				
ORICK	216	15 (<2)	51(<2)	137 (<2)
O'KANE	163	10 (<2)	43 (<2)	114 (8)
LACKS	277	11 (<2)	48 (<2)	160 (2)
KNEELAND	n/a	n/a	n/a	136 (<2)

* 1964 storm total for the Redwood Creek basin from T. Nicolini, personal communication, 2006

Redwood Creek basin rainfall intensity and duration were compared to values presented in a study by Caine (1980). Caine examined relatively undisturbed slopes where shallow landslides and debris flows occurred. Caine gathered rainfall and landslide data from around the globe. I plotted the 1-, 6-, 24-, 48-, and 96-hour rainfall intensities from the Redwood Creek basin along with the data generated by Caine (Figure 3).

Caine (1980) states that the rainfall intensity-duration thresholds are most accurate for 1-hour to 10-hour intensities. The Redwood Creek rainfall intensity and duration data for the January 1997 storm (Figure 3) fell barely within or below the lower threshold of the intensity and duration from other regions where shallow landslides and debris flows occur on relatively undisturbed slopes. Mass movement initiation in Redwood Creek basin, which is highly disturbed through timber harvest and associated roads, occurred at lower rainfall intensities for 1-, 6-, 12-, 24-, 48-, and 96-hour durations than at most of the Caine sites. The 1964 data show that the intensity and duration of that storm rainfall were much higher than during the January 1997 storm.

Antecedent Precipitation Index

The antecedent precipitation index (API) is used to determine the effect of previous rainfall in wetting the soil and of natural drainage and evapotranspiration in reducing the soil moisture at an exponentially decreasing rate over time (Dunne and Leopold, 1998, p. 287-290). Thus, the higher the API, the wetter the soils were prior to the storm event. The major storms and the associated antecedent precipitation index (API) are listed in

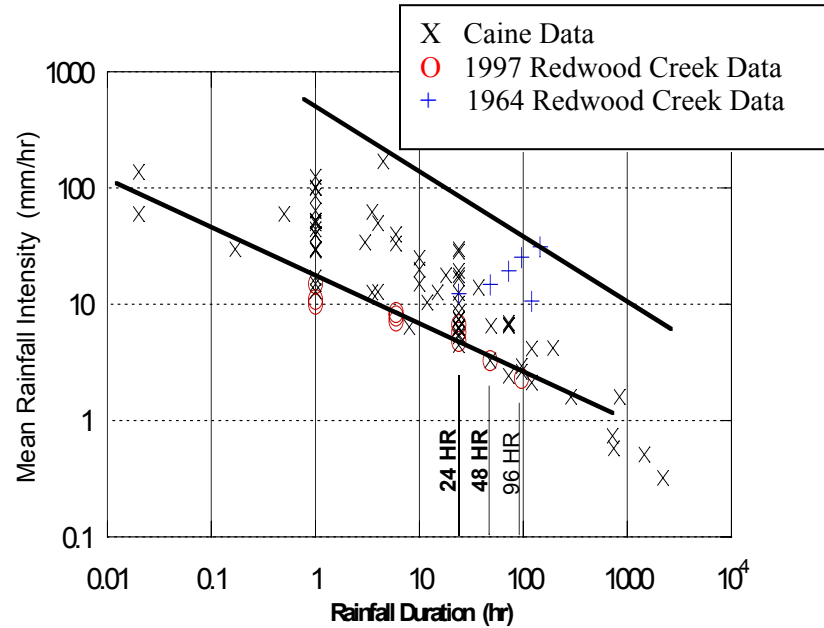


Figure 3. Comparison of Redwood Creek rainfall intensities and durations from the January 1997 storm (red circles) and the December 1964 storm (blue crosses) with those from regions experiencing shallow debris slide activity at reported rainfall intensities and durations. The lower curve is the minimum critical intensity-duration threshold and the upper curve is the maximum critical intensity-duration threshold. (Modified from Caine, 1980; 1997 and 1964 data from California Department of Water Resources (CDWR-California Data Exchange Center), 2005).

Table 6. API's are calculated using the exponential decay equation, which is calculated daily:

$$I_t = I_{t-1} * (k^t) + P_t$$

where t is the day number since the last preceding day with rainfall, I_t is the API on day t , I_{t-1} is the API on the day previous to t , k is a recession factor which was given the value of 0.90 (Klein, personal communication, 2000), and P_t is the precipitation on day t . The calculations for API in Redwood Creek basin start 60 days before the beginning of the storm event in question (Harden, 1995). Initial API was assumed to be 16 mm at the beginning of the water year (October 1) based on field studies in the Redwood Creek basin (Ziemer, 1984). The Redwood Creek basin had a high antecedent precipitation index before the 1997 storm. It was the second highest API when compared to the other large storms in the Redwood Creek basin since 1954. The March 1972 storm had the highest API on record at the Orick gage.

Comparison of the 1964 Storm to the 1997 Storm

The largest storm between 1954 and 1997 was the 1964 storm. The peak flow had a 50-year recurrence interval at the Orick gage. Rainfall total for the storm was 264 mm. The 1964 storm was a rain-on-snow event. Melting snow in 1964 may have augmented peak flows in Redwood Creek (Harden, 1995). There is also documentation that the mass movement from the 1964 storm was more prevalent in the upper Redwood Creek basin (Kelsey et al, 1995; Pitlick, 1995; Harden, 1995), a pattern that would be consistent with the presence of rain-on-snow runoff. The peak flow in Redwood Creek

Table 6. Maximum API for Redwood Creek at Orick at the onset of the large storms in the Redwood Creek basin (modified from Redwood National and State Parks records, 1997).

YEAR	API
December 1955	170
December 1964	175
January 1972	114
March 1972	218
March 1975	125
January 1997	188

during the 1964 storm was 50,500 cfs on December 22, 1964, and the API at the Orick gage was 175 mm.

During the January 1997 storm, the peak flow at Orick was 40,300 cfs on January 1, 1997, a discharge having a recurrence interval of about 12 years. The January 1997 storm rainfall was 216 mm at the Orick gage. This storm was also a rain-on-snow event and the API was 188 mm.

The January 1997 peak flow was 80% of the peak flow during the 1964 storm. The API for the basin in 1997 was 1.1 times greater than the 1964 API and the storm rainfall at the Orick gage was 48 mm less than during the 1964 storm.

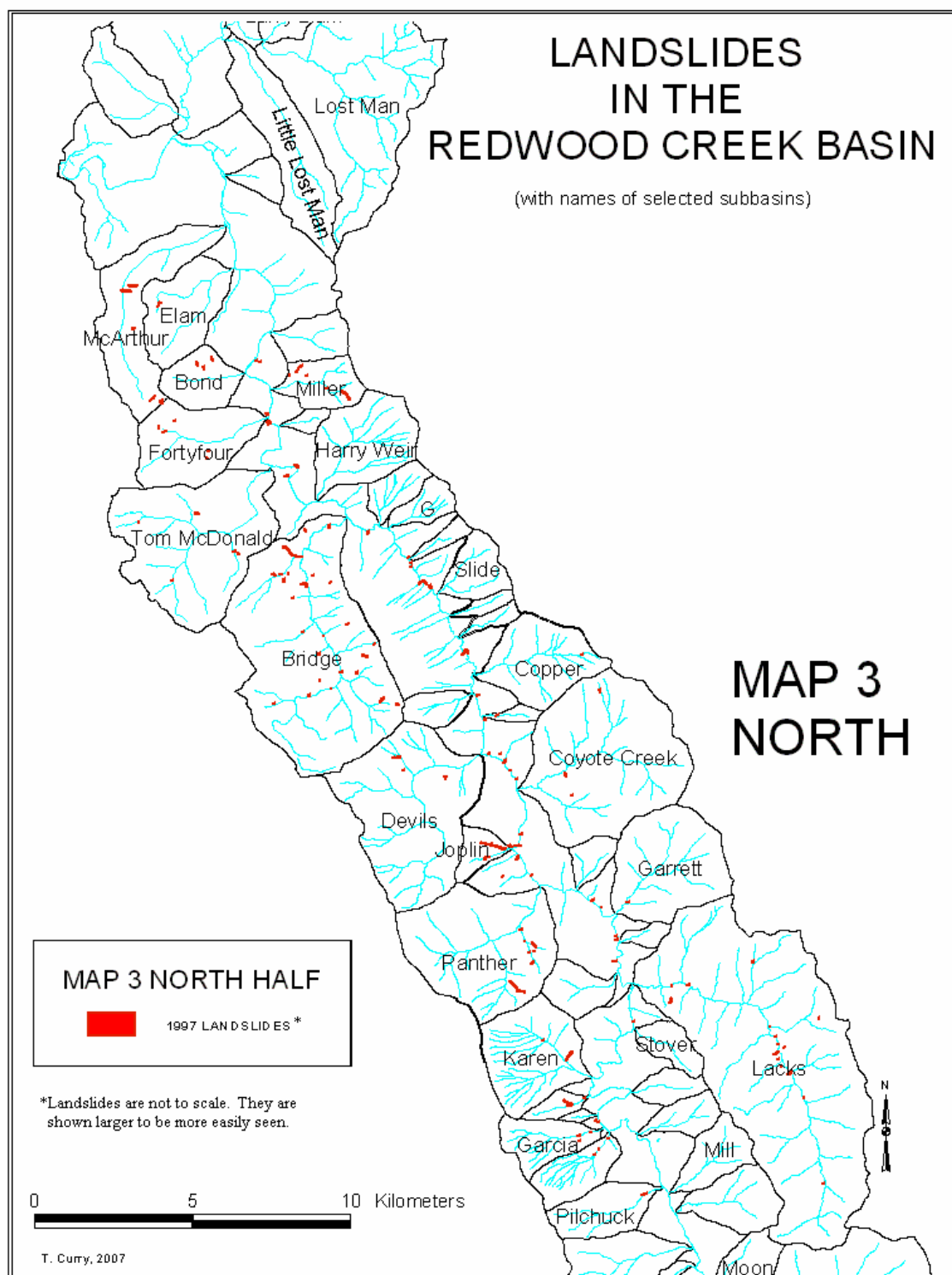
METHODS

Air Photo Interpretation Methods

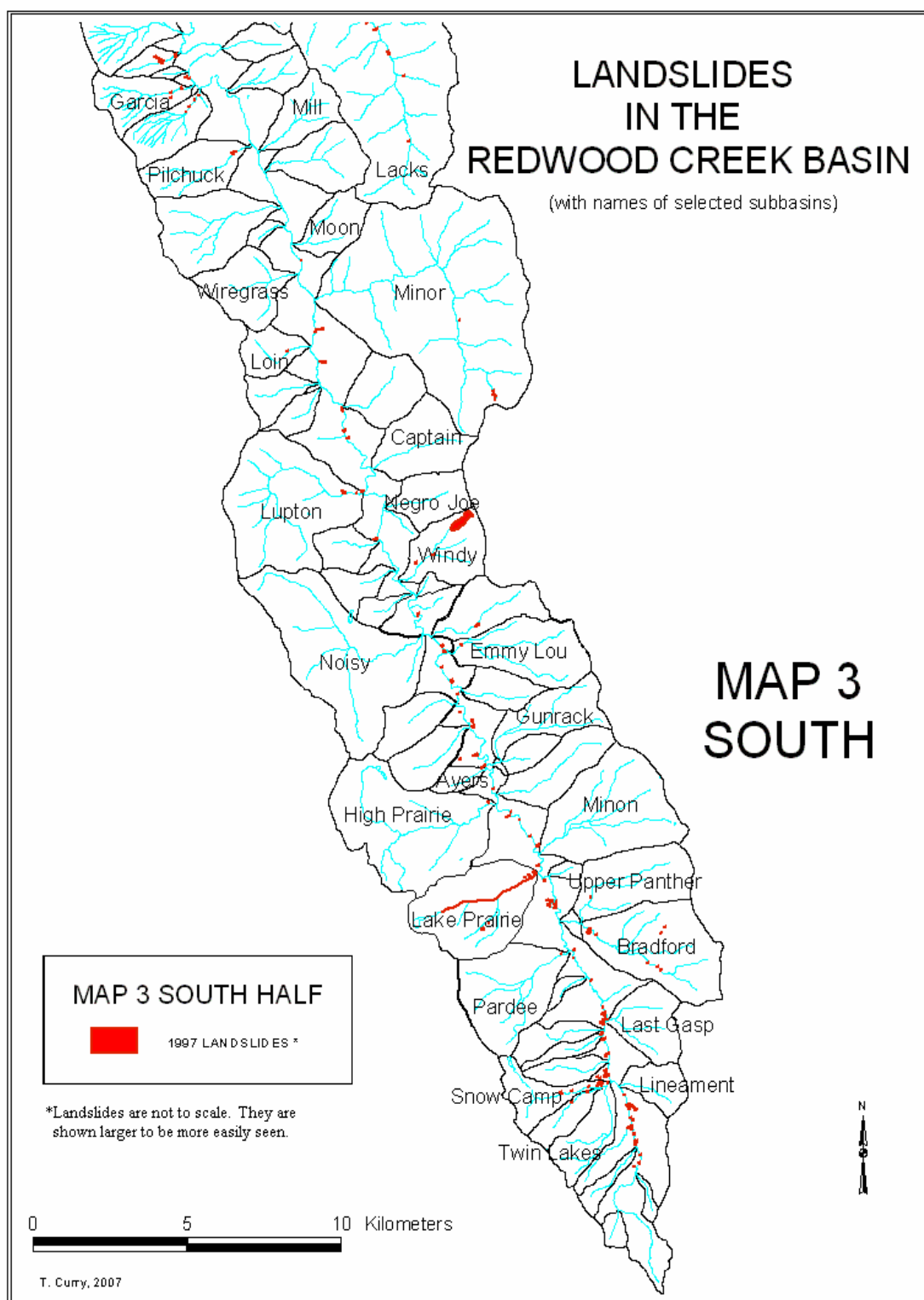
Black and white air photos taken in June 1997 at a 1:6,000 scale were used to map the landslides generated in the January 1997 storm throughout the watershed and to gather geomorphic and land-use data for all landslides (Map 3). Data gathered for each landslide include:

- type of failure (shallow debris slide, debris flow, stream bank failure),
- hillslope position in relation to major streams (upper 1/3 of hillslopes, middle 1/3 of hillslopes, lower 1/3 of hillslopes, inner gorge, and headwall swale),
- hillslope form (the major hillslope form for 300 m along contour on both sides of the failure: concave, convex, or planar),
- and road association (landslide either initiates on a road bench or within 30 m of the centerline of the road or is considered not to be road-related).

Shallow debris slides were identified on air photos by examining each air photo for the typical crescent shape of the top of the landslide. During extensive fieldwork in various areas of the Redwood Creek basin, I observed that vegetation regenerates rapidly. Even a year's growth on a stream bank in the Redwood Creek basin is distinguishable on air photos. Once a shallow debris slide was identified I determined whether or not it was a



Map 3 North Half. 1997 landslides with subbasin boundaries (Redwood National and State Parks, 1998).



Map 3 South Half. 1997 landslides with subbasin boundaries (Redwood National and State Parks, 1998).

fresh, or 1997, landslide by looking for a surface with bare ground. The typical shape for a debris torrent is narrow and long (Knighton, 1998). Landslide features that were narrow and long with bare ground were mapped as fresh debris torrents. Recent bank failures occur along the banks of streams, generally on an outside bend where the force of the stream water wears away the bank. Bank failures tend to be nearly vertical and are not very high. Bank failures are the most difficult mass movement feature to identify on air photos. Bank failures were distinguished from stable riverbanks and older bank failures by the lack of vegetation that was visible on the air photos and on the ground. In total, I identified 250 landslides of these three types within the study area. Earthflows are also present in the watershed but I did not include them in this study.

While looking at the air photos I visually divided the hillslope into thirds: upper, middle, and lower. I assumed that each hillslope class encompassed one third of the watershed. I assigned the upper and middle hillslope positions 205 km^2 and the lower position 206 km^2 to equal the 616 km^2 of the study area. The inner gorge is a subset of the lower hillslope position. Bundros and Andras (2001) measured an inner gorge area of 32 km^2 from air photos and from extensive field knowledge of the Redwood Creek basin. The 32 km^2 is subtracted from the 206 km^2 for a total of 174 km^2 for the lower hillslope position.

Based on the air photo mapping I estimated that each hillslope class included 2 km² of headwall swale area. I subtracted 2 km² from each of the hillslope positions for a final estimate of 203 km² for the upper and middle hillslope positions, 172 km² for the lower hillslope position, 32 km² for the inner gorge hillslope position, and 6 km² for the headwall swale hillslope position.

A post-1997-storm inventory to document road damage was completed in Redwood National and State Park watersheds by Redwood National Park geologists in late January 1997 (Redwood National and State Parks, 1997). The geologists categorized the damage from erosion into several categories including, but not limited to, failed culverts, stream diversions, cutbank failures, plugged ditches, and fill failures. Data sheets that included information on type of failure and estimated volume of the failure, among other information, had been filled out for erosion sites on all roads and sub-watersheds within the Redwood Creek basin. However, only the 21 data sheets from the M-Line and the M-8 Line roads, which span a portion of Redwood Creek and the Bridge Creek sub-watershed, could be found at the time I was analyzing the inventoried erosion sites.

On the 21 data sheets that could be located, there were 11 features mapped as landslides. I compared those landslides with the landslides from my study, and found that I was able to see five of the 11 features on the 1:6,000 air photos. The six features that I could not see were all less than 25 m wide and less than 400 m² in area, and were obscured by vegetation. The Redwood National and State Parks road-damage inventory mass movement volumes were reported in broad ranges: <50 cubic yards, 50-100 yd³,

100-500 yd³, 500-1,000 yd³, 1,000-3,000 yd³, 3,000-10,000 yd³, and >10,000 yd³. I used the midpoint of each range from the Redwood National and State Parks study to compare volumes to this study. The total volume of the voids at the 11 landslides from the road-damage inventory was 7,100 m³, according to the Redwood National and State Parks data sheets. Of that total I mapped 5,900 m³ of the volume, so I was able to map 80% of the landslide volume. The road-damage inventory landslides have a similar size distribution as the 250 landslides from this study so I applied the findings from the road-damage inventory landslides to the entire study area by assuming that I mapped approximately 80% of the landslide material in this study. I limited this study to landslides that were greater than 400 m² because I could not accurately map landslides that were smaller.

Each landslide was traced from an air photo onto a mylar sheet. Next, each landslide was traced onto 1:24,000 orthophoto quads and then digitized into the Redwood National and State Park's Geographical Information System (GIS). The GIS was queried to determine the plan area of each slide. The GIS landslide coverage was then overlain on the Redwood National and State Parks geology and road coverages to measure the distance of each slide to the nearest road. Many roads in the Redwood Creek basin were difficult to see on recent air photos because of thick vegetation, shadows, and view angle, but the GIS road coverages are excellent because of extensive field checking supplementing the study of older air photos. I defined a landslide as road-associated if it was within 30 m of the center line of a road, either upslope or downslope. The portion of this study area that is road-associated is about 160 km² or 26%.

Estimation of Volume

Estimation of landslide volumes for this study used the relation between landslide area and depth that was defined using results of field measurements made in the early 1980's by Kelsey et al (1995) and Pitlick (1995) in the Redwood Creek basin. They measured landslide length, width, and depth on more than 1,000 streamside landslides. They calculated volume for each landslide by multiplying hillslope landslide area by the average depth of each landslide.

The planimetric area of each 1997 landslide was calculated using the GIS, but the depth of each 1997 landslide needed to be estimated to calculate volumes for the landslides. Time and access issues prevented actual field measurement of the depth of each landslide.

Two steps were used to estimate a reasonable depth for each 1997 landslide. First, because the 1995 data set (Kelsey et al, 1995) used hillslope area, the planimetric areas from 1997 landslides were converted to hillslope areas by using the average hillslope gradient at landslide sites of 55% (29 degrees; see next section):

$$\text{GIS planimetric area} / \cos 29^\circ = \text{Hillslope area.}$$

Next, a regression analysis was conducted using the 1980 landslide data to define the relationship between depth and area. The volumes of the earlier landslides were transformed logarithmically, and then linear regression was performed on the data set (see Appendix C for regression graph). The regression equation is:

$$\ln (\text{Volume (m}^3)) = -0.71 + 1.12 * \ln(\text{Area (m}^2))$$

For debris torrents greater than 3,000 m² in area, an average depth of 1.2 m was used to calculate volume. This depth value is based on actual depths measured in the field on massive debris torrents. The field measurements show that after a certain point the average depth of the debris torrent does not increase with increasing area of the debris torrent.

Estimation of Hillslope Gradient

The hillslope gradient was first estimated using GIS. The GIS-generated hillslope gradients were compared to hillslope gradients on 25 landslides mapped in the field by Best (1995) that had been reactivated during the January 1997 storm. I assumed that the hillslope gradient after reactivation would be comparable to that measured by Best (1995). I found that the GIS-generated slope gradients were in error by up to 55%. The GIS-generated hillslope gradients were always less than the field-measured hillslope gradient, especially in steep areas near stream channels.

After finding such a large error in the GIS-generated hillslope gradients, I decided to estimate hillslope gradient from USGS topographic maps. I first overlaid the digital landslide coverage on the digital USGS maps with 80-foot contour lines. The view scale was set to 1:3,000. The spaces between contour lines were divided visually into quarters (or 20-ft sections) to estimate the map difference in elevation between the head and toe of the landslides. The map view length of the landslide scar (total length) was measured using ArcView's measuring tool. Gradient was then calculated by dividing the landslide height by the landslide length. Once slope gradient was obtained, landslides were

divided into 4 slope gradient classes; gentle (0-30%), moderate (31-50%), steep (51-65%), and extremely steep (>65%).

I used the GIS-generated hillslope gradient coverage as an overlay with bedrock and inner gorge GIS coverages to attempt to separate the influence of each factor from that of the other. The GIS-generated hillslope gradient coverage does not match the Bundros and Andras inner gorge coverage; it shows about half of the inner gorge area as having a hillslope gradient less than 50%, which by definition is not true. Part of this discrepancy is a scale problem in that the Bundros and Andras inner gorge coverage used air photos to delineate the steep inner gorge slopes, whereas the GIS-based slope coverage detected smaller areas of more gentle slopes within the broad inner gorge classification. Field checking would be necessary to verify if these more gentle benches are real or are an artifact of the digital elevation models. As better tools to measure accurate hillslope gradients become available, these coverages should be updated.

Estimation of Sediment Delivered to Redwood Creek and its Tributaries

While viewing the air photographs, I estimated the amount of material from each landslide that was delivered to Redwood Creek and its tributaries. I used three categories while looking at each landslide: 0 to 24% delivery to stream channels, 25 to 74% delivery to stream channels, and 75 to 100% delivery to stream channels.

Kelsey et al (1995) and Pitlick (1995) measured void space of streamside landslides in the field and report it as 100% delivery to streams. Pitlick also mapped landslides from air photos. After comparing field and air photo-mapped landslides, he

estimates that 80 to 98% of all the sediment that was delivered to Redwood Creek tributaries could be measured from the air photos. Pitlick used air photo series from 1954, 1958, 1962, 1966, 1970, 1974, and 1978 to constrain the timing of the landslides. Of the volume of material he measured from 1954 to 1966, 79% was delivered to Redwood Creek tributaries between 1962 and 1966.

In order to compare the volume of material delivered to stream channels in this study with that from the previous Redwood Creek landslide studies, I identified the subset of landslides that were streamside landslides that delivered directly into Redwood Creek and its tributaries. I then divided the streamside volumes into ‘mainstem’ volumes, which were delivered directly to Redwood Creek, and ‘tributary’ volumes that were delivered directly into the tributaries. Pitlick measured the volume of landslides in 16 tributaries of Redwood Creek. I compared the 1997 storm landslide volume from the same 16 tributaries with the 1964 landslide volume that Pitlick measured.

Kelsey et al (1995) used only two time periods to constrain the timing of landslides, the periods 1954 to 1966 and 1966 to 1980. Since Pitlick has tighter constraints on landslide timing, I applied the 79% from Pitlick’s study to the landslide inputs reported by Kelsey et al to estimate the amount of sediment delivered to streams between 1962 and 1966 on the mainstem of Redwood Creek. I made the assumption that all of the sediment in Pitlick’s study in the 1962 to 1966 time period was derived from the 1964 storm.

Measuring Inner Gorge Landslide Volume in Association with Timber Harvest Units

To analyze the association of timber harvest with inner gorge landslides I needed to calculate the volume of landslides per unit length of inner gorge under various harvest classifications. I measured lengths of inner gorge channel reaches mapped by Bundros and Andras (2001) in the upper Redwood Creek basin. I calculated the lengths of inner gorge on both sides of Redwood Creek and its tributaries for a total bank length of 240 km.

I used three classifications of post-1977 timber harvest units in relation to the inner gorge (Figure 4): Case 1) a timber harvest unit within the inner gorge, Case 2) a timber harvest unit upslope of the inner gorge, but at least partly within 200 m of the upslope inner gorge boundary, and Case 3) no timber harvest units within 200 m of the inner gorge. Two hundred meters corresponds to about three tree heights of mature Douglas-fir and is also about half the width of a typical timber harvest unit. Each site was classified according to the lower-most timber harvest unit; a Case 1 site, for example, could also have harvest units upslope of the inner gorge.

It is important to explain the proximity of timber harvest units in the Case 3 scenario. In the Case 3 scenario there were no timber harvest units within 200 feet of the top of the inner gorge boundary from 1977 to 1997 when I did the analysis. However, there had been timber harvest before 1977 in the inner gorge areas at all Case 3 sites (as well as at all Case 1 and Case 2 sites), and many had also experienced additional timber

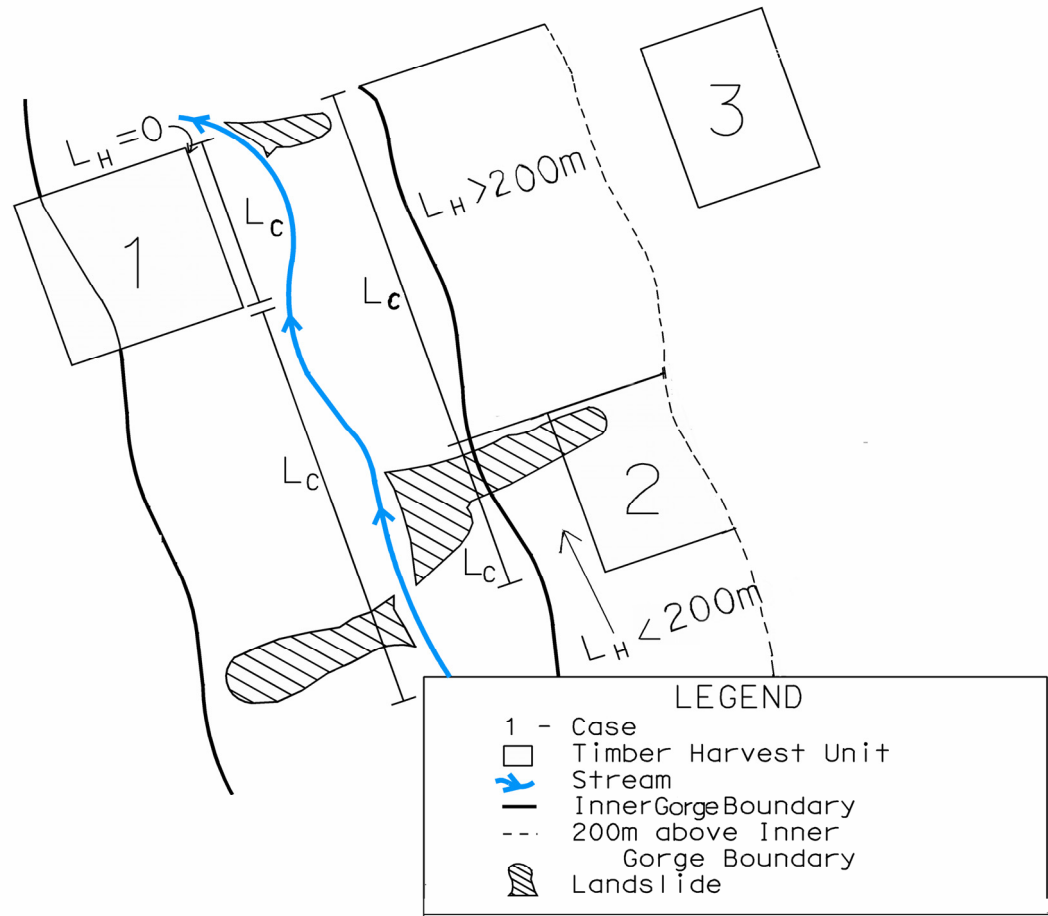


Figure 4. Diagram of channel and inner gorge harvest unit classifications. Case 1, timber harvest unit inside inner gorge: Case 2, timber harvest unit within 200 m upslope of the inner gorge: Case 3, bottom of the timber harvest unit > 200 m from top of inner gorge. L_H = distance from top of inner gorge boundary to bottom of timber harvest unit. L_C = bank segment length.

harvest more than 200 meters above the top of the inner gorge boundary during the period between 1977 and 1997.

First, I measured the distance between the upslope boundary of the inner gorge and the downslope boundary of the lowest timber harvest unit, if present, (LH) (Figure 4) and placed the reach into one of the three above-mentioned categories. Next, I measured the lengths of channel bank of the inner gorge (LC) for each category and recorded landslide identification number of inner gorge landslides in each bank segment. Volumes of landslides for each classification were obtained from the landslide database through the unique identification numbers of each landslide. Finally, I summed the lengths of channel bank segments and the associated landslide volumes for each category. Only timber harvest units dating from 1977 to 1997 were evaluated because site-specific information on pre-1977 timber harvest location was not available.

RESULTS

Quantification of Sediment

The total volume of landslide material from the 250 landslides included in this study is about 570,000 m³. The minimum, maximum, mean, and median volumes are shown in Table 7. Landslide volume distributions are displayed in Figures 5a and 5b. A cumulative volume-frequency graph shows that 20% of the landslides contributed about 50% of the total landslide volume (Figure 5b). Relatively few, large landslides contributed at least half of the landslide material discussed in this study. While landslides smaller than 400 m² were missed on the 1:6,000 scale air photos, it is the large slides that contributed the bulk of the sediment to Redwood Creek and its tributaries.

The estimated amount of sediment that reached Redwood Creek and its tributaries from the landslides mapped for this study is from 345,000 m³ to 496,000 m³ (Table 8). This range represented the totals calculated using first the lower and then the upper bounds of the three delivery categories used in mapping: 0 to 24% material delivered to streams, 25 to 74% material delivered to streams, and 75 to 100% material delivered to streams (Table 8).

Table 7. Landslide volume statistics.

STATISTIC	LANDSLIDE VOLUME (m ³)
Total volume	570,000
Mean	2,300
Median	1,400
Maximum	12,400
Minimum	500
Sediment Delivered to Streams	345,000 to 496,000

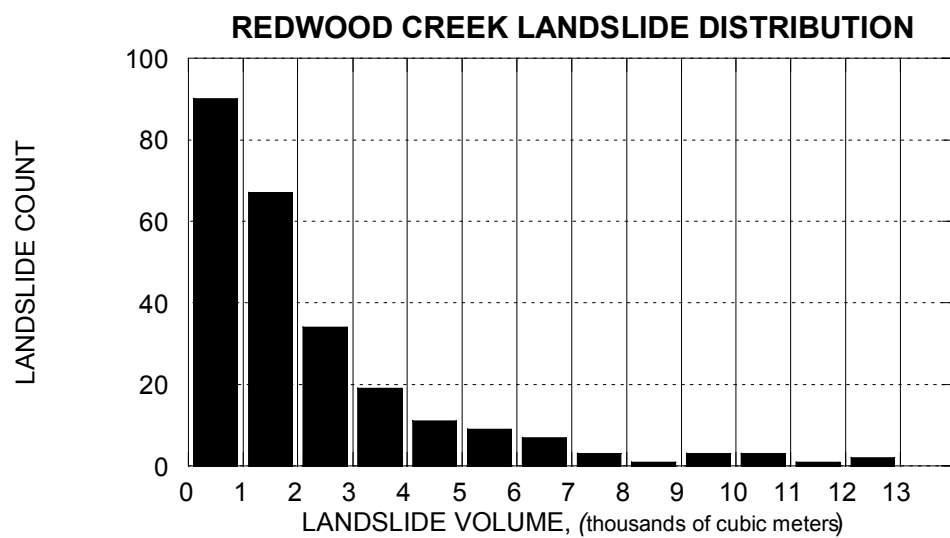


Figure 5a Landslide volume distribution from the 1997 storm in Redwood Creek basin.

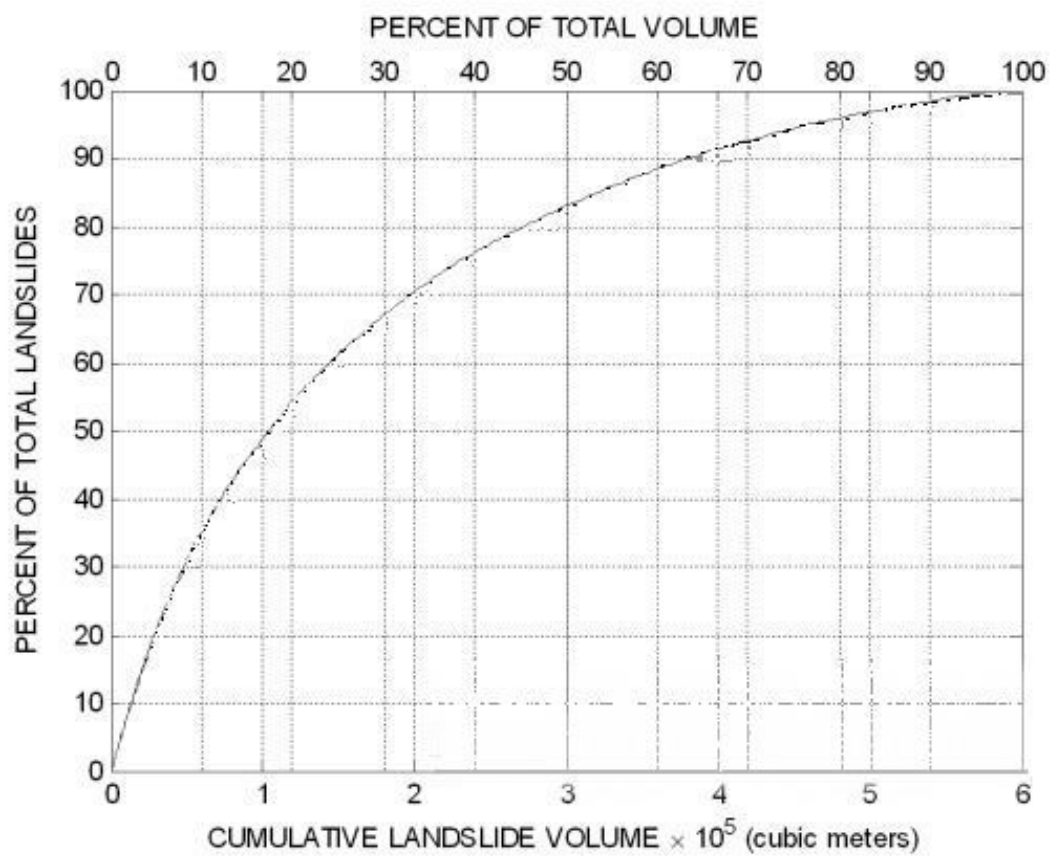


Figure 5b. Cumulative volume frequency relation for landslides.

Table 8 Sediment delivered to stream channels in Redwood Creek basin from 1997 landslides.

DELIVERED SEDIMENT CATEGORIES	TOTAL LANDSLIDE VOLUME (m ³)	LANDSLIDE COUNT	MAXIMUM * SEDIMENT (m ³)	MINIMUM * SEDIMENT (m ³)
HIGH (75 - 100%)	448,000	181	448,000 (100% delivery)	336,000 (75% delivery)
MEDIUM (25 TO 74%)	36,000	22	27,000 (74% delivery)	9,000 (25% delivery)
LOW (0 TO 24%)	86,000	47	21,000 (24% delivery)	0 (0% delivery)
TOTAL	570,000	250	496,000	345,000

* The range of estimated sediment delivery volumes was calculated using the lower and upper limits of my air photo volume delivery classes.

The best estimate of sediment volume from landslides delivered to Redwood Creek basin and its tributaries was 421,000 m³ (mid-point of total maximum and minimum delivered sediment). The total volume of material delivered to the mainstem of Redwood Creek from the 1997 storm was 161,000 m³. The 1997 sediment volume delivered to the 16 tributaries in which Pitlick and I both mapped landslides is 138,000 m³. I estimated that I accounted for about 80% of the total sediment volume from landslides in this study (Methods section). Correction for the underestimate would increase the estimated total volume delivered from landslides to the Redwood Creek and its tributaries to 526,000 m³, the total volume of landslide material delivered to the mainstem of Redwood Creek to 201,000 m³, and the sediment volume delivered to the 16 tributaries in which Pitlick and I mapped landslides to 173,000 m³.

There was slightly more sediment per unit area in the lower portion (Redwood National and State Parks) of the Redwood Creek basin from the January 1997 storm than in the upper Redwood Creek basin (privately-owned lands) (Table 9). The boundary between the upper and lower basin is the southern boundary of Redwood National Park.

Data show that the streamside landslides, a subset of the 1997 landslides, delivered as much as 48% of the sediment that the 1964 storm delivered to a tributary basin (Devil's Creek) but contributed only 6% of the volume to the mainstem that the 1964 slides had contributed (Table 10).

Table 9 Sediment delivered to Redwood Creek and its tributaries from the January 1997 storm.

	AREA (km ²)	SEDIMENT DELIVERED (m ³)	LANDSLIDE VOLUME PER UNIT AREA (m ³ /km ²)
UPPER BASIN	419	273,000	650
LOWER BASIN	197	137,000	700

Table 10 Material delivered to streams from a subset of 1997 and 1964 storm streamside landslides.

SUBBASIN	AREA (km ²)	BEDROCK TYPE (SH=schist, SS=sandstone)	1997 STREAMSIDE DELIVERED VOLUME (m ³)	PITLICK VOLUME (m ³) ^a	KELSEY VOLUME (m ³)	1997 VOLUME PER AREA (m ³ /km ²)	1964 VOLUME PER AREA (m ³ /km ²)	PERCENT 1997-1964 VOLUME
Mainstem Redwood Creek Previously Sampled Tributaries ^B			161,000		2,640,000	260	4,300	6
Lacks	44.0	SS	23,300	266,000		530	6,000	9
Minor	33.6	SS	7,200	182,000		210	5,400	4
Bridge	29.4	SH	34,500	129,000		1,170	4,400	27
Coyote	20.4	SS	5,100	95,000		250	4,700	5
Devils	18.0	SH	4,800	10,000		270	600	48
Tom McDonald	18.0	SH	1,800	14,100		100	800	13
Bradford	16.5	SS	16,100	76,200		980	4,600	21
Upper Redwood	11.1	SS	31,200	76,400		2,800	6,900	41
Garrett	10.8	SS	900	14,800		80	1,400	6
Snowcamp	8.2	SS/SH	9,800	111,000		1,200	13,500	9
Forty Four	8.1	SH	1,900	9,900		240	1,200	19
Harry Weir	7.8	SS/SH	0	10,400		0	1,300	0
Copper	7.4	SS	0	11,800		0	1,600	0
Windy	4.5	SS	1,100	104,000		240	22,600	1
Simon	4.5	SS	0	180,000		0	39,900	0
North Fork Slide	1.6	SS	0	2,100		0	1,300	0
Tributary Totals	244.0		137,700	1,292,700		560	5,300	

^a converted to cubic meters from 1,460,000 tonnes using material density of 1.6g/cm³

^b Pitlick (1995) only measured landslides in 16 tributary basins

Another way to assess the impact that the sediment from landslides is having on the Redwood Creek basin is in terms of sediment yield. The Redwood Creek basin was listed in 1998 as 'sediment impaired.' Suspended sediment yield data are available from 1971 to 2001 from the Orick gage. Years with high peak flows are generally associated with high suspended sediment yields (Figure 6).

Efforts are being made to reduce the average annual sediment yield of Redwood Creek to 1,900 tons/mi² (670 Mg/km²), based on the EPA's TMDL report (1998). Annual suspended sediment for 1997 at Orick, the downstream-most gage on Redwood Creek, was 1,970 Mg/km² (5,625 tons/mi²), or a total of 1,419,000 Mg of suspended sediment between October and April of the 1997 water year (Table 11). The estimated delivered sediment from the 1997 landslides was 421,000 m³ or 674,000 Mg.

The contribution of landslide material to the suspended sediment yield at the Orick gage is from 39% to 56% of the total sediment yield from October 1996 to April 1997. As discussed earlier in this paper, the volume estimates are most likely low for this study by about 20% due to the number of landslides that I missed while mapping from the air photos. If I had added the 20% to the volume estimates, the contribution of landslide material would have ranged from 49% to 70% of the suspended sediment yield for the Redwood Creek watershed.

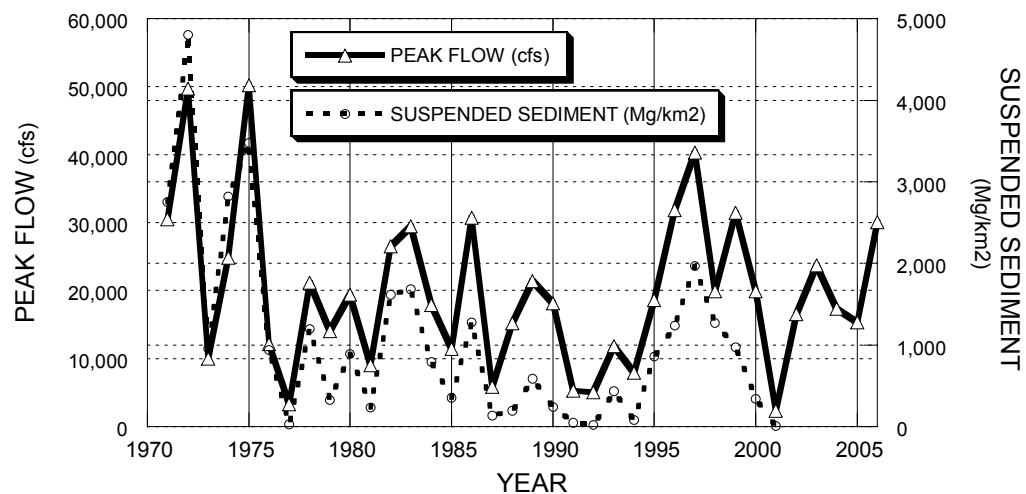


Figure 6. Comparison of peak flows and suspended sediment from 1971 to 2006 at the Orick gage, Redwood Creek.

Table 11 Suspended sediment yield from October to April of the 1997 water year and sediment delivered to Redwood Creek and its tributaries from landslides (Redwood National and State Parks in-house records, 2005).

	DELIVERED SEDIMENT (m ³)	DELIVERED SEDIMENT (Mg) ¹	PERCENT OF SUSPENDED SEDIMENT AT ORICK GAGE
ESTIMATED DELIVERED SEDIMENT	421,000	674,000	48
MINIMUM DELIVERED SEDIMENT	345,000	552,000	39
MAXIMUM DELIVERED SEDIMENT	496,000	794,000	56
SUSPENDED SEDIMENT YIELD AT ORICK GAGE		1,419,000	

¹ Calculated using a conversion factor of material density of 1.6g/cm³ for the landslide material (ie., 421,000 m³ * 1.6 Mg/m³ = 673,600 Mg)

Patterns of Landslide Distribution

For each landslide that occurred in 1997, I documented the type of landslide, bedrock type, slope form, slope position, proximity to roads, timber harvest history, and slope gradient. Table 12 lists landslide density and landslide volumes categorized by the above factors. Table 12 also shows the estimated amount of landslide material per unit area for each category. Table 13 is a record of the amount of sediment that was delivered into Redwood Creek and its tributaries from the 1997 storm.

When looking at Tables 12 and 13, one should note that the critical part of the analysis is the volume of landslide material per square kilometer. Numbers of slides and landslide volume alone do not show the true impact within each category because each category has a different area associated with it. For example, in Table 13, the ‘steep’ and ‘very steep’ hillslope gradient classifications are associated with similar landslide volumes and similar numbers of landslides. However, the ‘very steep’ category contributed about three times as much material per square kilometer as the ‘steep’ hillslope gradient category.

The high density of roads in the Redwood Creek basin was associated with a high proportion of the landslide-generated sediment contributed to Redwood Creek and its tributaries. Road-associated landslides contributed 2.6 times more than the basin average of sediment volume per unit area to Redwood Creek and its tributaries.

Table 12 Sediment volume of landslides per square kilometer categorized by potential controlling variables. (Percentages within each controlling variable classification may not add up to 100% due to the effect of rounding.)

	SLIDE COUNT	SLIDE %	LANDSLIDE VOLUME (m ³)	LANDSLIDE VOLUME %	AREA (km ²)	AREA %	SLIDES PER KM ²	VOLUME (m ³ /km ²)
BASIN AVERAGE	250		570,000		616		0.4	930
FAILURE TYPE ^a								
Shallow Debris Slide	123	49	246,000	43	-			
Debris Torrent	114	46	309,000	54	-			
Bank Failure	13	5	16,000	3	-			
HILLSLOPE POSITION ^b								
Upper	21	8	67,000	12	203	33	0.1	330
Middle	34	14	71,000	13	203	33	0.2	350
Lower	71	28	127,000	22	172	28	0.4	740
Inner Gorge	118	47	290,000	51	32	5	3.7	9,100
Headwall Swale	6	2	15,000	3	6	1	1.0	2,500
SLOPE FORM ^a								
Concave	133	53	326,000	57	-			
Convex	8	3	21,000	4	-			
Planar	109	44	224,000	39	-			
BEDROCK TYPE								
KJfr Schist	124	50	286,000	50	310	50	0.4	920
KJfg Grogan FZ	89	36	188,000	33	19	3	4.7	9,900
KJfl Lacks	12	5	41,000	7	70	11	0.2	590
KJfc Coyote Cr	25	10	56,000	10	178	29	0.1	310
Other	0	0	0	0	39	6	0	0
SLOPE GRADIENT								
Gentle (0 to 30%)	9	4	26,000	5	228	37	0.04	110
Moderate (31 to 50%)	82	33	196,000	34	302	49	0.3	650
Steep (51 to 65%)	97	39	213,000	37	68	11	1.4	3,100
Very Steep (>65%)	62	25	136,000	24	18	3	3.4	7,600
ROAD	158	63	401,000	70	160	26	1.0	2,500
ASSOCIATED ^c								
NOT ROAD								
ASSOCIATED								
Pre-1977 THP	65	26	112,000	20	110	18	0.6	1,000
1977-1987 THP	15	6	26,000	5	80	13	0.2	330
1988-1997 THP	9	4	26,000	5	60	10	0.2	430
Old Growth	0	0	0	0	100	16	0	0
Oak Woodlands	0	0	0	0	55	9	0	0
Prairie	0	0	0	0	51	8	0	0

^a Area was not measured for these features

^b I assumed that the upper, middle, and lower hillslope positions were each 1/3 of the basin area and subtracted the inner gorge area from the lower hillslope position and the headwater swale from the study area.

^c Three landslides were labeled 'not sure' for road association

Table 13 Evaluation of delivered sediment volume per square kilometer to Redwood Creek and its tributaries categorized by potential controlling factors. Delivered volumes are estimated using the midpoints of the delivery categories. (Percentages within each controlling variable classification may not add up to 100% due to the effect of rounding.)

	SLIDE COUNT	SLIDE %	ESTIMATED DELIVERED VOLUME (m ³) ± (range from midpoint of sediment delivery)	VOLUME PER SQUARE KILOMETER (m ³ /km ²) ^c	ESTIMATED PERCENTAGE DELIVERY (%) ^d
BASIN AVERAGE	250		421,000 ± 76,000	680	74
FAILURE TYPE^a					
Shallow Debris Slide	123	49	176,000 ± 32,000		72
Debris Torrent	114	46	231,000 ± 42,000		75
Bank Failure	13	5	14,000 ± 2,000		88
HILLSLOPE POSITION					
Upper	21	8	51,000 ± 8,500	250	76
Middle	34	14	49,000 ± 10,000	240	69
Lower	71	28	87,000 ± 17,000	510	69
Inner Gorge	118	47	222,000 ± 38,000	6,900	77
Headwall Swale	6	2	11,000 ± 2,000	1,800	73
SLOPE FORM^a					
Concave	133	53	234,000 ± 44,000		72
Convex	8	3	15,000 ± 3,000		71
Planar	109	44	172,000 ± 29,000		77
BEDROCK TYPE					
KJfr Schist	124	50	217,000 ± 39,000	700	76
KJfg Grogan FZ	89	36	130,000 ± 25,000	6,800	69
KJfl Lacks	12	5	35,000 ± 5,000	500	85
KJfc Coyote Cr	25	10	39,000 ± 7,000	220	70
Other	0	0	0	0	0
SLOPE GRADIENT					
Gentle (0 to 30%)	9	4	21,000 ± 3,000	90	81
Moderate (31 to 50%)	82	33	139,000 ± 28,000	460	71
Steep (51 to 65%)	97	39	154,000 ± 27,000	2,300	72
Very Steep (>65%)	62	25	106,000 ± 18,000	5,900	78
ROAD ASSOCIATED^{b,c}	158	63	287,000 ± 53,000	1,800	72
NOT ROAD					
ASSOCIATED					
Pre-1977 THP	65	26	92,000 ± 15,000	840	82
1977-1987 THP	15	6	17,000 ± 3,000	210	65
1988-1997 THP	9	4	21,000 ± 3,000	350	81
Old Growth	0	0	0	0	0
Oak Woodlands	0	0	0	0	0
Prairie	0	0	0	0	0

^a Area was not measured for these features

^b Three landslides were labeled 'not sure' for road association

^c Volume per km² was calculated by dividing the delivered volume by the category area from Table 12.

^d Estimated delivered volume percentage was calculated by dividing the delivered volume in Table 13 by the corresponding total landslide material volume in Table 12.

Pre-1977 timber harvest areas contributed a larger amount of sediment to Redwood Creek and its tributaries from landslides than the basin average. This result may be due to the prevalence of minimally regulated tractor yarding before 1977. These areas would have had high densities of skid trails that would not have been included in the area considered to be associated with roads. The timber harvest units that were harvested from zero to 10 years prior to the 1997 storm contributed less sediment than the basin average, but contributed 1.7 times as much as the areas logged 10 to 20 years before the storm. These conclusions must be considered preliminary because of the small sample size in the 'no road-1977 to 1987 timber harvest unit' (n=15) and the 'no road-1988 to 1997 timber harvest unit' (n=9).

The inner gorge and lower hillslope positions, the steep and very steep hillslope gradients, and the Grogan Fault Zone bedrock type frequently occurred together in this study. I attempted to separate the influence of each factor from that of the others by constructing overlays of these three features in ArcView to identify and measure the areas of portions of the inner gorge with different combinations of hillslope class and bedrock.

There were eight possible classifications for the inner gorge. I collected data on the area and the total volume from landslides of the intersection of each of the four different bedrock types with the steep and very steep slope classifications (Table 14). The low slope gradient classes (less than 50% gradient) were not relevant to the inner gorge classifications.

Table 14 Inner gorge landslides and their relation to slope gradient and bedrock type.
This table includes information only for inner gorge landslides upstream of Redwood National Park boundaries.

	KJfr REDWOOD CREEK SCHIST	KJfg GROGAN FAULT ZONE	KJfl LACKS CREEK	KJfc COYOTE CREEK	BASIN TOTAL
Steep gradient (51 to 65%)					
Landslide volume (m ³)	32,000	5,600	5,800	11,000	570,000
Landslide count	11	7	3	5	250
Area (km ²)	1.5	2.0	2.5	1.0	616
Landslides per km ²	7	4	1	5	0.4
Landslide volume per unit area (m ³ /km ²)	21,000	2,800	2,300	11,000	930
Very steep gradient (>65%)					
Landslide volume (m ³)	17,000	110,000	24,000	12,000	570,000
Landslide count	7	46	6	5	250
Area (km ²)	0.9	1.1	4.3	1.1	616
Landslides per km ²	8	42	1	5	0.4
Landslide volume per unit area (m ³ /km ²)	19,000	100,000	5,600	11,000	930

The total landslide volume per unit area from the inner gorge in the Grogan Fault Zone bedrock type on slopes over 65% gradient was 100 times greater than the basin average of $930 \text{ m}^3/\text{km}^2$. The results in Table 14 will need to be updated as more accurate hillslope gradient classifications are obtained. The separation of the influence of slope steepness and the bedrock type in the inner gorge showed that there are more landslides and more landslide volume per unit area in the Grogan Fault Zone rocks than in the other bedrock types. The Grogan Fault Zone bedrock is highly sheared and weakened. In addition, in all bedrock and slope gradient classifications in the inner gorge, landslides per unit area and landslide volume per unit area are much higher than the basin average.

Methods to Decrease the Number of Landslides in Highly Susceptible Areas

The inner gorge was the most susceptible area for landslides that deliver sediment to the Redwood Creek channel system. Timber harvest and presence of roads in the inner gorge were associated with a greater amount of sediment delivery per unit area than the other factors that were analyzed in this study, so a reduction of timber harvest in the inner gorge might lead to less sediment delivery into Redwood Creek and its tributaries. To determine whether such a change might be useful, I determined the amount of sediment delivery from landslides associated with logging in or immediately above the inner gorge.

This analysis was done on the private lands above Redwood National and State Parks lands because there is still active timber harvest occurring in that area. The Redwood National and State Parks lands have not had any active timber

harvesting since the late 1970's, nor have any new roads been built. The timber harvest units that were part of this analysis began in 1977. There was extensive logging in the upper and lower basin before 1977, so this analysis considers only a portion of the total sediment input.

There was a total of 90 landslides in the inner gorge area outside of Redwood National and State Parks lands. Of these, 19 landslides had a post-1977 timber harvest unit 0-200 m upslope of the top boundary of the inner gorge units, and 31 landslides had a post-1977 timber harvest unit directly in the inner gorge (Table 15). The category named 'NO HARVEST UNIT ASSOCIATED' in Table 15 includes bank lengths along which there was no harvest unit within 200 feet of the top of the inner gorge since 1977. In fact, all the areas included in Table 15 had been previously logged and some of the areas had post-1977 harvesting upslope of the 200-m band. The amount of sediment volume delivered to Redwood Creek and its tributaries per unit channel length was highest from landslides that had an associated timber harvest unit in the inner gorge.

The distance from the downslope boundary of the timber harvest units to the upper boundary of the inner gorge was measured along 240 km (both sides of the channel) of the upper Redwood Creek basin. The lengths of the timber-harvest-associated channel reaches and the non-timber-harvest-associated channel reaches were similar, 97 km and 143 km, respectively. For logging within the 200 m band upslope of the inner gorge boundary, there appeared to be a decrease in delivered landslide material as the distance increased between the top boundary of the inner gorge and the bottom

Table 15 Sediment input from 1997 landslides to the inner gorge of Redwood Creek upstream from Redwood National and State Parks lands.

POST-1977 TIMBER HARVEST LOCATION	NUMBER OF LANDSLIDES	VOLUME (m ³)	CHANNEL LENGTH (km)	VOLUME PER UNIT LENGTH (m ³ /km)
WITHIN INNER GORGE	31	67,000	29	2,300
WITHIN 200 METERS of the INNER GORGE	19	52,000	68	770
NO HARVEST UNIT WITHIN 200 METERS of the INNER GORGE	40	98,000	143	690

boundary of a timber harvest unit (Figure 7). Data suggest that logging within 100 m of the top of the inner gorge might be associated with a higher volume of sediment input, though this pattern would need to be examined in more detail to determine whether it is statistically significant.

Over three times more sediment per unit bank length was delivered to the inner gorge of Redwood Creek (upstream from Redwood National and State Parks lands) by landslides that were in harvest units inside the inner gorge than by inner gorge landslides that were not associated with timber units (Table 15).

To calculate the reduction of sediment that might have occurred if no units had been harvested in the inner gorge after 1977, I used the sediment delivered from the ‘inner gorge-no timber harvest’ classification from Table 15 ($690 \text{ m}^3/\text{km}$) and applied it to the 29 km of inner gorge with a timber harvest unit inside it:

$$29 \text{ km} \times 690 \text{ m}^3/\text{km} = 20,000 \text{ m}^3 \text{ of sediment.}$$

The amount of sediment delivered to the channel from landslides in reaches where a timber harvest unit was inside the inner gorge boundary was $67,000 \text{ m}^3$ and by recalculating, using $690 \text{ m}^3/\text{km}$, the sediment was reduced to $20,000 \text{ m}^3$. This is a reduction of sediment by $47,000 \text{ m}^3$ ($67,000 \text{ m}^3 - 20,000 \text{ m}^3 = 47,000 \text{ m}^3$) and a percent decrease in sediment of 70% (Calculation: $100 * ((20,000 \text{ m}^3 - 67,000 \text{ m}^3) / 67,000 \text{ m}^3) = -70\%$). Consequently, the estimated no-harvest landslide rate represented a decrease of 70% in sediment input from within these reaches of the inner gorge.

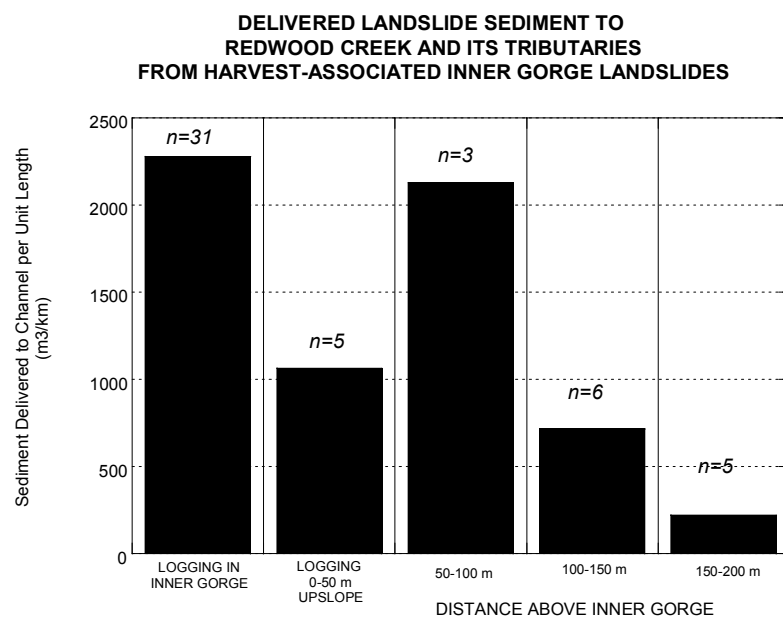


Figure 7 Delivered landslide sediment in upper Redwood Creek inner gorge.

If this reduction of sediment is compared to landslide input over the entire study area ($421,000 \text{ m}^3$), the overall reduction of delivered landslide material was 11% (Calculated as $421,000 \text{ m}^3 - 47,000 \text{ m}^3 = 374,000 \text{ m}^3$ or 11% sediment reduction overall). Above Redwood National Park the inner gorge comprises 3.5% of the land base. This means that the 11% reduction of sediment input is on a small area of land.

DISCUSSION AND CONCLUSIONS

The quantification of the sediment produced from the landslides in the Redwood Creek basin reported by this study depends upon the visibility of landslides on the 1:6,000 air photos. I checked my accuracy in mapping the landslides by using a post-storm road inventory completed by Redwood National and State Parks geologists in the Bridge Creek watershed. On the basis of this comparison between my air-photo mapped landslide measurements and the on-the-ground landslide measurements done by the Redwood National Park geologists in the Bridge Creek watershed, I estimate that the sediment input reported in this study is about 20% lower than the actual sediment that was delivered to the Redwood Creek basin.

The major portion of mobilized material from landslides comes from relatively few, but large, landslides. In this study 50% of the landslides accounted for about 84% of the volume of landslide-derived material. This result, showing the dominance of large landslides in sediment delivery to Redwood Creek, is similar to that of Kelsey et al (1995), who found that 50% of the landslides contribute 95% of the volume of landslide derived material.

Two of the questions that I originally posed are: How does the quantity of material from the landslides that occurred from the January 1997 storm compare to the sediment production from the 1964 storm and flood? and How much does the sediment from the 1997 landslides that is contributed to Redwood Creek and its tributaries

contribute to the suspended sediment load of Redwood Creek at the Orick gage in Water Year 1997?

The amount of landslide-derived sediment reported in this study is less than the estimated sediment from the 1964 storm in the Redwood Creek basin. The total sediment delivered to Redwood Creek and its tributaries from the 1997 storm was about 421,000 m³ and the 1964 sediment from both the Pitlick (1995) and the Kelsey et al (1995) studies is about 4 million cubic meters. The 1997 storm contributed only 6% of the sediment volume into the mainstem of Redwood Creek as the 1964 storm and up to 48% of the 1964 volume into a subset of 16 tributaries measured by Pitlick (1995).

The suspended sediment load of Redwood Creek at the Orick gage in water year 1997 was 1,970 Mg/km². The amount of sediment from landslides that was contributed to Redwood Creek and its tributaries is up to 56% of the total suspended sediment that was measured at the Orick gage from October 1996 to April, 1997, which supports the contention that landslides are a major sediment source in this watershed.

It would be helpful to understand in which settings the landslides from the 1997 storm occurred and to see if any factors stand out as producing a higher risk of landslide occurrence. This goal led to identification of the next question: What do the patterns of landslide distribution in the Redwood Creek basin suggest are the most important risk factors in the initiation of the landslides?

The most important risk factors in the initiation of landslides in the Redwood Creek basin during the 1997 storm were the inner gorge, the Grogan Fault Zone bedrock type, hillslope gradient greater than 50%, and areas within 30 m of a road. This

conclusion was based on the number of landslides per square kilometer, and more importantly, the amount of sediment produced by these landslides per square kilometer.

During the 1997 storm, the Redwood Creek basin had an average of 0.41 landslides/km², which represented an average of 680 m³ of delivered landslide material per square kilometer. Both the inner gorge and headwall swale hillslope positions exceeded the basin average sediment contribution to the Redwood Creek watershed. The Grogan Fault Zone bedrock type exceeded the basin average sediment contribution by 10 times, as did the inner gorge hillslope position, and these factors appeared to be the most important influences on sediment contribution from landslides to Redwood Creek and its tributaries. When the Grogan Fault Zone bedrock type is associated with the inner gorge and with slopes having gradients of greater than 65%, the total landslide volume per unit area is 100 times greater than the overall basin average of 930 m³/km². As discussed in the 'Methods' section, the GIS-generated hillslope gradient classification that was used to determine areas of different slope classes showed results that differed from the broader inner gorge classification because of scale issues. When the hillslope gradient coverage accuracy improves, this part of the analysis will need to be re-examined.

This study showed that inner-gorge landslides were a major contributor of sediment to Redwood Creek and its tributaries. Would the amount of sediment delivered to the Redwood Creek basin have been less if there had been no timber harvest in the landslide-susceptible inner gorge?

This study showed that inner-gorge landslides along channel reaches with timber harvest units that are inside the inner gorge contributed at least three times more

landslide-derived sediment per unit channel length than inner-gorge landslides along channel reaches where a timber harvest unit is 1 to 200 m above the inner gorge.

Results of the study suggest that sediment delivery from the inner gorge to Redwood Creek and its tributaries could have been reduced by 70% if there had been no timber harvests inside the inner gorge. By keeping timber harvest outside the inner gorge, there could have been an overall reduction of landslide-derived sediment equal to about 11% across the study area.

REFERENCES

- Abe, K., and Ziemer, R.R., 1991. Effect of tree roots on shallow-seated landslides. USDA Forest Service General Technical Report PSQ-GTR-130, p 11-20.
- Baeza, C., and Corominas, J., 2001. Assessment of shallow landslide susceptibility by means of multivariate statistical techniques. *Earth Surface Processes and Landforms* 26:1251-1263.
- Best, D.W., 1984. Land use of the Redwood Creek basin. Redwood National Park Research and Development Technical Report #9. National Park Service, Redwood National Park, Arcata, California.
- Best, D.W., 1995. History of timber harvest in the Redwood Creek basin, northwestern California. *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, northwestern California*, US Geological Survey Professional Paper 1454-C.
- Bloom, A. L., 1998. An assessment of road removal and erosion control treatment effectiveness: a comparison of 1997 storm erosion response between treated and untreated roads in Redwood Creek basin, northwestern California. Master's Thesis. Department of Geology, Humboldt State University, Arcata, California.
- Brardinoni, F., Slaymaker, O., and Hassan, M.A., 2002. Landslide inventory in a rugged forested watershed: A comparison between air-photo and field survey data. *Geomorphology* 54:179-196.
- Bundros, G., and Andras, K., 2001. Redwood Creek's inner gorge. ArcInfo coverage G15, Redwood National and State Parks, Arcata, CA.
- Bundros, G., 2004. Land ownership chart for the Redwood Creek drainage, northwestern California. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.
- Cafferata, P.E., and Spittler, T.E., 1998. Logging impacts of the 1970's vs. the 1990's in the Caspar Creek watershed. US Forest Service General Technical Report PSW-GTR-168.
- Caine, N., 1980. The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annaler* 62(1-2):23-27.
- California Department of Water Resources, 2005. Department of Flood Management; daily and hourly rainfall and river stage data for the Orick, O'Kane, and Kneeland rainfall and stream flow gages. <http://cdec.water.ca.gov>.

- Cashman, S.M., Kelsey, H.M., and Harden, D. R., 1995. Geology of the Redwood Creek basin, Humboldt County, California. *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, northwestern California*, US Geological Survey Professional Paper 1454-B.
- Chen, H., Harmon, M.E., and Griffiths, R.P., 2001. Decomposition and nitrogen release from decomposing woody root in coniferous forests of the Pacific Northwest: a chronosequence approach. *Canadian Journal of Forestry Resources* 31:246-260.
- Colman, S.M., 1973. The history of mass movement processes in the Redwood Creek Basin, Humboldt County, California. Paper presented in lieu of Master's thesis. Pennsylvania State University, Department of Geosciences, University Park, Pennsylvania.
- Crozier, M.J., 1999. Prediction of rainfall-triggered landslides: a test of the antecedent water status model. *Earth Surface Processes and Landforms* 24:825-833.
- de la Fuente, J., and Elder, D., 1998. The flood of 1997 Klamath National Forest, United States Forest Service Phase I Final Report: November 24, 1998. In-house report, Klamath National Forest, Yreka, California.
- Dhakal, A.S., and Sidle, R.C., 2002. Long-term modeling of landslides for different forest management practices. *Earth Surface Processes and Landforms* 28:853-868.
- Dietrich, W. E., Reiss, R., Hsu, M., and Montgomery, D., 1995. A process-based model for colluvial soil depth and shallow landsliding using digital elevation data. *Hydrological Processes* 9:383-400.
- Dunne, T., and Leopold, L.B., 1998. *Water in environmental planning*. W.H., Freeman and Company, New York, New York, 818 p.
- Guthrie, R.H., and Evans, S.G., 2004. Analysis of landslide frequencies and characteristics in a natural system, coastal British Columbia. *Earth Surface Processes and Landforms* 29:1321-1339.
- Harden, D.R., 1995. A comparison of flood-producing storms and their impacts in Northwestern California. *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, northwestern California*, US Geological Survey Professional Paper 1454-D.

- Harden, D.R., Kelsey, H.M., Morrison, S.D., and Stephens, T.A., 1982. Geologic map of the Redwood Creek drainage basin, Humboldt County, California. US Geological Survey Open-File Report 81-496, scale 1:62,500.
- Hare, V.C., 2003. Evaluation of a geographic information system model of shallow landsliding in Redwood Creek, California. Master's Thesis, Humboldt State University, Arcata, California.
- Iwatsubo, R.T., Nolan, K.M., Harden, D.R., Glysson, G.D., and Janda, R.J., 1975. Redwood National Park Studies, Data Release Number 2, Redwood Creek, Humboldt County, California, April 11, 1974 to September 30, 1975. US Department of the Interior, Geological Survey, Menlo Park, California.
- Jakob, M., 2000. The impacts of logging on landslide activity at Clayquot Sound, British Columbia. *Catena* 38:279-300.
- Kelsey, H.M., 1988. Formation of inner gorges. *Catena* 15:433-458.
- Kelsey, H.M., Coghlan, M., Pitlick, J., and Best, D., 1995. Geomorphic analysis of streamside landslides in the Redwood Creek Basin, Northern California. Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, northwestern California, US Geological Survey Professional Paper 1454-J.
- Knighton, D., 1998. Fluvial forms and processes. John Wiley, New York, New York, 383 p.
- LaHusen, R.G., 1984. Characteristics of management-related debris flows, Northwestern California. Symposium on the Effects of Forest Land Use on Erosion and Slope Stability, Environment and Policy Institute, East-West Center, May 7-11, 1984, University of Hawaii, Honolulu, HI.
- Laird, J.R., 2001. The current state of engineering geology, slope stability, and harvest unit plans. Paper from The International Mountain Logging and 11th Pacific Northwest Skyline Symposium, Seattle, Washington.
- Lee, P., Smyth, C., and Boutin, S., 2003. Quantitative review of riparian buffer width guidelines from Canada and the United States. *Journal of Environmental Management* 70:165-180.
- Madej, M. A. 2001. Erosion and sediment delivery following removal of forest roads. *Earth Surface Processes and Landforms* 26(2):175-190.
- Madej, M.A. 1999. Temporal and spatial variability in thalweg profiles of a gravel bed river. *Earth Surface Processes and Landforms* 24:1153-1169.

- Madej, M.A., and Ozaki, V., 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surface Processes and Landforms* 21:911-927.
- Meyer, G.A., Pierce, J.L., Wood, S.H., and Jull, A.J.T., 2001. Fire, storms, and erosional events in the Idaho batholith. *Hydrological Processes* 15(15):3025-3038.
- Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., and Dietrich, W.E., 2000. Forest clearing and regional landsliding. *Geology* 28(4):311-314.
- Pitlick, J., 1995. Sediment routing in tributaries of the Redwood Creek basin, Northwestern California. *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, northwestern California*, US Geological Survey Professional Paper 1454-K.
- Redwood National and State Parks, 1997. Redwood National and State Parks storm damage road inventory update data sheets. Redwood National and State Parks, Orick, California.
- Redwood National and State Parks, 1997. In-house records for rainfall, peak discharges, return intervals for rainfall and peak discharges, and antecedent precipitation index. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.
- Redwood National and State Parks, 1998. Redwood Creek subbasin GIS coverage HOME/DATA3/COVER/WSHD/W02/RW0W02S6. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.
- Redwood National and State Parks, 2001. Redwood Creek drainage roads data. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.
- Redwood National and State Parks, 2003. Peak flow chart at the Orick, California gage. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.
- Redwood National and State Parks, 2005. Suspended sediment yield data. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.
- Redwood National and State Parks, 2006. Location map for Redwood National and State Parks. Redwood National and State Parks, 1655 Heindon Road, Arcata, California, 95521.

- Robison, E.G., Mills, K., Paul, J.T., and Dent, L., 1999. Landslides and channel impacts associated with extreme storm events in Oregon in 1996: The Oregon Department of Forestry Study. Wildland Hydrology, American Water Resources Association, June/July 1999.
- Siuslaw National Forest, 1996. Assessment of the Effects of the 1996 Flood on the Siuslaw National Forest. U.S. Department of Agriculture, Siuslaw National Forest, Corvallis, Oregon.
- Tang, S.M., and Montgomery, D.R., 1995. Riparian buffers and potentially unstable ground. *Environmental Management* 19(5):741-749.
- United States Environmental Protection Agency, 1998. Total maximum daily load for sediment, Redwood Creek, California. United States Environmental Protection Agency, Region 9, San Francisco, California.
<http://www.epa.gov/region09/water/tmdl/rwctmdl.pdf>.
- Urner, S. and M.A. Madej, 1998. Changes in riparian composition and density following timber harvest and floods along Redwood Creek, California. Abstract from the annual meeting of the Society for Ecological Restoration, Northwest Chapter, Tacoma Washington.
- Ziemer, R. R., 1984. Response of progressive hillslope deformation to precipitation. Symposium on the Effects of Forest Land Use on Erosion and Slope Stability, Environment and Policy Institute, East-West Center, May 7-11, 1984, University of Hawaii, Honolulu, HI.

PERSONAL COMMUNICATIONS

Klein, R., 2000. Hydrologist, Redwood National Park, 1655 Heindon Road, Arcata, California, 95521.

Nicolini, T., 2006. National Weather Service, Eureka Weather Forecast Office, 300 Startare Drive, Eureka, CA 95501.

Nordquist, P. 2000, National Weather Service, Eureka Weather Forecast Office, 300 Startare Drive, Eureka, CA 95501.

APPENDIX A

DATA SHEETS FOR 1997 LANDSLIDES

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ay-2	467	Ayers	524	3	0	131	1	2	1	3	1	2
ay-3	519	Ayers	591	3	0	148	1	2	2	3	1	4
ay-4	501	Ayers	568	2	142	426	2	2	2	3	2	2
bc-1	593	Bridge	689	2	172	517	1	1	1	1	2	2
bc-10	1,146	Bridge	1,467	1	1,100	1,467	1	1	2	1	2	4
bc-12	2,394	Bridge	3,417	3	0	854	2	1	2	3	1	2
bc-14	1,149	Bridge	1,472	1	1,104	1,472	2	1	1	4	2	4
bc-16	806	Bridge	979	1	734	979	1	1	2	4	2	4
bc-18	608	Bridge	709	2	177	532	2	1	1	4	1	2
bc-19	795	Bridge	965	3	0	241	2	1	1	2	1	2
bc-2	2,013	Bridge	2,800	1	2,100	2,800	2	1	2	3	1	2
bc-20	3,794	Bridge	4,553	1	3,415	4,553	2	1	2	4	2	4
bc-21	1,074	Bridge	1,362	1	1,022	1,362	2	1	2	4	2	4
bc-22	435	Bridge	483	1	362	483	2	1	2	4	2	3
bc-23	466	Bridge	522	3	0	130	2	1	1	3	2	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
bc-25	9,030	Bridge	10,836	1	8,127	10,836	2	1	1	4	1	2
bc-26	1,834	Bridge	2,517	3	0	629	2	1	1	5	1	3
bc-27	4,737	Bridge	5,684	1	4,263	5,684	2	1	1	2	1	3
bc-28	3,228	Bridge	3,873	3	0	968	2	1	1	1	1	2
bc-29	547	Bridge	628	3	0	157	2	1	1	5	1	3
bc-3	443	Bridge	492	1	369	492	1	1	2	3	2	4
bc-31	469	Bridge	526	3	0	131	2	1	1	1	1	4
bc-34	550	Bridge	631	3	0	158	2	1	2	1	1	2
bc-36	539	Bridge	618	3	0	154	2	1	1	1	1	2
bc-37	776	Bridge	937	3	0	234	2	1	2	3	1	1
bc-38	2,959	Bridge	4,357	1	3,268	4,357	2	1	1	1	2	2
bc-39	1,817	Bridge	2,490	1	1,868	2,490	2	1	1	1	1	2
bc-41	4,672	Bridge	5,606	1	4,204	5,606	2	1	2	4	2	3
bc-42	1,045	Bridge	1,319	3	0	330	2	1	2	2	1	2
bc-6	1,078	Bridge	1,368	2	342	1,026	2	1	1	3	2	2

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
bc-9	1,629	Bridge	2,197	1	1,648	2,197	2	1	1	1	2	1
bn-1	1,758	Bond	2,398	3	0	599	2	1	1	1	1	2
bn-2	1,172	Bond	1,506	3	0	376	1	1	1	2	1	2
bn-5	1,471	Bond	1,954	1	1,466	1,954	2	1	1	1	2	2
br-1	7,359	Bradford	12,394	1	9,295	12,394	1	3	2	4	1	4
br-11	1,305	Bradford	1,703	1	1,277	1,703	2	4	2	3	1	3
br-2	2,072	Bradford	2,895	1	2,171	2,895	1	3	1	4	2	3
br-3	1,131	Bradford	1,445	1	1,084	1,445	1	3	2	4	1	4
cg-1	516	Cashmere/ Garcia	588	1	441	588	1	1	2	3	1	3
cg-2	556	Cashmere/ Garcia	639	1	479	639	2	1	2	3	1	3
cg-3	1,568	Cashmere/ Garcia	2,102	1	1,576	2,102	1	1	1	3	1	3
cg-4	1,040	Cashmere/ Garcia	1,313	1	985	1,313	2	1	1	3	1	2

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
cg-5	577	Cashmere/Garcia	668	1	501	668	1	1	2	3	1	2
cg-6	670	Cashmere/Garcia	792	1	594	792	2	1	2	3	2	3
cg-7	431	Cashmere/Garcia	478	1	359	478	2	1	2	3	2	2
cg-8	557	Cashmere/Garcia	641	1	481	641	1	1	2	3	2	4
cg-9	488	Cashmere/Garcia	551	1	413	551	1	1	2	3	1	3
cy-1	471	Coyote	529	1	397	529	1	3	3	4	1	3
cy-10	715	Coyote	853	2	213	640	1	4	1	5	1	1
cy-2	2,934	Coyote	4,314	1	3,236	4,314	2	4	3	3	1	4
cy-3	1,032	Coyote	1,300	3	0	325	1	4	1	2	1	2
cy-8	475	Coyote	535	1	401	535	1	4	2	2	2	3
dc-1	4,540	Devil's	5,449	1	4,086	5,449	2	1	1	2	1	2
dc-2	917	Devil's	1,136	2	284	852	2	1	2	3	1	2

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
dc-6	1,745	Devil's	2,377	3	0	594	2	1	1	3	1	3
dc-7	713	Devil's	851	3	0	213	2	1	2	3	1	3
em-3	1,637	Elam	2,208	1	1,656	2,208	2	1	2	3	1	1
em-4	652	Elam	768	1	576	768	2	1	2	3	1	1
ff-1	769	Forty Four	928	1	696	928	2	1	1	1	1	2
ff-2	1,679	Forty Four	2,274	1	1,705	2,274	2	1	1	3	1	2
ff-3	650	Forty Four	766	1	574	766	2	1	1	3	1	3
ff-4	541	Forty Four	620	1	465	620	2	1	1	2	2	3
ff-5	411	Forty Four	452	1	339	452	1	1	1	2	2	4
ff-6	497	Forty Four	563	1	422	563	2	1	1	2	2	3
ff-7	628	Forty Four	735	1	552	735	2	1	1	2	1	4

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ga-2	822	Garrett	1,003	1	752	1,003	1	4	1	4	2	2
hp-1	776	High Prairie	938	2	235	704	1	2	1	4	1	3
jc-pc-2	469	Panther	526	3	0	132	1	1	2	2	1	3
jc-pc-3	806	Panther	979	3	0	245	2	1	2	2	1	3
jp-1	9,396	Joplin	11,275	1	8,456	11,275	2	1	1	2	1	2
jp-2	487	Joplin	549	3	0	137	2	1	1	2	3	2
jp-3	3,766	Joplin	4,519	2	1,130	3,389	2	1	1	3	1	2
kr-1	6,337	Karen	7,604	1	5,703	7,604	2	1	1	4	1	1
kr-2	1,149	Karen	1,472	1	1,104	1,472	1	1	1	3	2	3
lc-1	3,629	Lacks	4,355	3	0	1,089	2	4	3	3	1	2
lc-16	519	Lacks	591	1	443	591	5	3	2	4	2	4
lc-21	5,702	Lacks	6,843	1	5,132	6,843	2	3	1	4	2	4
lc-29	1,115	Lacks	1,422	1	1,066	1,422	1	3	3	4	2	4

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
lc-31	727	Lacks	870	2	218	653	2	3	3	4	1	4
lc-32	1,632	Lacks	2,201	1	1,651	2,201	1	3	1	3	2	2
lc-33	675	Lacks	799	1	600	799	1	3	2	3	2	2
lc-4	2,893	Lacks	4,245	1	3,184	4,245	1	4	1	4	2	4
lc-6	1,330	Lacks	1,741	3	0	435	1	4	1	4	2	3
lc-7	1,394	Lacks	1,837	1	1,378	1,837	2	4	3	4	2	4
lc-8	1,594	Lacks	2,143	1	1,607	2,143	2	4	3	4	2	3
lc-9	4,494	Lacks	5,392	1	4,044	5,392	2	4	3	4	2	3
le-1	8,893	Lee	10,671	1	8,003	10,671	2	1	1	3	1	3
le-4	929	Lee	1,154	1	865	1,154	1	1	2	3	2	2
le-5	697	Lee	830	1	622	830	1	1	2	3	2	2
ln-1	1,826	Loin	2,503	1	1,878	2,503	1	1	1	2	2	3
ln-3	1,103	Loin	1,404	1	1,053	1,404	2	1	1	1	1	2
lp-1	4,771	Lake Prairie	7,539	1	5,654	7,539	1	1	1	1	2	2

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
lp-3	550	Lake Prairie	632	3	0	158	1	1	1	2	1	3
lp-4	826	Lake Prairie	1,007	3	0	252	1	2	2	4	2	2
lp-5	1,252	Lake Prairie	1,624	2	406	1,218	2	2	2	4	2	2
lp-9	2,533	Lake Prairie	3,645	1	2,734	3,645	1	2	2	4	2	2
lu-1	520	Lupton	592	1	444	592	1	1	1	4	2	2
lu-2	972	Lupton	1,215	1	911	1,215	1	1	1	4	2	2
ma-1	2,422	McArthur	3,463	1	2,597	3,463	2	1	1	5	1	2
ma-2	956	McArthur	1,191	1	893	1,191	2	1	1	5	1	2
ma-3	3,356	McArthur	4,028	1	3,021	4,028	2	1	2	1	1	2
ma-4	1,412	McArthur	1,865	2	466	1,398	2	1	1	2	3	2
ma-5	8,746	McArthur	10,495	1	7,871	10,495	2	1	2	2	1	2
ma-6	5,513	McArthur	6,616	1	4,962	6,616	2	1	1	5	1	2
ml-1	2,595	Miller	3,748	1	2,811	3,748	2	2	2	1	2	2

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ml-4	1,347	Miller	1,765	3	0	441	1	2	2	2	2	2
ml-5	6,038	Miller	7,246	1	5,434	7,246	2	4	1	1	2	2
ml-6	1,495	Miller	1,990	1	1,493	1,990	2	4	1	1	1	2
mr-1	6,843	Minor	8,212	1	6,159	8,212	2	3	1	1	1	3
ms-1	672	Redwood	796	1	597	796	1	2	2	3	1	2
ms-100	1,532	Redwood	2,047	1	1,535	2,047	2	1	2	4	1	3
ms-101	607	Redwood	707	3	0	177	1	2	2	4	1	4
ms-102	1,551	Redwood	2,077	1	1,557	2,077	2	1	2	4	1	3
ms-104	1,568	Redwood	2,102	1	1,577	2,102	5	4	1	4	2	4
ms-105	2,527	Redwood	3,636	1	2,727	3,636	1	2	1	4	1	4
ms-106	1,504	Redwood	2,004	1	1,503	2,004	1	4	2	3	2	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-107	588	Redwood	683	1	512	683	1	2	2	4	2	3
ms-108	1,659	Redwood	2,243	1	1,683	2,243	1	4	1	3	2	3
ms-109	4,285	Redwood	6,664	3	0	1,666	1	2	2	4	1	3
ms-110	1,013	Redwood	1,274	1	955	1,274	5	4	1	4	2	3
ms-113	1,004	Redwood	1,260	3	0	315	1	2	1	3	1	3
ms-116	508	Redwood	577	1	433	577	2	4	1	4	2	3
ms-117	776	Redwood	938	1	704	938	5	2	1	3	1	3
ms-118	607	Redwood	707	1	531	707	1	2	1	3	2	3
ms-119	892	Redwood	1,101	1	826	1,101	5	2	1	3	1	3
ms-12	1,753	Redwood	2,389	1	1,792	2,389	1	2	1	4	1	4

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-120	2,414	Redwood	3,449	1	2,587	3,449	1	1	1	3	2	3
ms-121	828	Redwood	1,010	1	758	1,010	1	1	1	3	1	3
ms-123	2,013	Redwood	2,800	1	2,100	2,800	2	2	2	4	1	3
ms-124-	478	Redwood	538	3	0	135	2	1	1	3	2	3
ms-125	1,722	Redwood	2,342	1	1,756	2,342	1	2	2	4	2	3
ms-127	794	Redwood	963	1	722	963	1	2	2	4	2	3
ms-13	692	Redwood	823	1	617	823	1	2	2	4	2	4
ms-131	3,642	Redwood	4,370	1	3,277	4,370	2	1	2	3	1	3
ms-135	1,331	Redwood	1,742	2	435	1,306	2	1	1	3	1	4
ms-139	957	Redwood	1,194	1	895	1,194	2	1	2	3	2	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-14	1,974	Redwood	2,738	1	2,053	2,738	1	2	1	4	2	4
ms-141	1,884	Redwood	2,595	1	1,946	2,595	2	1	2	3	1	3
ms-143	561	Redwood	647	1	485	647	2	1	2	3	1	3
ms-145	3,791	Redwood	4,550	1	3,412	4,550	2	1	1	3	1	3
ms-152	829	Redwood	1,012	1	759	1,012	1	1	2	3	2	3
ms-155	608	Redwood	709	1	532	709	2	1	2	3	1	3
ms-157	1,297	Redwood	1,691	1	1,268	1,691	2	1	2	3	1	3
ms-159	2,270	Redwood	3,214	1	2,410	3,214	2	1	2	3	1	3
ms-169	2,305	Redwood	3,271	1	2,453	3,271	2	1	1	3	1	3
ms-171	2,415	Redwood	3,452	2	863	2,589	1	2	1	4	2	4

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-173	552	Redwood	635	3	0	159	1	2	2	3	1	3
ms-176	1,780	Redwood	2,432	3	0	608	2	4	2	3	1	3
ms-18	4,082	Redwood	6,303	1	4,727	6,303	1	2	2	4	2	2
ms-19	1,128	Redwood	1,441	1	1,081	1,441	1	2	2	4	2	3
ms-2	865	Redwood	1,062	1	797	1,062	5	2	2	4	1	1
ms-20	3,931	Redwood	4,717	1	3,538	4,717	2	2	1	4	1	2
ms-21	1,363	Redwood	1,791	1	1,343	1,791	1	2	1	4	2	4
ms-23	2,483	Redwood	3,563	1	2,672	3,563	2	2	2	4	1	3
ms-28	628	Redwood	736	2	184	552	1	2	1	4	2	3
ms-29	1,491	Redwood	1,984	1	1,488	1,984	1	2	1	4	1	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-3	672	Redwood	795	1	596	795	2	2	2	4	1	2
ms-30	854	Redwood	1,047	1	785	1,047	1	2	1	4	1	4
ms-31	506	Redwood	575	1	431	575	1	2	2	4	1	4
ms-32	1,126	Redwood	1,438	1	1,078	1,438	1	2	1	4	1	4
ms-34	850	Redwood	1,041	3	0	260	1	2	1	4	1	3
ms-35	4,325	Redwood	6,735	3	0	1,684	1	2	1	3	2	4
ms-37	858	Redwood	1,053	2	263	790	2	2	1	4	2	4
ms-38	1,258	Redwood	1,632	1	1,224	1,632	1	2	2	4	1	3
ms-39	613	Redwood	716	2	179	537	2	2	1	4	1	4
ms-4	949	Redwood	1,181	1	886	1,181	1	2	2	4	2	4

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-40	902	Redwood	1,115	1	836	1,115	1	2	2	4	1	4
ms-41	836	Redwood	1,022	1	766	1,022	2	2	1	4	1	4
ms-42	5,631	Redwood	9,118	1	6,838	9,118	1	2	2	4	1	3
ms-45	3,679	Redwood	5,594	1	4,195	5,594	1	2	2	4	1	3
ms-46	899	Redwood	1,110	1	833	1,110	5	2	1	4	1	3
ms-47	672	Redwood	795	1	596	795	1	2	2	4	2	4
ms-48	646	Redwood	760	1	570	760	5	2	2	3	1	4
ms-49	575	Redwood	665	1	498	665	5	2	2	4	2	4
ms-5	608	Redwood	708	1	531	708	5	2	2	4	1	1
ms-50	3,383	Redwood	5,081	3	0	1,270	1	2	1	4	1	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-51	1,271	Redwood	1,653	1	1,240	1,653	1	2	2	4	2	2
ms-52	2,502	Redwood	3,593	3	0	898	1	2	1	4	1	3
ms-53	1,015	Redwood	1,277	1	957	1,277	1	2	2	4	2	3
ms-54	1,421	Redwood	1,878	1	1,408	1,878	5	2	2	3	1	3
ms-55	3,898	Redwood	5,977	1	4,483	5,977	1	2	1	4	1	4
ms-56	687	Redwood	816	1	612	816	1	2	1	4	1	4
ms-57	1,658	Redwood	2,242	1	1,681	2,242	1	2	1	4	2	4
ms-58	3,630	Redwood	5,508	1	4,131	5,508	1	2	2	3	1	4
ms-59	1,447	Redwood	1,918	1	1,438	1,918	2	2	2	4	2	3
ms-60	1,310	Redwood	1,710	1	1,283	1,710	1	2	1	4	1	4

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-61	5,752	Redwood	9,341	1	7,006	9,341	1	2	2	4	1	4
ms-62	1,394	Redwood	1,837	1	1,378	1,837	1	2	2	3	1	4
ms-63	711	Redwood	848	1	636	848	1	2	1	4	1	4
ms-64	952	Redwood	1,185	1	889	1,185	1	2	2	3	2	2
ms-65	745	Redwood	895	1	671	895	2	2	2	4	1	4
ms-67	581	Redwood	675	2	169	500	2	2	1	4	1	4
ms-69	433	Redwood	480	2	120	360	2	2	1	4	1	4
ms-70	1,989	Redwood	2,762	1	2,071	2,762	5	1	2	4	1	4
ms-72	2,134	Redwood	2,994	2	749	2,246	2	1	1	4	1	2
ms-74	501	Redwood	568	1	426	568	5	2	1	3	1	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-8	2,650	Redwood	3,839	1	2,879	3,839	1	2	1	4	3	4
ms-80	431	Redwood	478	1	358	478	1	2	2	3	1	3
ms-81	1,092	Redwood	1,388	1	1,041	1,388	1	2	1	3	1	4
ms-82	1,221	Redwood	1,577	1	1,183	1,577	1	1	1	4	1	3
ms-83	5,313	Redwood	6,375	3	0	1,594	2	2	1	4	1	3
ms-84	1,627	Redwood	2,193	1	1,644	2,193	1	1	2	4	1	2
ms-86	1,526	Redwood	2,038	1	1,528	2,038	1	1	2	4	1	2
ms-87	974	Redwood	1,217	1	913	1,217	1	2	1	4	1	2
ms-88	2,202	Redwood	3,104	1	2,328	3,104	2	1	2	4	2	4
ms-9	634	Redwood	744	1	558	744	1	2	2	4	2	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
ms-90	2,518	Redwood	3,620	1	2,715	3,620	2	1	2	4	1	4
ms-91	507	Redwood	575	1	431	575	1	2	2	4	1	4
ms-92	433	Redwood	480	1	360	480	1	1	2	4	1	3
ms-93	1,586	Redwood	2,130	3	0	533	1	2	1	4	1	3
ms-94	767	Redwood	925	1	694	925	1	1	1	4	1	4
ms-95	1,149	Redwood	1,472	1	1,104	1,472	1	2	2	4	1	2
ms-96	696	Redwood	827	1	620	827	1	1	2	4	2	3
ms-97	4,574	Redwood	5,489	1	4,117	5,489	2	2	2	4	1	2
ms-98	1,413	Redwood	1,866	1	1,399	1,866	2	1	1	4	1	2
ms-99	2,069	Redwood	2,889	3	0	722	1	2	1	4	1	2

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
pc-1	2,000	Pilchuck	2,780	1	2,085	2,780	1	1	1	4	1	3
pn-1	7,672	Panther	9,207	1	6,905	9,207	1	1	1	1	1	1
pn-10	2,998	Panther	4,422	1	3,317	4,422	2	1	1	2	1	3
pn-13	860	Panther	1,055	1	791	1,055	2	1	2	4	1	3
pn-2	1,318	Panther	1,722	3	0	430	1	1	1	1	1	2
pn-3	433	Panther	480	1	360	480	2	1	1	2	1	2
pn-4	699	Panther	832	1	624	832	1	1	1	2	1	2
pn-6	1,157	Panther	1,483	2	371	1,112	2	1	1	2	1	2
pn-7	2,686	Panther	3,899	2	975	2,924	2	1	1	2	1	2
pn-8	420	Panther	463	3	0	116	1	1	1	2	1	2
pn-9	439	Panther	488	3	0	122	1	1	1	2	2	3
sh-1	2,040	Smoke-house	2,843	1	2,132	2,843	1	1	2	4	1	3
sh-11	2,648	Smoke-house	3,836	1	2,877	3,836	1	2	1	4	1	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
sh-12	472	Smoke-house	530	3	0	133	1	1	2	3	1	3
sh-13	1,133	Smoke-house	1,448	3	0	362	1	1	2	3	1	2
sh-14	921	Smoke-house	1,142	1	856	1,142	1	2	1	4	2	4
sh-2	489	Smoke-house	552	1	414	552	1	2	1	4	2	2
sh-3	442	Smoke-house	492	1	369	492	1	2	1	4	2	3
sh-4	637	Smoke-house	748	1	561	748	1	1	1	4	2	2
sh-5	1,053	Smoke-house	1,332	1	999	1,332	1	2	1	2	1	3
sq-2	1,745	Squirrel-tail	2,377	1	1,783	2,377	2	3	1	4	1	3
tm-10	505	Tom Mcdonald	572	3	0	143	2	1	2	2	2	3

Slide ID	Hillslope Area (m ²)	Subbasin	Volume (m ³)	Sediment Delivery	Lower Vol Del (m ³)	Upper Vol. Del. (m ³)	Type	Bedrock	Hillslope Form	Hillslope Position	Road Association	Slope Gradient
tm-11	2,432	Tom Mcdonald	3,479	2	870	2,609	2	1	2	2	1	2
tm-7	500	Tom Mcdonald	566	1	425	566	2	1	1	2	1	2
tm-9	1,070	Tom Mcdonald	1,355	1	1,016	1,355	2	1	2	2	1	2
up-1	445	Upper Panther	495	1	372	495	1	4	1	4	2	4
up-3	763	Upper Panther	920	1	690	920	1	4	2	3	1	3
wn-1	2,549	Windy	3,672	3	0	918	1	4	2	4	1	4
wn-2	1,002	Windy	1,257	1	943	1,257	1	4	2	4	1	2

Definition Of Terms Used In Landslide Classification

TYPE	BEDROCK	% SEDIMENT DELIVERED
1= shallow debris slide	1=KJfr schist Redwood Creek	1= 75-100%
2= debris flow/torrent	2=KJfg sandstone/mudstone Grogan Fault Zone	2= 25-75%
5= bank failure	3=KJfl sandstone/mudstone-coherent Lack's Creek unit	3= 0-25%
	4=KJfc sandstone/mudstone- incoherent Coyote Creek unit	
SLOPE FORM	SLOPE GRADIENT	HILLSLOPE POSITION
1= concave	1 = 0 - 30 %	1= upper
2= planar	2 = 31 - 50%	2= middle
3= convex	3 = 51 - 65%	3= lower
	4 = >65%	4= inner gorge
		ROAD PRESENT AT INITIATION
		1= Yes
		2=No
		3=Don't know

APPENDIX B
RAINFALL DATA

NAME	BASIN	Total Rainfall (in)	1-hr Intensity (RI*)	6-hr Intensity (RI*)	24-hr Intensity (RI*)
Orick	Redwood Creek	8.52	0.60 (<2)	2.00 (<2)	5.44 (<2)
Lost Man Creek	Redwood Creek	10.41	0.52 (<2)	2.14 (<2)	6.48 (7)
Elk Camp	Redwood Creek	14.28	0.50 (<2)	2.45 (<2)	7.61 (7)
Lacks Creek	Redwood Creek	10.90	0.44 (<2)	1.89 (<2)	6.00 (2)
O'Kane (Blue Lake)	Redwood Creek	6.40	0.40 (<2)	1.70 (<2)	4.50 (8)
Dr. Fine Bridge	Smith River	6.16	0.48 (<2)	1.60 (<2)	2.28 (4)
Hoopa	Trinity River	8.00	0.36 (<2)	1.44 (<2)	4.00 (<2)
Orleans	Klamath River	9.56	0.56 (<2)	2.18 (<2)	5.70 (12)

*Return Intervals (RI's) were calculated by the staff of Redwood National and State Parks, 1997.

APPENDIX C

REGRESSION GRAPH

1980 Landslide Area vs. Volume Regression

