SEDIMENT BUDGET FOR THE GROUSE CREEK BASIN, HUMBOLDT COUNTY, CALIFORNIA

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ABSTRACT

A sediment budget constructed for the Grouse Creek basin in northern California provides information on the sources and timing of sediment production to aid land managers in understanding the effects of logging impacts in a sensitive watershed. The sediment budget yields a sediment production rate of 1,750 t/km^2/yr for a 29-year period. This rate is among the highest for such disturbed forested basins in the Pacific Northwest. Approximately 40 percent of the Grouse Creek basin, which is bisected by regional structural features that have created zones of weak and altered rock, has been logged in the last 35 years.

Sediment production is dominated by mass wasting and is concentrated in areas of geologic instability and logging and during major storms. Over 86 percent of all sediment was produced by landsliding, with 71 percent of landslide volumes generated during a six-year period that includes the flood of December 1964. Ninety-three percent of all sediment volumes were generated during the 15-year period from 1960 to 1975 that included four major storm events, the completion of 74 percent of basin logging activity and 80 percent of road building. Landsliding in old growth was found to be spatially related to erosion in managed areas. Sediment produced in logged and roaded areas increased the frequency of streamside landsliding in some downstream, unmanaged areas by channel aggradation and lateral corrasion of the streambanks.

The remainder of sediment produced from erosion of streambanks, bare hillslopes, and roads is less than 14 percent of the total sediment production. However, as landsliding decreased after 1975, the relative importance of hillslope erosion and road-related erosion increased. Erosion rates from roads are 20 to 140 times the erosion rates in the unmanaged areas and 7 to 34 times those in logged areas.

Erosion processes in Grouse Creek were found to differ by stream order. Debris torrents and streambank erosion dominate in second and third-order channels, whereas streamside landsliding was more frequent in fourth through sixth-order streams. An estimate of the increase in stored sediment indicates 27 percent of the sediment introduced to stream channels during the 29-year period of the study is still in the system.

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INTRODUCTION

Sediment discharge in Grouse Creek (Figure 1) and many north coastal California streams increased following the flood of December 1964 [Knott, 1974; State of California, 1979]. The increase in sediment production radically changed local channel morphology and compromised many aspects of the resource base resulting in reduced water quality, decreased anadromous fish populations, damage to roads and bridges, and removal of land from lumber production. To understand the role of management activties in sediment production and the long-term effects of increased sediment production, it is necessary to first quantify the sediment input.

The purpose of this study is to construct a sediment budget for the Grouse Creek basin (Figure 1) to aid land managers in determining the past effects of logging on sediment production and the effects of further harvesting on the resource base of the Grouse Creek watershed. The primary objective is to assess the relative importance of sediment contributions from different sources to total sediment production by investigation of the processes of sediment transport and storage in Grouse Creek using the sediment budget concept. Sediment budget data are used to interpret the major controls of sediment production.

Sediment Budgets

The sediment budget concept was first used by Leopold et al. [1966] to identify erosion processes associated with widespread, post-Pleistocene valley alluviation in the southwestern U.S. In recognition of human-induced erosion influences, sediment budgets are now employed as a tool useful in assessing the relative contribution of land-use activities or potential development projects to sediment production.

A sediment budget for a drainage basin identifies sediment sources and provides a quantitative statement of the rates of production, transport, and discharge of sediment [Dietrich et al., 1982]. The sediment budget is most simply expressed as:

$$I \pm \Delta S = O \qquad (1)$$

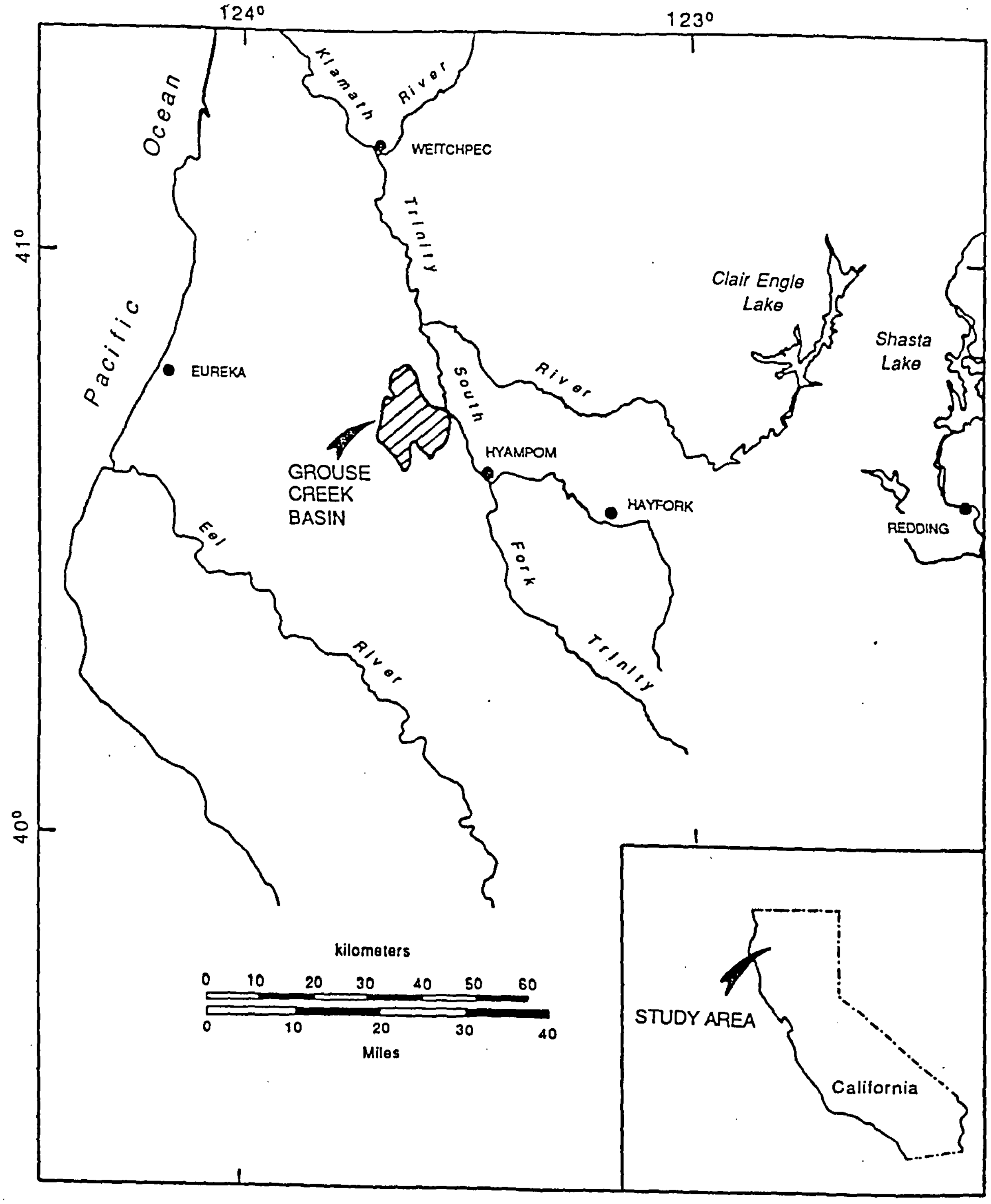


Figure 1. Location map for the Grouse Creek basin.

where I is sediment production, $\triangle S$ is the change in sediment storage, and O is the sediment discharge out of the basin. If no change in storage occurs, then production equals discharge.

A sediment budget is constructed by identification and measurement of the above components. Field measurements are designed to sample the sediment production and transfer processes. Reid and Dunne [Reid, personal communication, 1990] have found that this technique introduces no more error than those introduced by short-term monitoring programs. Grouse Creek is an ungaged basin, so sediment discharge is calculated as the difference between sediment production and the change in storage.

Study Area

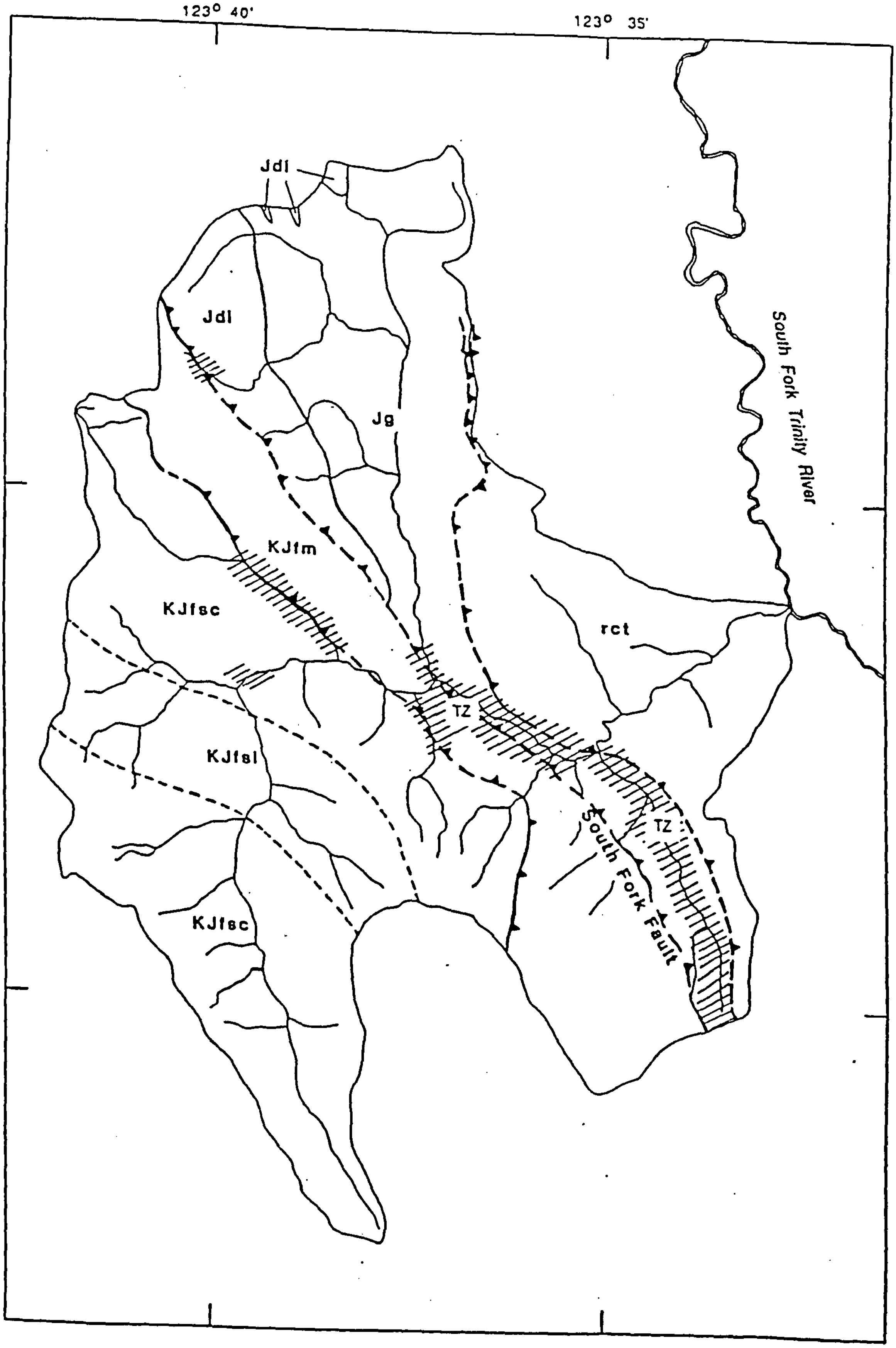
Grouse Creek is a 147 km^2 tributary basin of the South Fork Trinity River in Humboldt County, California (Figure 1). Relief in the basin is 1,461 meters. Three major thrust faults that cut across the basin separate Northern Coast Range Province rocks on the west from Klamath Mountains Province rocks on the east (Figure 2) [Young, 1978; Aalto et al., 1988]. Several major fault zones and a heterogeneity of rock types in the basin result in a wide range of rock competence. Soils in the Grouse Creek basin are predominately gravelly loams, with many areas of deep colluvial soils and deeply-weathered regolith [Howell and Smith, 1989].

Vegetation is dominated by mixed conifer forests of Douglas-fir and white fir, along with minor amounts of tanoak, madrone, incense cedar, and pine [Howell and Smith, 1989]. Areas of grass and oak woodland are scattered on southwest-facing slopes.

Precipitation in Grouse Creek varies both as a function of elevation and distance from the coastal marine influence. Annual precipation, averaged over the basin, is approximately 1800 mm, but ranges from about 1200 mm at the eastern mouth of the basin to 2350 mm in the western upper watershed. Rainfall is seasonal and occurs mainly from October through May.

Approximately 55 percent of the watershed is National Forest land. The remainder is privately owned. A little more than half the basin (58 percent) currently consists of old-growth forest. Thirty-nine percent of the basin has been logged in the last 35 years, with the majority of

Figure 2. Generalized geologic map of the Grouse Creek basin showing major faults, after Aalto et al, [1988] and Young [1978]. KJfsc, competent sandstone and siltstone of the Cretaceous-Jurassic Franciscan assemblage (unit CF in Appendix A); KJksi, incompetent sandstone and siltstone of the Franciscan assemblage (unit IF in Appendix A); KJfm, South Fork Mountain schist of the Franciscan assemblage (unit S in Appendix A); Jdi, Jurassic diorite of the Ammon Ridge pluton; Jg, Jurassic Galice Formation, argillites and metegreywackes (unit G in Appendix A); rct, Rattlesnake Creek terrane, melange (unit RT in Appendix A). Diagonally shaded areas are tectonized zones along stream corridors (unit TZ in Appendix A) that are more prone to gullying and mass movement than surrounding areas.



123° 40'
123° 35'
40° 45'
40° 40'
Jdl
Jdl
Jg
KJfm
KJfsc
KJfsl
KJfsc
rct
TZ
TZ
South Fork Fault
South Fork Trinity River

harvest on private land in the upper watershed. The remainder of the basin consists of grass and oak woodlands, roads, a brushed powerline right-of-way, and stream channels (Table 1).

Storm events and changing logging practices in the last 30 years play a dominant role in the erosion history of the basin. The most influential storm occurred in December 1964. The storm consisted of prolonged and intense precipation, and the resulting flood was augmented by snow-melt runoff [Harden et al., 1978]. Large storms also occurred in January and March of 1972 and in March of 1975. Coghlan [1984] has assigned recurrence intervals of 45-50 years for the 1964 storm, 25-30 years for the 1975 storm, and 10 years for the March 1972 storm based on an analysis for neighboring Redwood Creek.

About 75 percent of all logging and 80 percent of all road building in the Grouse Creek basin occurred prior to or during 1975 (Tables 2 and 3). Because major storm events also occurred during this interval, disturbance levels were compounded by the effects of both climate and logging activities. A major revision in the legislation governing California forest practices was enacted in 1973. Therefore, most logging in the basin also occurred prior to the enforcement of improved logging practices.

GROUSE CREEK SEDIMENT BUDGET

The Grouse Creek sediment budget covers the period from 1960 through 1989. This period was selected because aerial photographs were available as early as 1960, and field work was conducted between July and October, 1989. Aerial photographs were used to document logging history and expansion of roads at nine intervals over this period (Tables 2 and 3) and for the inventory of landslides and large sediment storage features. High-altitude photographs from 1972, 1982, and 1988 were used for the logging history and the road lengths but were of too small a scale to inventory landslides.

Logging in the basin began just prior to 1960. Aerial photograph coverage prior to this time is insufficient to assess pre-logging background rates of landsliding. Instead, the

Table 1. Areas within Grouse Creek basin, classified by land status as of 1988.

Land status	Area (ha)	% of total area
Old-growth forest (excluding roads)	8,495	58.0
Logged timber lands (excluding roads) *	5,576	38.1
Road surfaces **	153	1.0
Road cutbanks ***	112	0.8
Powerline right-of-way ****	61	0.4
Grass and oak woodland	210	1.4
Stream channels *****	48	0.3
TOTAL	14,655	100.0

* total logged area, does not count re-entered land twice
** 293,800 m of road, average width = 5.2 m
*** average map view width of cutbanks = 4.2 m, 91% of roads have cutbanks
**** width of right-of-way = 45 m
***** total length of 4, 5, and 6-order streams = 53,760 m assume average stream width = 9 m

Table 2. Areas logged* in the Grouse Creek basin as recorded by different years of aerial photography.

Harvest method	Year of aerial photograph 1960	1966	1970	1972	1975	1980	1982	1985	1988	Total	% of total
Tractor-yarded clear cut	19	672	280	9	145	82	50	206	223	1,685	28
Tractor-yarded partial cut	964	514	452	245	480	203	55	36	105	3,089	52
Cable-yarded clear cut	0	241	198	124	68	84	88	106	98	1,007	17
Cable-yarded partial cut	0	0	0	16	0	0	28	39	107	190	3
Helicopter-yarded clear cut	0	0	0	0	0	0	0	0	5	5	0
Total hectares logged	982	1,427	929	394	693	369	222	388	573		
Cumulative total	982	2,409	3,338	3,733	4,425	4,794	5,016	5,404	5,976	5,976	100
Actual cut-over area **	982	1,322	929	394	693	358	222	341	508		
Cumulative total	982	2,304	3,233	3,628	4,320	4,678	4,900	5,241	5,749	5,749	
Percent of basin area logged **	7	16	22	25	30	32	33	36	39	39	

* areas (hectares) include all roads within the logged areas.

** re-entered logged areas counted once

Table 3. Road density and length of road for three different road-use types in different time periods as bracketed by aerial photographs.

Length of road by road use (km)	Road density (km/km2)	Year of aerial photograph 1960	1966	1970	1972	1975	1980	1982	1985	1988
Moderate-use road		50	127	126	108	110	112	80	91	116
Light-use road		3	10	39	62	77	73	92	87	85
Abandoned road		0	2	22	32	46	68	91	97	93
Cumulative total		53	139	187	202	234	254	264	274	294
	Road density of total basin area	0.36	0.95	1.27	1.38	1.59	1.73	1.79	1.86	2.00
	Road density of total roads to actual cut area	5.38	6.04	5.77	5.57	5.41	5.43	5.38	5.29	5.17

contribution of landslide sediment to Grouse Creek is compared among aerial photographs covering the budget period.

U.S. Forest Service personnel provided data on logging and road history and road-fill failures in Grouse Creek, in addition to providing field assistance for landslide and slope erosion data collection. Field data were collected as volumes. Measurements are expressed in volumes, except where use of empirical methods produced yields in terms of mass. Conversion of all volumes to metric tonnes facilitated comparison of sediment production, storage, and discharge components.

The Grouse Creek watershed was divided into eight sub-basins (Figure 3). The sub-basins allow comparison of landslide sediment production by areas within the watershed.

Data collection, analysis, and interpretation for each of the sediment budget components of equation (1) are discussed separately below.

Sediment Production

Sediment production is that quantity of sediment delivered to the stream channels. Dominant hillslope erosion processes vary according to climate, geology, and land use. From field and aerial photograph surveys, four major erosion processes have been identified in Grouse Creek: streamside landsliding, streambank erosion, hillslope erosion, and road-related erosion exclusive of large landslides. Sediment production from all sources is summarized in Table 4, so the relative importance of each process will be apparent. The majority of sediment produced in Grouse Creek is generated by streamside landsliding.

Streamside Landslides

Streamside landslides are mass movements that deliver sediment directly into perennial or intermittent channels. A total of 385 landslides were inventoried from both field mapping and six sets of aerial photographs (Appendix A). The scale of the 1988 high-flight photographs precluded their use for inventorying any except the larger landslides. Landslides initiated or

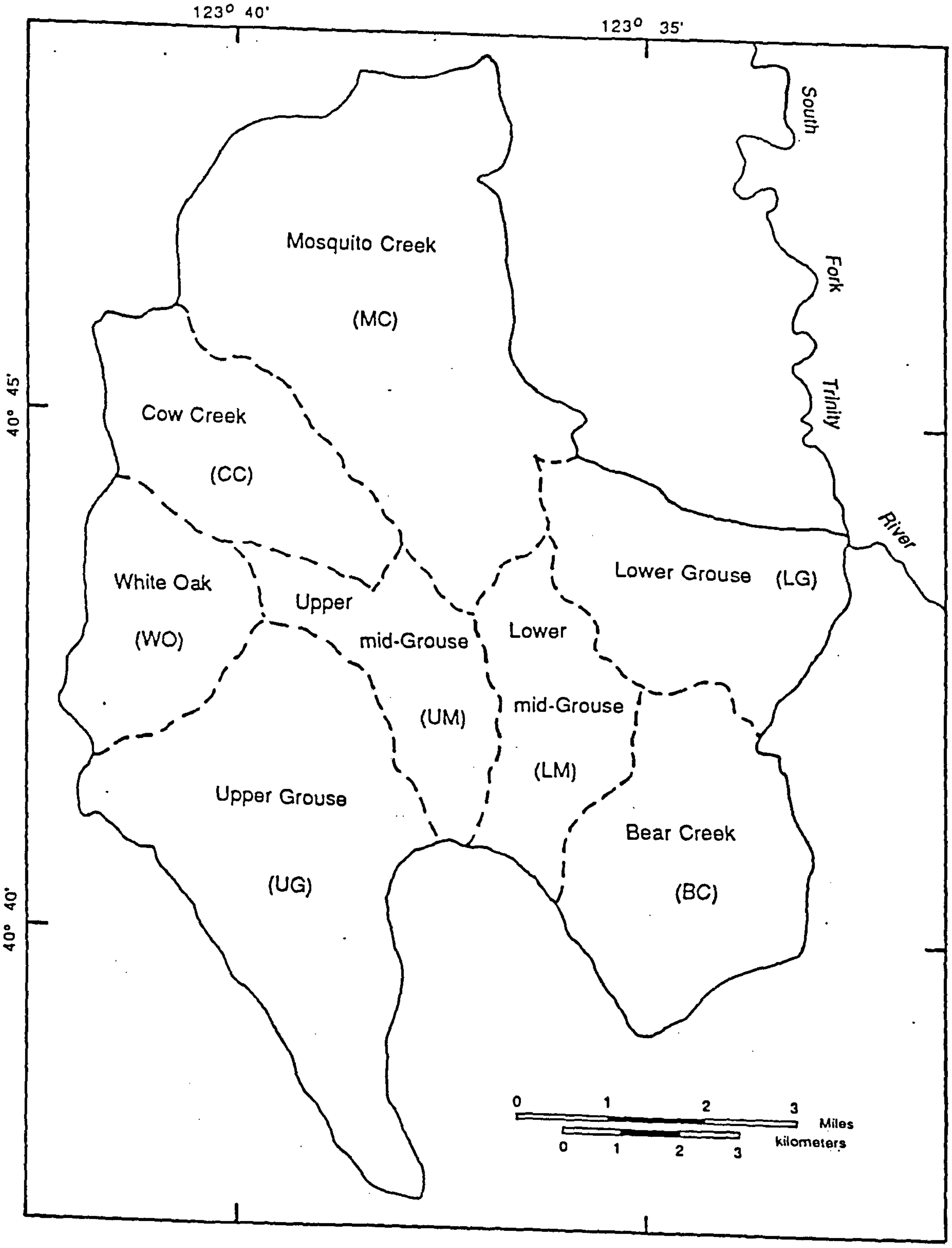


Figure 3. Map showing drainage sub-basins, Grouse Creek basin. Parentheses denote symbols for the sub-basins that are used in Appendix A.

Table 4. Grouse Creek sediment budget, 1960-1989.

SEDIMENT BUDGET COMPONENT	Tonnes of sediment	Percent of total	Total < 2mm	Total > 2mm
SEDIMENT PRODUCTION				
STREAMSIDE LANDSLIDING *				
Debris slides	4,448,000			
Complex slides	672,100			
Rockfalls	182,600			
Debris torrents	710,100			
Slump/earthflows	430,600			
Subtotal	6,443,000	86.7	2,255,000	4,188,000
STREAMBANK EROSION **				
First-order streams	118,400			
Second-order streams	276,600			
Third-order streams	86,800			
Fourth-order streams	5,800			
Fifth-order streams	4,700			
Sixth-order streams	6,500			
Subtotal	499,000	6.7	259,400	239,400
HILLSLOPE EROSION ***				
Logged areas				
Sheetwash and rilling	60,000		60,000	
Gullying	272,100		141,500	130,600
Mid-slope landsliding	9,000		3,150	5,860
Subtotal	341,000	4.6		
Grass and oak woodlands				
Sheetwash and rilling	120		120	
Gullying	1,280		960	320
Mid-slope landsliding	4,350		2,780	1,570
Subtotal	5,800	0.08		
Old-growth forest				
Sheetwash and rilling	0	0.0		
ROAD-RELATED EROSION ****				
Sheetwash and rilling of road surfaces	45,100		45,100	
Sheetwash and landsliding of cutbanks	47,400		47,400	
Road crossing failures *****	45,200		23,500	21,700
Subtotal	138,000	1.9		
TOTAL SEDIMENT PRODUCTION	7,427,000	100.0	2,839,000	4,588,000
SEDIMENT STORAGE	2,018,000		644,000	1,374,000
SEDIMENT DISCHARGE	5,409,000		2,195,000	3,213,000

* density conversion factor of 1.83 t/m^3
** density conversion factor of 1.3 t/m^3
*** see Table 16 for density conversion factors
**** exclusive of landslides
***** density conversion factor of 1.8 t/m^3

enlarged between the 1985 aerial photographs and 1989 were field inventoried. Field visits to areas of persistent landsliding and recently logged areas produced only one new landslide and two enlargements since 1985. Review of film from a helicopter flight of Grouse Creek channels flown in April of 1989 revealed no additions to inventoried landslides. With the exception of a storm in February of 1986 precipitation has been scarce between 1985 and 1989, and it is assumed that few, if any, new landslides were left unventoried. Landslides visible on the 1960 photographs were not inventoried unless they expanded between 1960 and 1989 or the raw scars contributed significant sediment during the budget period. The area of the smallest landslide visible within old-growth forest on aerial photographs (250 m^2) was used as the lower limit to inventoried slides. Ten field-mapped slides with areas less than 250 m^2 were included in measurements for streambank erosion (below). Tabulated landslide data include landslide areas and volumes, geology, slope, land use, and aspect (Appendix A).

Not all slides visible on aerial photographs could be visited in the field to estimate volumes. Instead, relationships between field-estimated volumes and map areas were used to estimate volumes for most of the slides.

The procedure to measure landslides in the field involved first dividing the scar area into geometric segments with relatively uniform cross-sectional dimensions (Figure 4). The average width, depth perpendicular to slope, and length of each segment was then recorded. Area measurements were made with a tape or rangefinder and depth was estimated on the basis of the geometry of the void [illegible] landsliding. Landslide volumes were computed as the sum of the segment volumes. The volume delivered to the channel is the difference between the measured scar area and any volume of material stored on the slope or at the toe.

Volumes of approximately 17 percent of inventoried landslides were measured in the field, and 27 percent of slides were site visited. Field measurement of the same slides by different workers agreed within 15 percent. When subject to both methods, measurement of slide areas on photographs was within 10 percent of the field-measured areas. Due mainly to

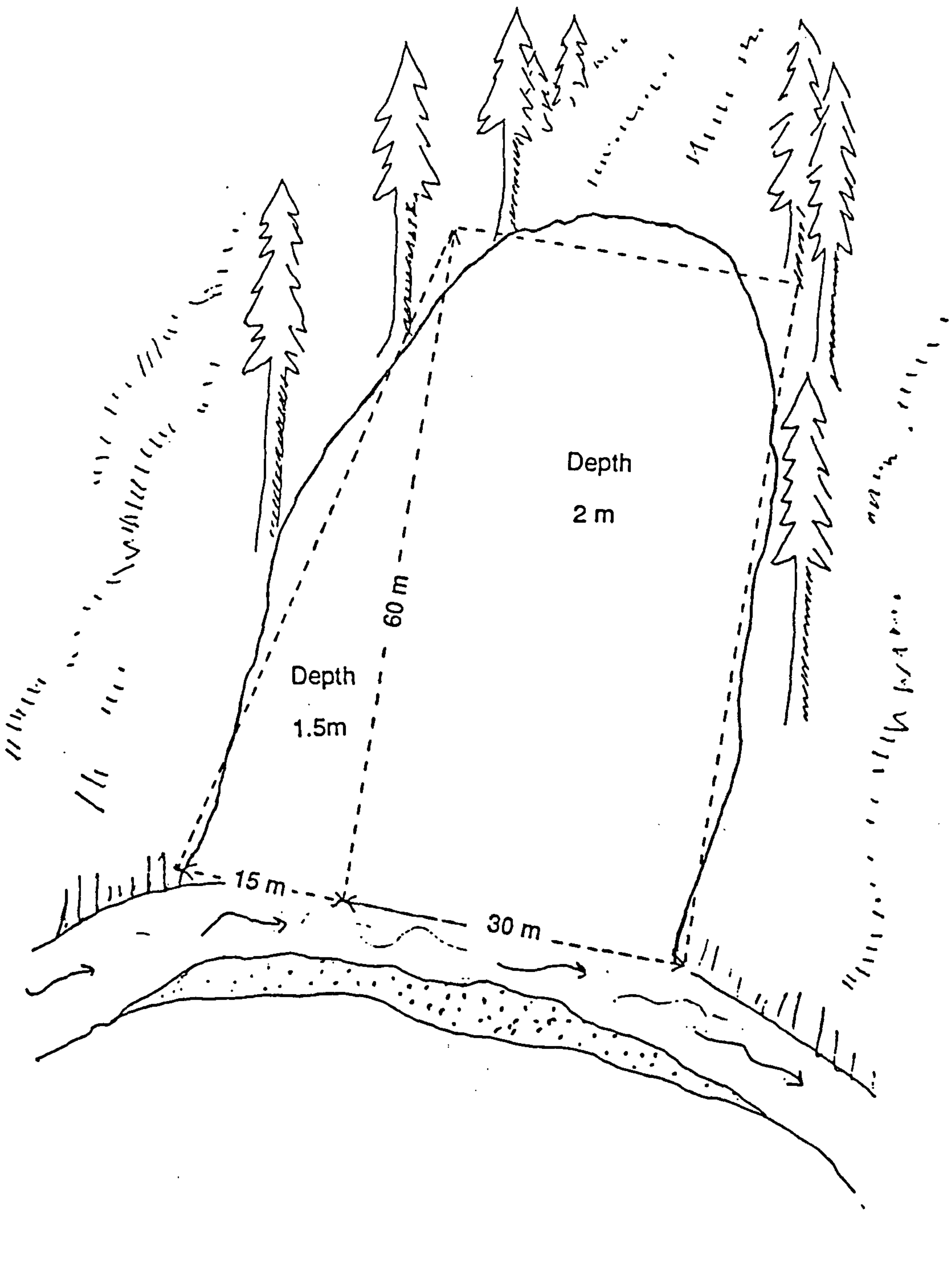


Figure 4. Example of field measurement of landslide scars. Scar area is divided into geometric segments, dimensions are measured, and segments summed for total landslide volume.

uncertainty in measuring landslide depth, landslide erosion estimates are considered accurate to within plus or minus 15 to 20 percent.

Landslides were classified by type of slope movement as either debris slides, slumps, earthflows, rock falls, or complex slides [Varnes, 1978]. Debris torrents also were included in the landslide inventory. Landslides were tallied by land use according to the classification on Table 5. Landslides were classified as either occurring on managed land (logged slopes), unmanaged land, or both. A slide was also classified as road-related if a road or landing existed at or very near (within 25 meters) the head scarp or went through the middle of a slide area.

Debris slides. The majority (81 percent) of slides inventoried are debris slides that account for 69 percent of landslide derived sediment (Table 4). These are rapid, shallow failures of soil-mantle material with failure planes approximately parallel to the slope. The average depth of measured debris slides is 1.8 meters, and average slope is 40°. In Grouse Creek failures commonly involve both colluvial soils and fractured and weathered bedrock.

For debris slides, a relationship between map area and volume was established from field measurements of 47 slides (Figure 5):

$$V_{del} = 0.821A^{1.134} \quad r = 0.947 \qquad (2)$$

where V_{del} is the volume (m^3) of sediment delivered to the channel, A is the map area (m^2) of the debris slide, and r is the coefficient of correlation for the relationship. The relationship in Figure 5 was used to estimate sediment contributions from debris slides mapped on aerial photographs. An area-to-volume relationship was not determined for the remaining slide types.

The relationship between V_{del} and map area (Figure 5) is defined for a data set of slides that are less than 10,000 m^2 in area. The volumes of seven debris slides with map areas greater than 10,000 m^2 were estimated from equation (2) and account for approximately 8 percent of the total slide volume.

Slumps, earthflows, rock falls, and complex slides. The remaining landslide types contribute 20 percent of landslide sediment during the budget period. Slumps fail along a

Table 5. Relationship of management to volume of sediment produced by streamside landslides (1960-1989).

Land use classification number *	Land use classification description of landslide site	Number of landslides	Sediment delivered to channels (m^3)	Percent of total
1	Unmanaged land - not road related	192	1,721,700	49
2	Unmanaged land - landing or road related	16	199,600	6
1,2	Initiated in unmanaged land, enlarged after logging **	43	551,800	15
3	Managed land - not road related	61	344,500	10
4	Managed land - road or landing related	57	434,300	12
5	Unmanaged - clearly related to upslope managed land	8	238,200	7
6	Both managed and unmanaged land	8	30,700	1
	TOTAL	385	3,521,000	100

* number classification used in landslide inventory (Appendix A).

** landslides separated out of classifications 1 & 2 after aerial photograph analysis

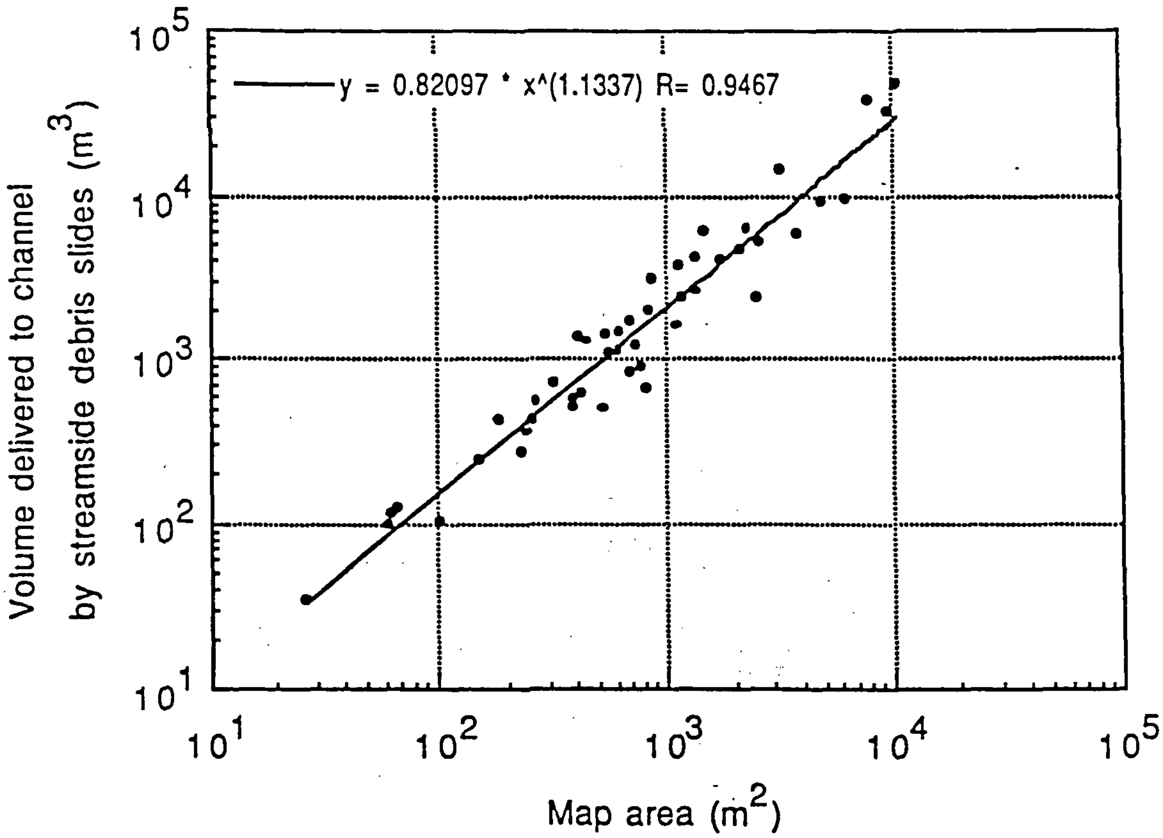


Figure 5. Relationship between the volume of sediment delivered to the channel by streamside debris slides and the map area of the debris slide (n=47).

rotational shear surface, and earthflows exhibit a fluid-like downslope movement of the soil mass. A rock fall is a fall of newly detached mass from an area of bedrock that involves little or no shear displacement. Complex slides involve a combination of slope movement processes and rates of movement. The volumes of these features were estimated from aerial-photograph-measured areas plus depth and movement distance based on slide morphology and degree of slide activity. Some of these landslides were measured in the field, and field experience served to facilitate aerial-photograph measurement of the other features.

In areas of bench-slope morphology, particularly common in the incompetent Franciscan unit, massive earthflows and slumps move large quantities of debris downslope where shallow debris slides deliver sediment into the channel. Not all of these areas could be distinguished by disturbed vegetation on aerial photographs. However, where areas of bench-slope morphology could be identified, the debris slides associated with them were classified as complex slides. Similar slope morphology is described by Swanston et al. [1983] in adjacent Redwood Creek.

Devastation Slide is a large earthflow, approximately 0.5 km^2 in area, located 2.7 km upstream of the mouth of Grouse Creek. The slide toe encroaches into the stream channel and creates a barrier to anadromous fish migration. Mark Smith, Six Rivers National Forest geologist, estimated the sediment contribution from Devastation Slide during the budget period to be between 160,000 and 240,000 m^3 using aerial photographs and recent surveyed movement rates. We independently estimated the volume to be approximately 210,000 m^3 using aerial photograph measurements of slide and gully compartments and a field estimated depth of the toe. Since our estimate fell within the range of values of the first estimate, we used our mid-range value for the sediment budget.

Debris torrents. Debris torrents are either channel-confined debris flows or dam-break floods, and are not differentiated in this study. Debris torrents supplied 11 percent of the total landslide sediment during the budget period. To estimate sediment production by debris torrent in a particular channel, we calculated a unit volume of erosion per meter length of disturbed channel. This volume was calculated based on field observations and the severity of channel bank disturbance visible in aerial photographs. Where a discrete initiation point could be identified, the volume eroded from that point was included in the total estimate. Sediment volumes from discrete landslide scars along the length of debris torrent tracks were calculated separately.

When classified by stream order, the majority of debris torrents occurred in second and third-order streams. Out of approximately 38 km of debris torrent tracks, 21 percent were in first-order, 33 percent in second-order, 29 percent in third-order, and 17 percent in fourth-order streams.

Particle-size distribution of streamside landslides. Particle sizes of sediment produced by landsliding were estimated from soil surveys. Soil survey coverage in the Grouse Creek basin includes approximately 70 percent of the area. Particles sizes for all soil profiles involved in landsliding were calculated from profile descriptions or lab analysis if available. Profiles were extended to a depth of 1.8 meters, the average depth of most landsliding. Particle size is influenced by the presence of weathered rock in areas of shallow soils. Particles were divided into two size classes, less than or equal to 2 mm in diameter and greater than 2 mm. This particle-size division was chosen because 2 mm is the upper-size limit of particles that tend to travel as suspended load, and particles less than 2 mm in diameter are the size fraction of sediment most harmful to fish and water quality [Cederholm et al., 1981]. The percentage of particles equal to or less than 2 mm in landslide debris ranged from 17 percent in areas of shallow soils to 64 percent in deep, colluvial soils and averaged 42 percent.

Landslide volumes were multiplied by the fraction in each size class for the soil type mapped for that slide. Soil mapping based on geology and physiography was extended to unmapped areas. Slide volumes were totalled by particle size to obtain the distribution in Table 4.

Streamside landslide discussion. Three factors appear as dominant influences on Grouse Creek landsliding during the budget period: zones of unstable geology, major storm events between 1964 and 1975, and logging and road-building activity.

The majority of landsliding occurs on unlogged slopes where upslope roads were not related to the failure (Table 5). However, the data in Table 5 do not show the spacial relationship between areas of logging and instances of landsliding in the unmanaged areas downstream. Figures 6a-g illustrate these relationships by showing the expansion of logged areas, landslide initiations, and landslide enlargements for each aerial photograph interval. Roads are not included in Figures 6a-g, but expansion of the road network is implied by the logging expansion.

Landslides prior to 1960 (Figure 6a) are concentrated in areas of geologic instability. The slides are located in the middle of the basin where traces of several thrust faults cut through the region (Figure 2). In the upper Grouse Creek sub-basin, sliding occurs in the incompetent Franciscan unit. In lower Grouse Creek, sliding occurs locally within the Rattlesnake Creek terrane.

Photograph year 1966 (Figure 6b) shows that most landslides were either initiated or enlarged between 1960 and 1966. The December 1964 storm and flood was the event responsible for the notable increase and growth of landslides. Slides during this period account for 71 percent of the total slide volume (Table 6) and 62 percent of all sediment produced during the budget period. Many slides were initiated in logged areas in the upper watershed. Downstream from these logged areas, stream channels aggraded as a result of the increased sediment contributions, and additional slides occurred due to lateral scour of the streambanks.

Bear Creek (Figure 3) best exemplifies the impact to channels from 1964 landsliding. An estimated 30 percent of the Bear Creek sub-basin was logged prior to the storm. During the storm, landsliding was initiated in logged and roaded areas in the upper watershed (Figure 6b), a debris flow occurred, and the spacial relationship between landsliding and channel scour suggests that a dam-burst flood traveled down the channel. As a result, a six-meter-high debris fan was built at the mouth of Bear Creek. Landsliding in old growth near the mouth of the creek was caused by the extreme channel widening and streambank scour. Remnants of the 1964 debris-fan deposit are still plastered to the base of 1964 debris slide scars, effectively isolating these scars from the active channel.

Figures 6(a)-(g). Maps showing cumulative areas of land logged and landsliding initiated or enlarged between aerial photograph intervals. Diagonally striped areas are those logged in the most recent photograph interval. Stippled areas are those logged prior to the most recent photograph interval. Black circles represent landslides initiated within the most recent photograph interval, and open circles are previously existing landslides that have enlarged in the recent photograph interval. Circle diameters correspond to landslide volume as shown in the legend.

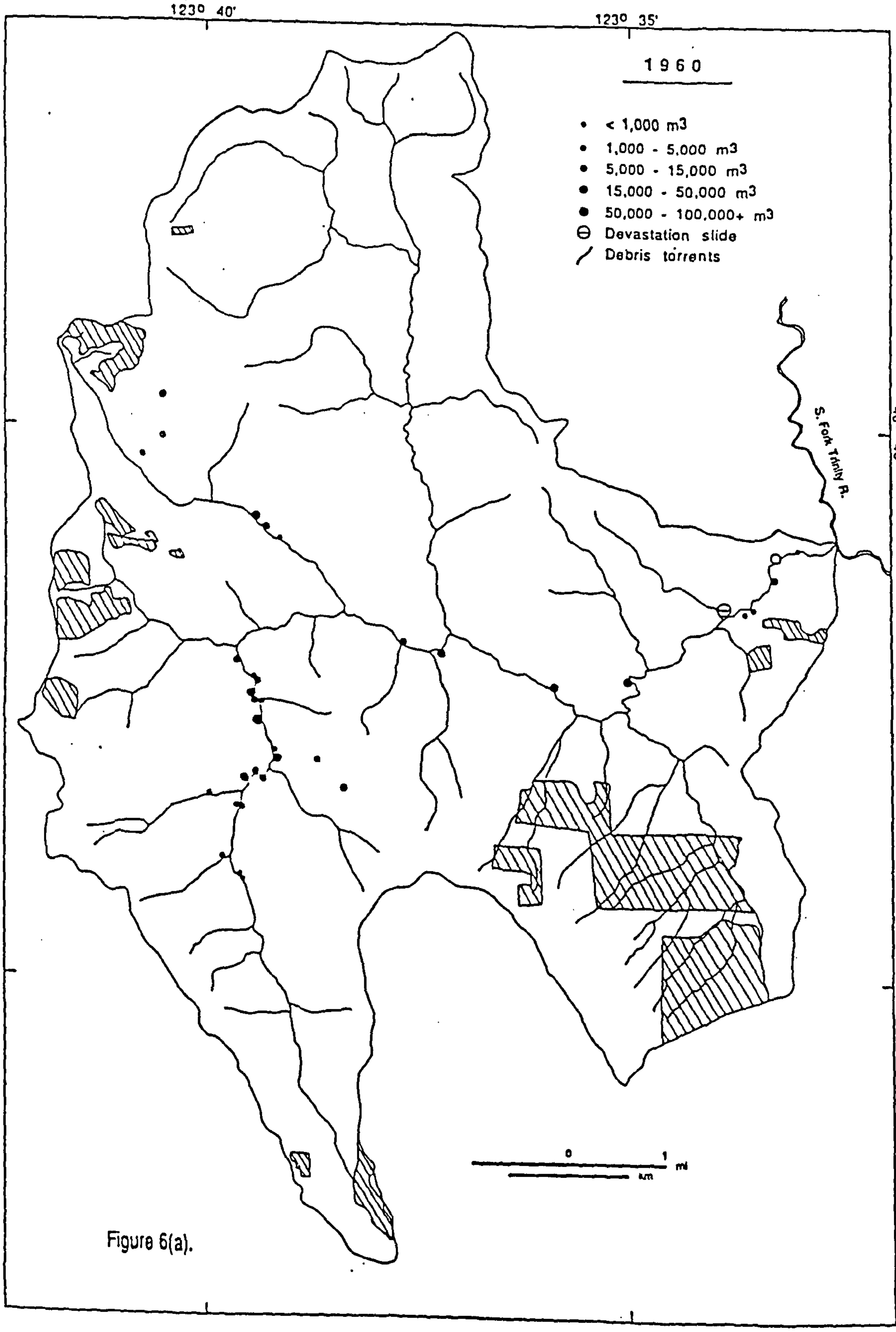
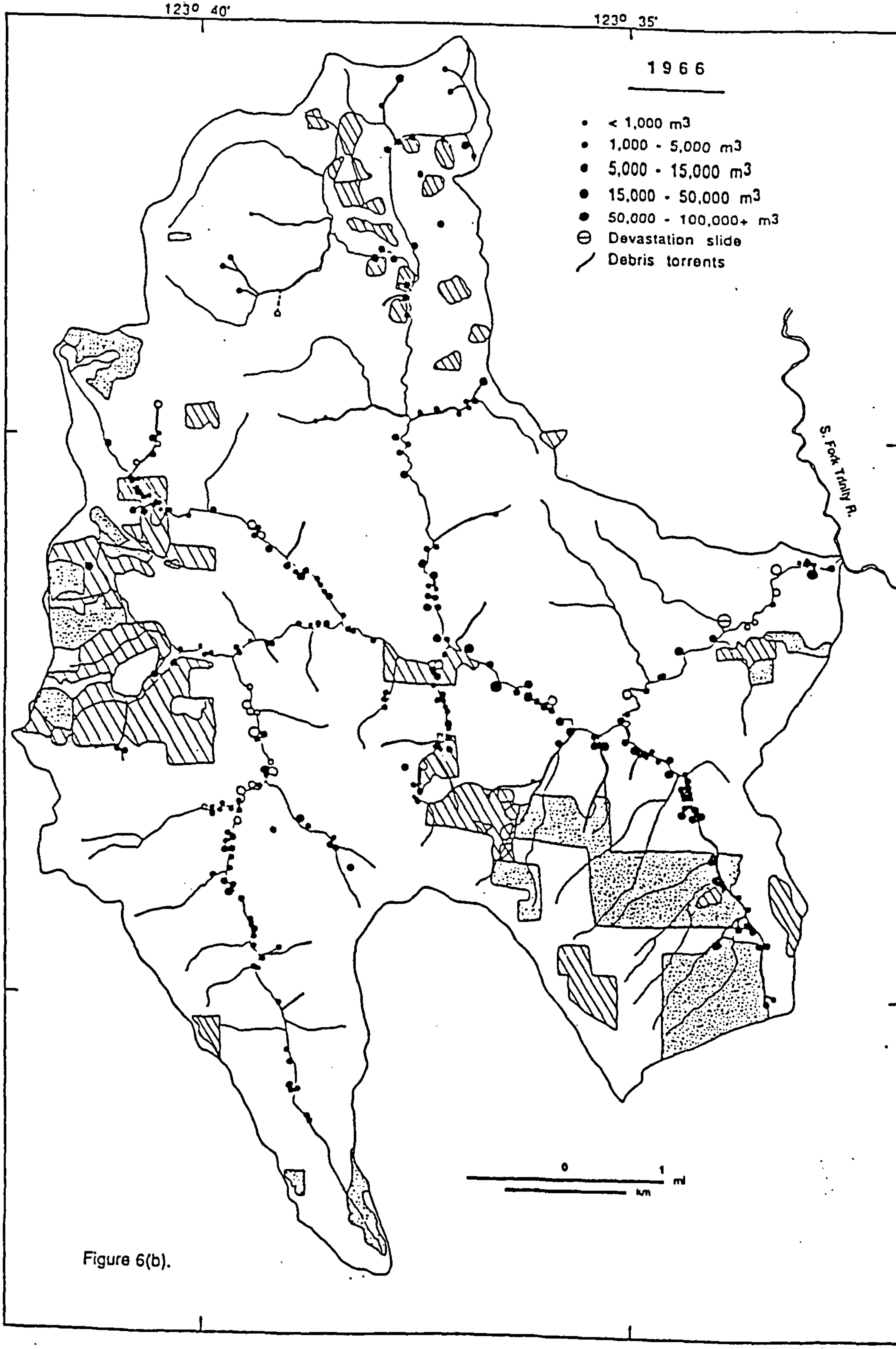

123° 40'
123° 35'
1960
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1 mi
km

Figure 6(a).



123° 40'
123° 35'
1966
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1
mi
km

Figure 6(b).

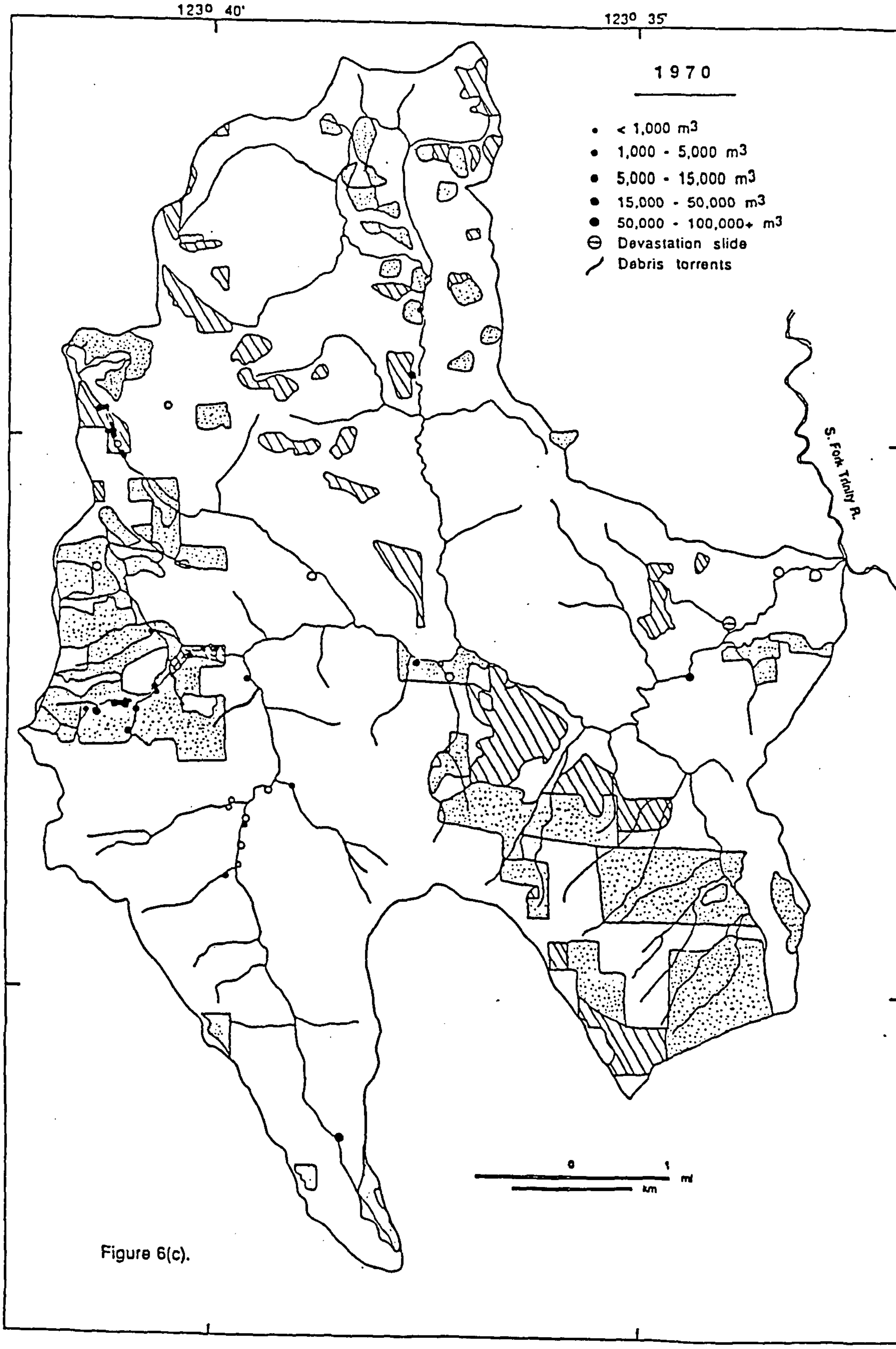

123° 40'
123° 35'
1970
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1
mi
km

Figure 6(c).

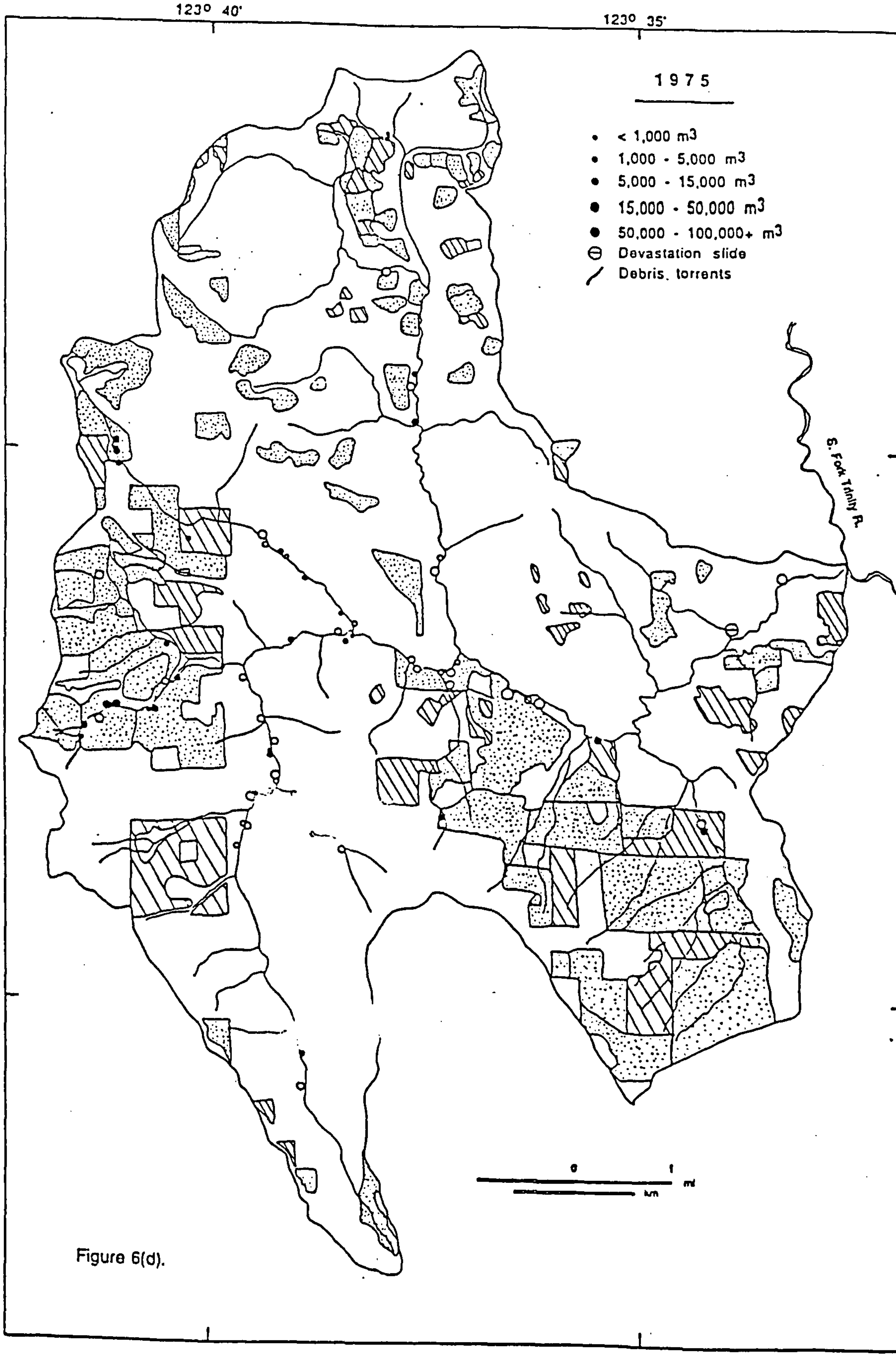

123° 40'
123° 35'
1975
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris. torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1
mi
km

Figure 6(d).

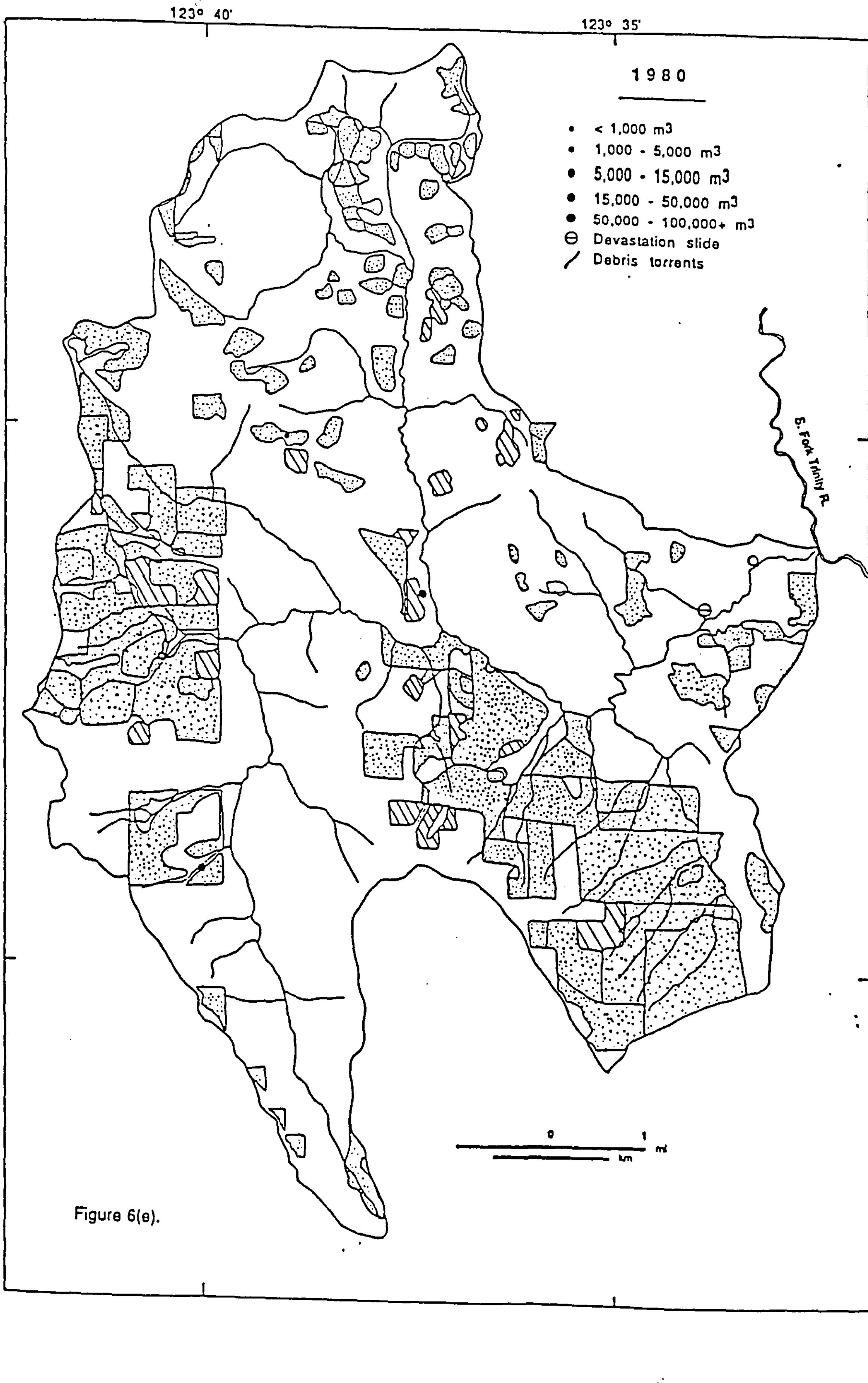

123° 40'
123° 35'
1980
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1
mi
km

Figure 6(e).

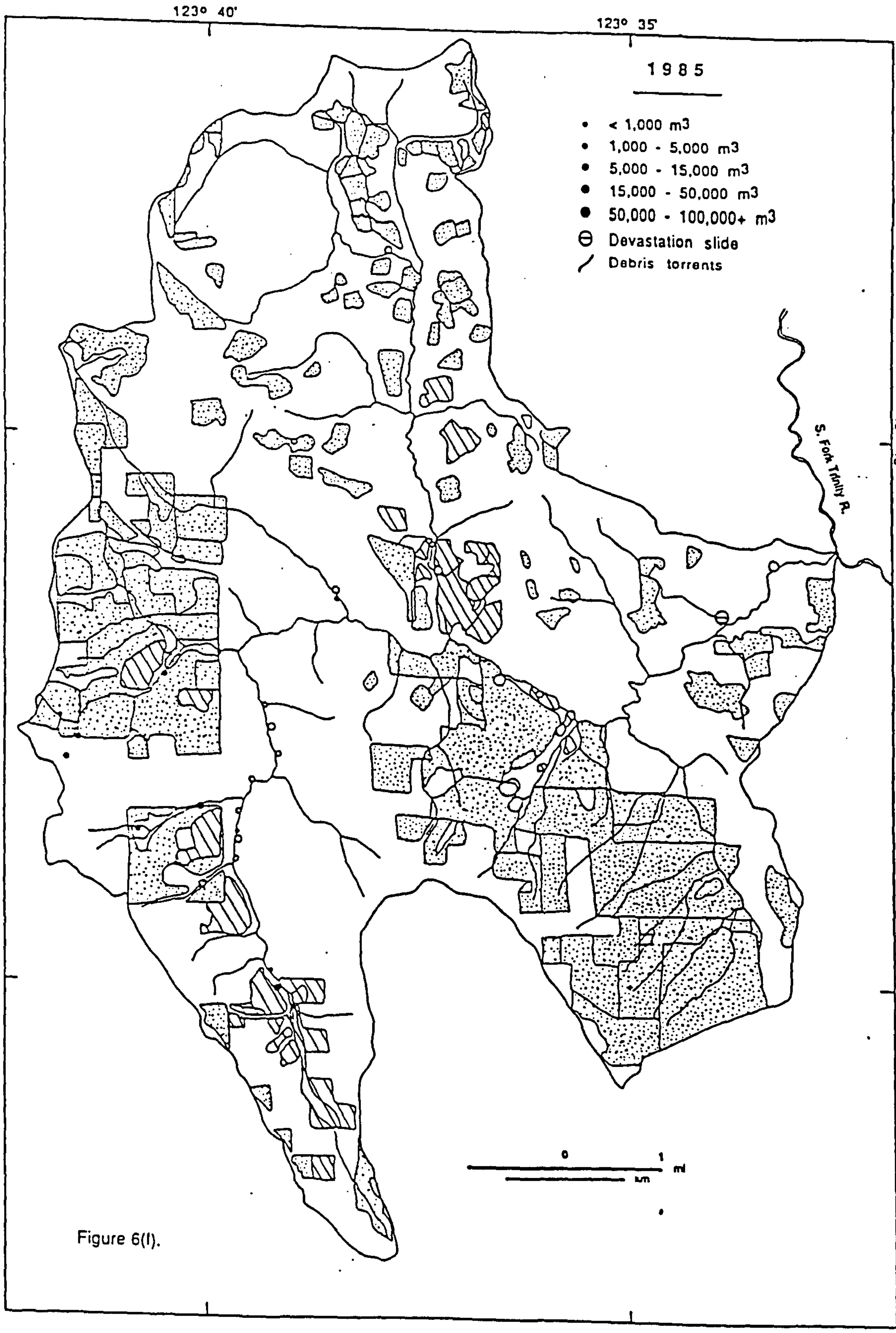

123° 40'
123° 35'
1985
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1
mi
km

Figure 6(l).

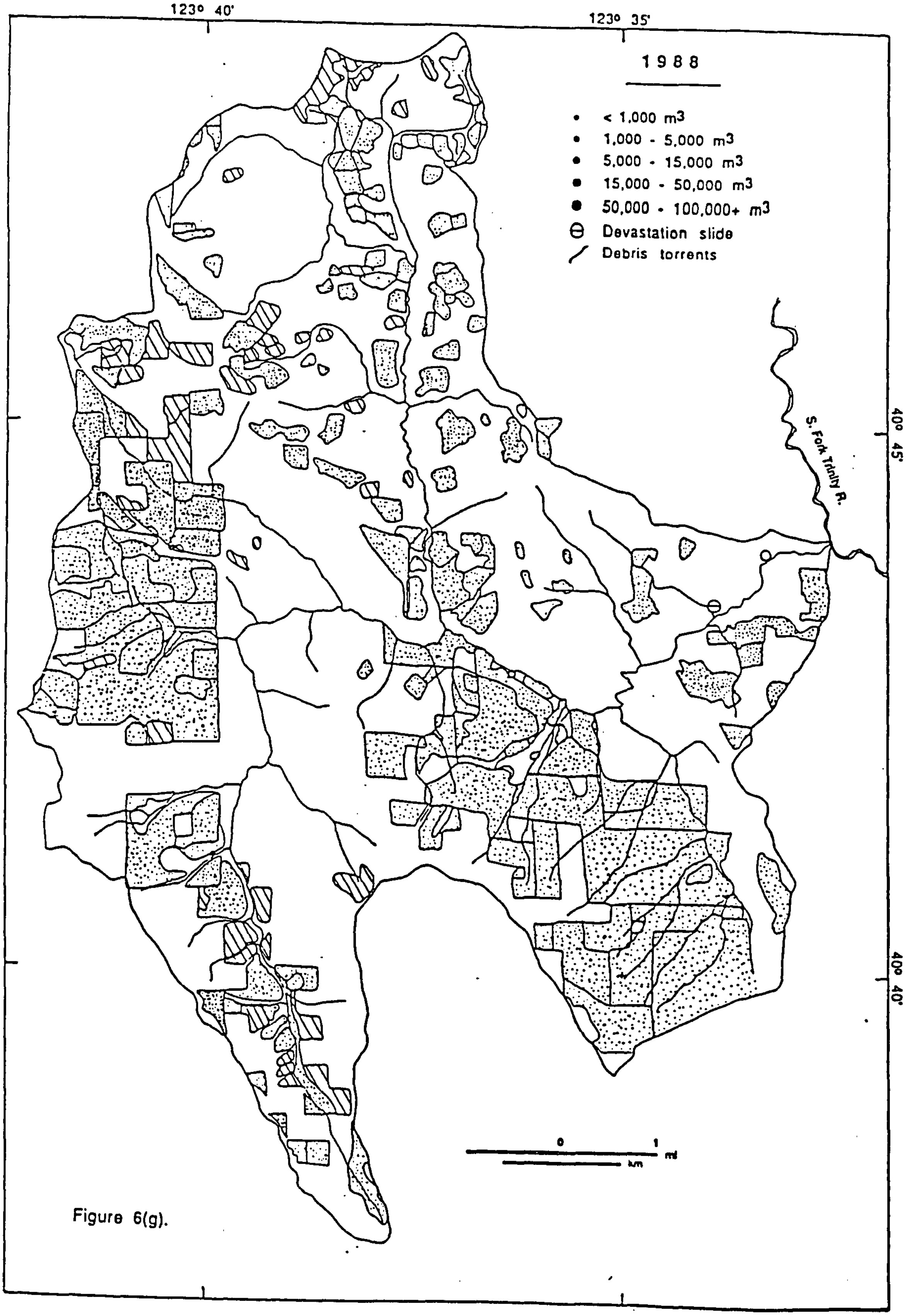

123° 40'
123° 35'
1988
< 1,000 m3
1,000 - 5,000 m3
5,000 - 15,000 m3
15,000 - 50,000 m3
50,000 - 100,000+ m3
Devastation slide
Debris torrents
S. Fork Trinity R.
40° 45'
40° 40'
0
1
mi
km
Figure 6(g).

Table 6. Grouse Creek landslide volumes (m^3) by sub-basin and aerial photograph interval.

Sub-basin	Area (ha)	1960-66	1967-70	1971-75	1976-80	1981-85	1986-89	Totals	Volume per area (m^3/ha)
Mosquito Creek	3,880	423,948	16,065	30,716	37,234	10,642		518,605	134
Upper Grouse	2,934	364,361	72,598	64,172	8,918	31,812	404	542,265	185
Bear Creek	1,744	394,431	4,875	4,240				403,546	231
Lower Grouse	1,515	312,339	146,284	130,932	*12,000	*15,000	*4,535	621,090	410
Cow Creek	1,382	240,196	53,934	40,692		1,780		336,602	244
Lower Mid-Grouse	1,088	523,598	6,437	43,992		33,642	2,436	610,105	561
White Oak	1,074	34,557	99,969	102,387	4,188	11,417		252,518	235
Upper Mid-Grouse	1,038	197,796	9,231	29,141				236,168	228
TOTALS	14,655	2,491,226	409,393	446,272	62,340	104,293	7,375	3,520,900	
Percent of total		71	12	13	2	3	0		

* Photo year totals are adjusted for enlargement of slides through the budget period; Devastation Slide volume is distributed throughout the budget period.

New and enlarged landslides are visible in aerial photographs taken in the early 1970's (Figures 6c and 6d) (Table 6). Landslide activity in the late 1960's (Figure 6c) occurred primarily in logged areas, and zones of geologic instability show continuing slide activity.

The landslide activity in the early 70's reflects the influence of the 1972 and 1975 storms, and is particularly noticeable in logged areas of the upper White Oak sub-basin. The majority of slide activity in the White Oak sub-basin occurs along Greenwood Creek, the southern tributary to White Oak Creek. Most logging activity in the Greenwood drainage visible on the 1966 aerial photographs took place after the 1964 storm. The majority of landslides occurred in response to the 1972 and 1975 storms after the slopes had been logged. Of the 31 landslides inventoried in Greenwood Creek (Appendix A), 84 percent occurred on logged land and 58 percent of those were directly road or landing related. In contrast, the upper White Oak Creek drainage showed little landslide activity, although the timing and aerial extent of logging is similar to the Greenwood drainage. The contrast in landsliding between the two drainages is ascribed to a difference in bedrock competency within the Franciscan assemblage (Figure 2). Landslide response in the Greenwood drainage, therefore, resulted from a combination of management activities on slopes underlain with unstable bedrock along with major storm events.

A small amount of new logging and landsliding occurred in the period 1975-1980 (Figure 6e). Landslide activity increased slightly by 1985 (Figure 6f), with new sliding in logged areas and renewed sliding in the unstable zones. A storm event in 1985 may have influenced this epidsode of sliding. By 1985, 30 percent of inventoried slides had revegetated (Figure 7) (Appendix B). The smallest amount of new landslide sediment production occurred in the interval 1986-1988 (Table 6, Figure 6g).

Sediment production from landslides is concentrated in the lower-mid Grouse and lower Grouse sub-basins (Figure 8; Table 6). Devastation Slide is the largest single source of sediment in Grouse Creek, and the estimated volume accounts for six percent of the total slide volume and five percent of the total sediment produced during the budget period. Landslide sediment production from lower mid-Grouse sub-basin alone equals landslide sediment production from

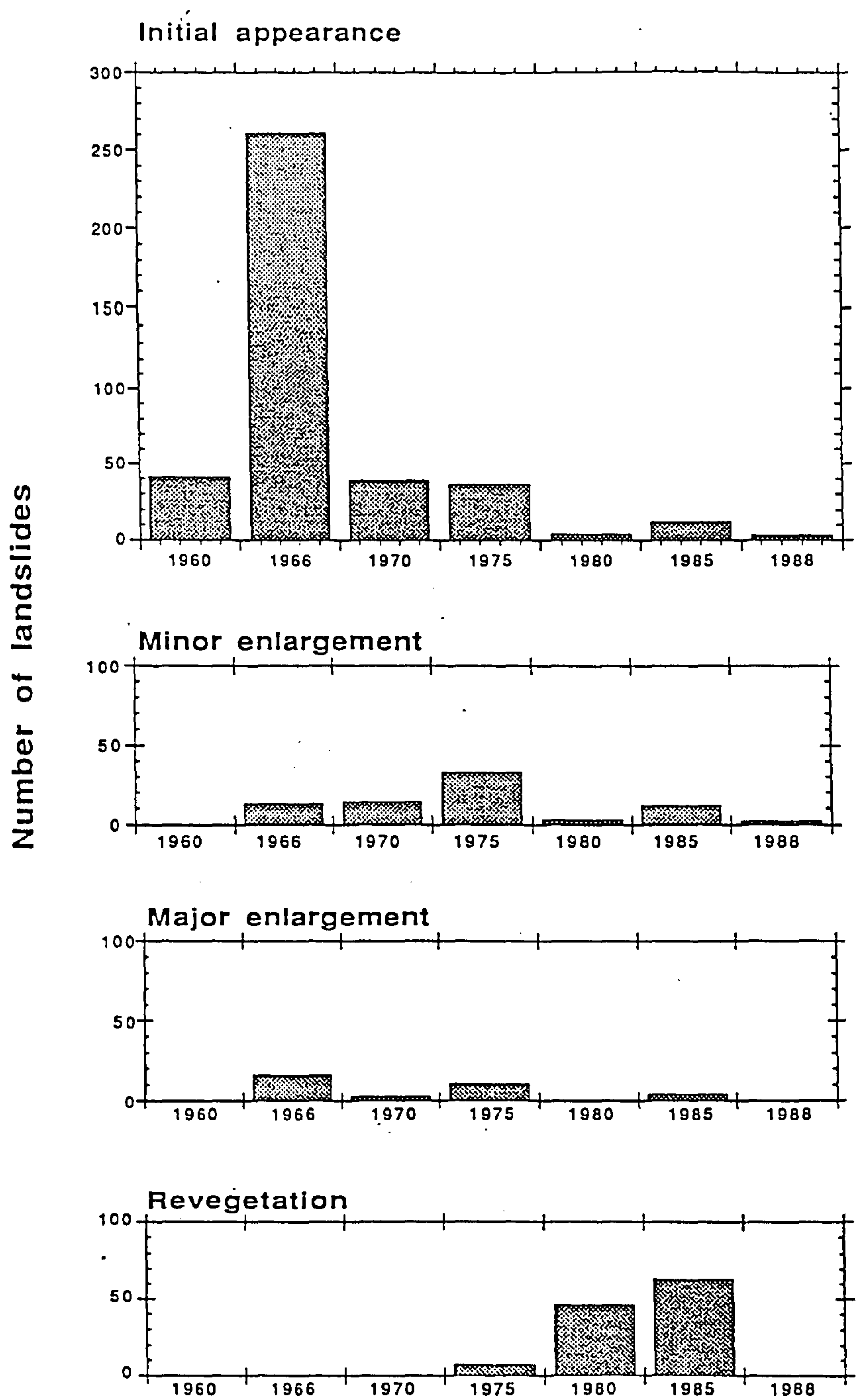


Figure 7. Activity history of streamside landslides, 1960-1985, showing numbers of landslides initiated, enlarged, or revegetated in different years of aerial photographgraphic record. Revegetation entails development of a vegetative cover over the entire landslide scar with no bare area visible on the aerial photograph.

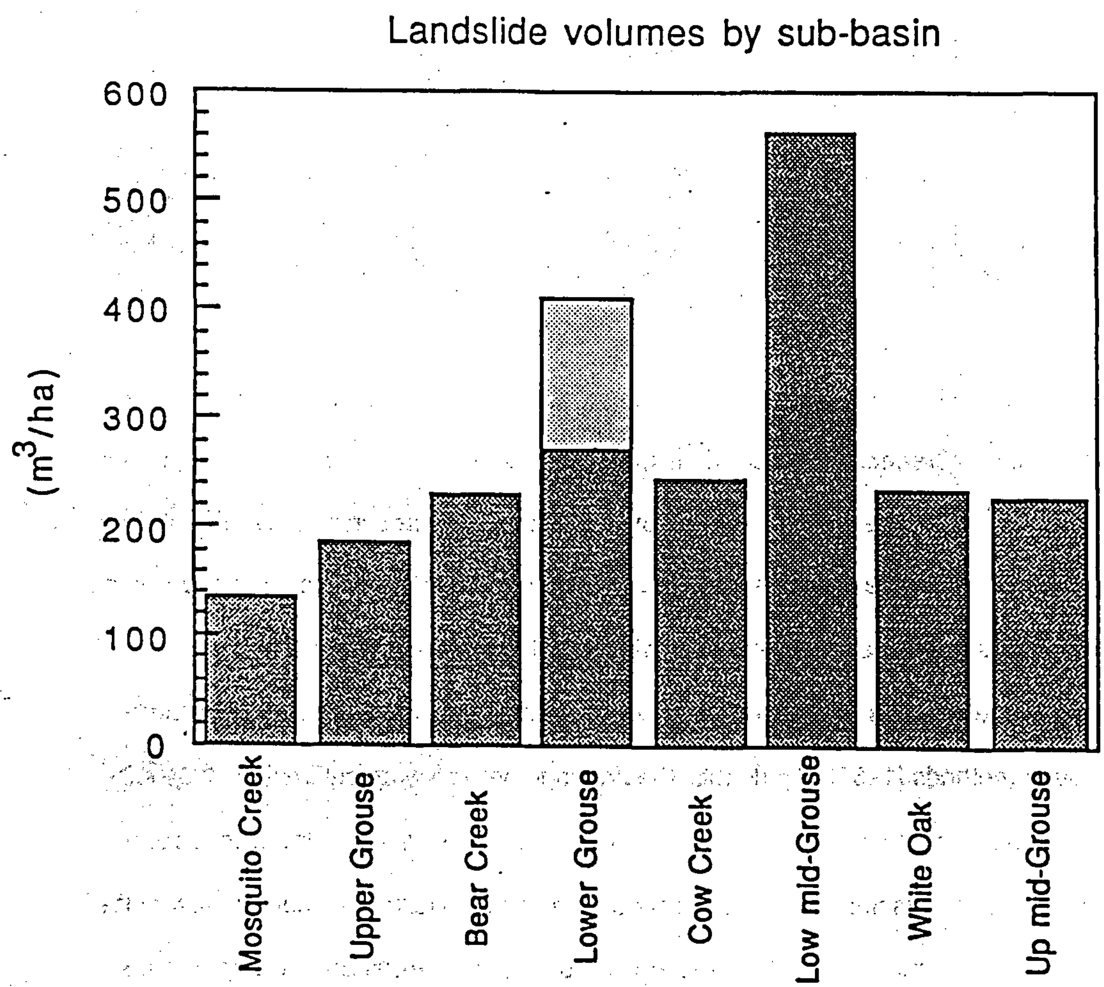


Figure 8. Sediment production (m^3/ha) of streamside landslides, separated by drainage sub-basins within the Grouse Creek basin. The upper 139 m^3/ha of LG (Lower Grouse) represents the contribution from Devastation Slide.

both the lower portion of Grouse Creek sub-basin and Devastation Slide. The reasons for the high productivity of the lower mid-Grouse area is that fault zones traverse the major channels and logging and roads further contribute hillslope instability. Lower Grouse sub-basin sediment production is increased by the production from Devastation Slide (see upper portion of the bar graph in Figure 8). In contrast, the lowest unit sediment production is in Mosquito Creek. The relative paucity of landslides in Mosquito Creek is attributed to the use of cable-yarding methods, dispersed cut units that transect fewer streams than in areas of concentrated harvest, and the lower percentage of area logged (Table 7). Sediment production in the other sub-basins is fairly evenly distributed.

Streambank Erosion

Streambank erosion is one of two processes of sediment production along intermittent or perennial channels. Streamside landsliding is the other process that delivers sediment from the stream margin to the channel. Fluvial erosion of the streambanks affects the lower banks, while landsliding involves the upper banks and slopes. In Grouse Creek, landslides with areas greater than 250 m^2 are visible on aerial photographs whereas streambank erosion is not.

To facilitate analysis of streambank erosion, streams in Grouse Creek were ordered using Strahler's methods [1957]. To do this, the drainage network was outlined on 1:24000 topographic maps using the contour crenulation method [Goudie, 1981]. First-order streams initiate where the contours first start to crenulate on a hillslope. Using this method, few of the smallest blue-line streams on 1:24000 maps are first-order; most are second-order streams.

Thirteen stream surveys were conducted along first to fifth-order streams (Table 8) (5 of the 13 streams surveyed by J. McHugh, Six Rivers National Forest). Surveyed streams flow through both logged and old-growth areas. We measured the length and height of the raw banks, and the estimated depth of lateral corrasion from root-mass overhang or morphology of adjacent uneroded banks. Small landslide volumes (<250 m^2) were also measured. Measurements were made with a tape or Jacob's staff. Stream distances were measured by

Table 7. Percent of sub-basin areas logged.

Sub-basin	Percent logged by 1988
Lower Grouse	17.4
Bear Creek	67.1
Lower mid-Grouse	59.1
Mosquito Creek	28.6
Upper mid-Grouse	26.4
Cow Creek	42.0
White Oak	87.1
Upper Grouse	24.0

Table 8. Field survey of streambank sediment production by stream order, Grouse Creek.

Reach	Stream order (Strahler method)	Length of survey (m)	Streambank erosion (m^3/m)	Small streamside landslides (m^3/m)	Total sediment production (m^3/m)
Grouse Mtn	1	183	0.04	0.00	0.04
Frustration*	1	308	0.07	0.01	0.08
Bean*	1	393	0.20	0.10	0.29
near White Oak	2	197	0.16	0.53	0.69
Buck*	2	342	2.24	0.34	2.58
Raccoon*	2	372	0.25	0.30	0.55
Lisa*	2	299	0.23	2.28	2.51
Champ 1000 bridge	3	440	0.02	1.45	1.47
confl. to bridge	3	156	0.09	0.16	0.25
Carson Creek	3	120	0.03	3.62	3.65
Greenwood Creek	4	86	0.12	0.08	0.20
Lower White Oak	5	280	0.30	0.66	0.96
Grouse above Cow	5	1410	0.04	0.14	0.18

* data from J. McHugh, Six Rivers National Forest

string box or from aerial photographs. Almost five kilometers of streams were surveyed, which represents less than one percent of the total length of streams in the basin.

For each survey, average sediment production per unit length was calculated by adding all erosion volumes and dividing by the total length of the survey for each stream order (Table 9). Sediment production from streambanks (Table 10) was calculated by using the average sediment production for each stream order (Table 9). Channel lengths of all debris torrents were subtracted from the appropriate stream-order lengths in order to avoid double counting sediment production.

Streambank erosion discussion. Streambank sediment production is highest in second and third order-streams (Table 9). Characteristics of the stream orders explain the differences in erosion. First-order streams are ephemeral or intermittent and less deeply incised than higher-order streams. Peak streamflows are lower, and less material is available from the smaller cutbanks. Stream gradients are steeper in second and third-order streams than in higher-order streams where scouring debris flows may lose momentum. The higher-order streams also occupy channels in which a high percentage of the bed and banks consist of alluvium rather than bedrock. Bank erosion of alluvium was not included as a component of streambank erosion because remobilized alluvium has already been accounted for as sediment produced by some other process farther upstream.

As a check on streambank erosion calculations, total production volumes were converted to creep rates that could be compared with published rates. Soil creep conveys soil downslope to landslide sites and eroding streambanks where it enters the stream channel. Soil creep is most marked in the upper meter of most soils [Kojan, 1967], and a soil depth of one meter was used in the conversion. Converted creep rates were halved to account for sediment contributed from both sides of the stream. The 29-year period of the budget was used as the length of record. Soil creep rates calculated this way for Grouse Creek range from 0.3 cm/yr in first-order streams to 3 cm/yr in second-order streams and averaged 0.9 cm/yr for all stream orders. For comparison, soil creep rates measured from borehole tubes in an adjacent basin (Redwood

Table 9. Averaged sediment production by stream order.

Stream order	Total length of sampled reaches (m)	Total sediment production in reaches (m^3)	Length-averaged streambank sediment production (m^3/m)
1	884	150	0.17
2	1210	1973	1.63
3	716	1124	1.57
4	86	17	0.20
5	1690	523	0.31

Table10. Streambank erosion (m^3) separated by drainage sub-basin and stream order.

Drainage sub-basin	Stream order	Total stream length (m) *	Unit sediment production (m^3/m)**	Total sediment production (m^3)
Upper Grouse	1	102,724	0.17	17,463
	2	20,922	1.63	34,103
	3	8,656	1.57	13,590
	4	7,071	0.20	1,414
	5	2,865	0.31	888
White Oak Cr	1	42,725	0.17	7,263
	2	8,453	1.63	13,778
	3	3,597	1.57	5,647
	4	1,951	0.20	390
	5	914	0.31	283
Cow Cr	1	50,628	0.17	8,607
	2	12,561	1.63	20,474
	3	4,267	1.57	6,700
	4	2,438	0.20	488
Mosquito Cr	1	142,132	0.17	24,162
	2	30,051	1.63	48,983
	3	11,244	1.57	17,653
	4	2,559	0.20	512
	5	3,901	0.31	1,209
	6	7,004	0.31	2,171
Upper mid Grouse	1	38,678	0.17	6,575
	2	8,477	1.63	13,818
	3	1,189	1.57	1,867
	4	1,987	0.20	397
Lower mid Grouse	1	45,035	0.17	7,656
	2	16,289	1.63	26,551
	3	1,169	1.57	1,835
	4	514	0.20	103
Bear Cr	1	59,863	0.17	10,177
	2	20,386	1.63	33,229
	3	4,461	1.57	7,004
	4	3,501	0.20	700
Lower Grouse	1	53,889	0.17	9,161
	2	13,411	1.63	21,860
	3	7,925	1.57	12,442
	4	2,377	0.20	475
Main Grouse Cr above Mosq. Cr	5	4,097	0.31	1,270
Main Grouse Cr below Mosq. Cr	6	9,004	0.31	2,791
TOTAL		758,917		383,693

* debris torrent lengths are subtracted from totals

** see Table 9

Creek) range from 0.10 to 0.25 cm/yr on schist slopes and from 0.30 to 13.1 cm/yr on sheared Franciscan graywacke and mudstone slopes [Swanston et al., 1983]. The higher rates on Franciscan slopes in Redwood Creek were measured on slow-moving block glides, and similar features in Grouse Creek were measured as landslides. If these faster creep rates are ignored, then the creep rates in the two basins are within the same range.

Sediment production from streambank erosion in Grouse Creek may be higher because evidence of streambank erosion may be covered by vegetation in less than 29 years (the budget period). We found 27 percent of the larger landslides and 47 percent of debris torrent tracks revegetated within 15 to 20 years. Therefore, some of these features would have been overlooked during the stream surveys, and streambank erosion could be underestimated by approximately 20 to 30 percent.

Hillslope Erosion

Hillslope erosion processes include rilling and sheetwash, gullying, and mid-slope landsliding (as opposed to a lower-slope, streamside location). Sediment production by these three processes was calculated from field measurements at selected slope erosion inventory sites. Hillslope erosion processes account for a similar percentage of total sediment production as streambank erosion (Table 4).

We selected the slope erosion inventory sites to include the major controls on erosion rates in Grouse Creek: geology, climate, and land use. The importance of any one of these variables would be most easily evaluated if the other two were constant. In the complex natural environment of the Grouse Creek basin, this is impossible, and thus the range of values for sediment production from slope erosion reflects the influence of all three variables.

Bedrock at slope erosion sites include four lithologic units: Franciscan sandstone and siltstone, Franciscan schist, Galice metasediments, and the Ammon Ridge pluton (Table 11) (Figure 2). We did not survey any slope erosion sites on the Triassic and Paleozoic metasediments and volcanics that underlie a minor portion of logged area in the lower basin

Table 11. Geology and land use data for slope erosion inventory sites

Site	Geology	Land use *	Year of timber harvest
Grouse Mtn	Franciscan sandstone/siltstone	tycc	1987
Powerline	Franciscan sandstone/siltstone	cycc	1987
Whiting Ridge	Franciscan sandstone/siltstone	tycc	1986
Cow Cr Ridge	Franciscan sandstone/siltstone	cycc	1986
Headwaters	Franciscan sandstone/siltstone	cycc	1985
Greenwood	Franciscan sandstone/siltstone	tycc	1984
1600 Rd	Franciscan sandstone/siltstone	tycc	1984
Mid Cow	Franciscan sandstone/siltstone	tycc	1974
Upper Cow	Franciscan sandstone/siltstone	tycc	1970
White Oak	Franciscan sandstone/siltstone	tycc	1964
Above confl.	Franciscan sandstone/siltstone	old growth	NA
Grouse Lookout	Franciscan schist	tycc	1987
Blue Goo	Franciscan schist (MSZ) **	tycc	1968
Upper Bear	Franciscan schist	typc	1959
Big Opening	Franciscan schist	grazing	NA
Ammon Ridge	Galice metasediments	typc	1986
Hot burn	Galice metasediments	cycc	1984
Above cabin	Galice metasediments	cypc	1984
Upper Mosq. 1	Galice metasediments	cycc	1973
Upper Mosq. 2	Galice metasediments	cycc	1964
Sugarloaf	Galice metasediments	cycc	1964
Grouse south	Ammon Ridge pluton	cypc	1987
Grouse north	Ammon Ridge pluton	cypc	1987

* tycc - tractor-yarded clear cut
typc - tractor-yarded partial cut
cycc - cable-yarded clear cut
cypc - cable-yarded partial cut

** MSZ - major shear zone

(Figure 2). Sampled sites represent the range of land uses in the basin, and timber harvest units of different ages were included (Table 11) in order to account for the erosional effects of episodic storms as well as gradual revegetation. The basin locations of slope inventory sites are shown in Figure 9.

Rilling and sheetwash. Soil particles on slopes are entrained by raindrop impact and the shear stress imparted by water flowing in sheets and rills. Bare soils on logged slopes in Grouse Creek often have a granule-to-pebble-sized surficial armor layer. The armor layer is the result of winnowing due to raindrop impact erosion. Field evidence of sheetwash consists of fine sediment ponded in depressions and behind woody debris, and evidence for rilling is a network of small-scale, anastomosing channels on the surface of the slope. Rills were found primarily on bare skid trails, whereas ponded sediment was noted both on skid trails and logged slopes. Rills were observed less frequently than evidence of sheetwash due to the short length of slopes unbroken by obstructions or vegetation.

Sheetwash and rill erosion is calculated by use of the Universal Soil Loss Equation (USLE) [Wischmeier and Smith, 1978] modified by Dissmeyer and Foster [1984] for use on forest land. Soil loss (A; units = tons^{1} acre^{-1} year^{1}) is calculated using a rainfall and runoff factor (R; units = ft-tons^{1} in^{1} 10^{-2} acre^{-1} hour^{1} year^{1}), a soil erodibility factor (K; units = tons^{1} acre^{1} hour^{1} acre^{-1} ft-tons^{-1} in^{-1} 10^{2}), a slope length and slope steepness factor (LS), a cover and management factor (C), and an erosion control practice factor (P). The USLE predicts soil loss, not that amount of soil delivered to the stream channel. Because the amount of soil entering the stream channel is of interest in this study, we have added a soil delivery factor (D) to the equation:

$$A = RKLSCPD \qquad (3)$$

All factors with the exception of R and K are dimensionless. Soil loss (A) was converted to metric units of tonnes ha^{-1} yr^{-1} for comparison with other budget components.

The rainfall and runoff factor R of the USLE is a measure of storm energy and intensity in an area [Dissmeyer and Foster, 1984]. R is assigned one value for all of the Grouse Creek basin

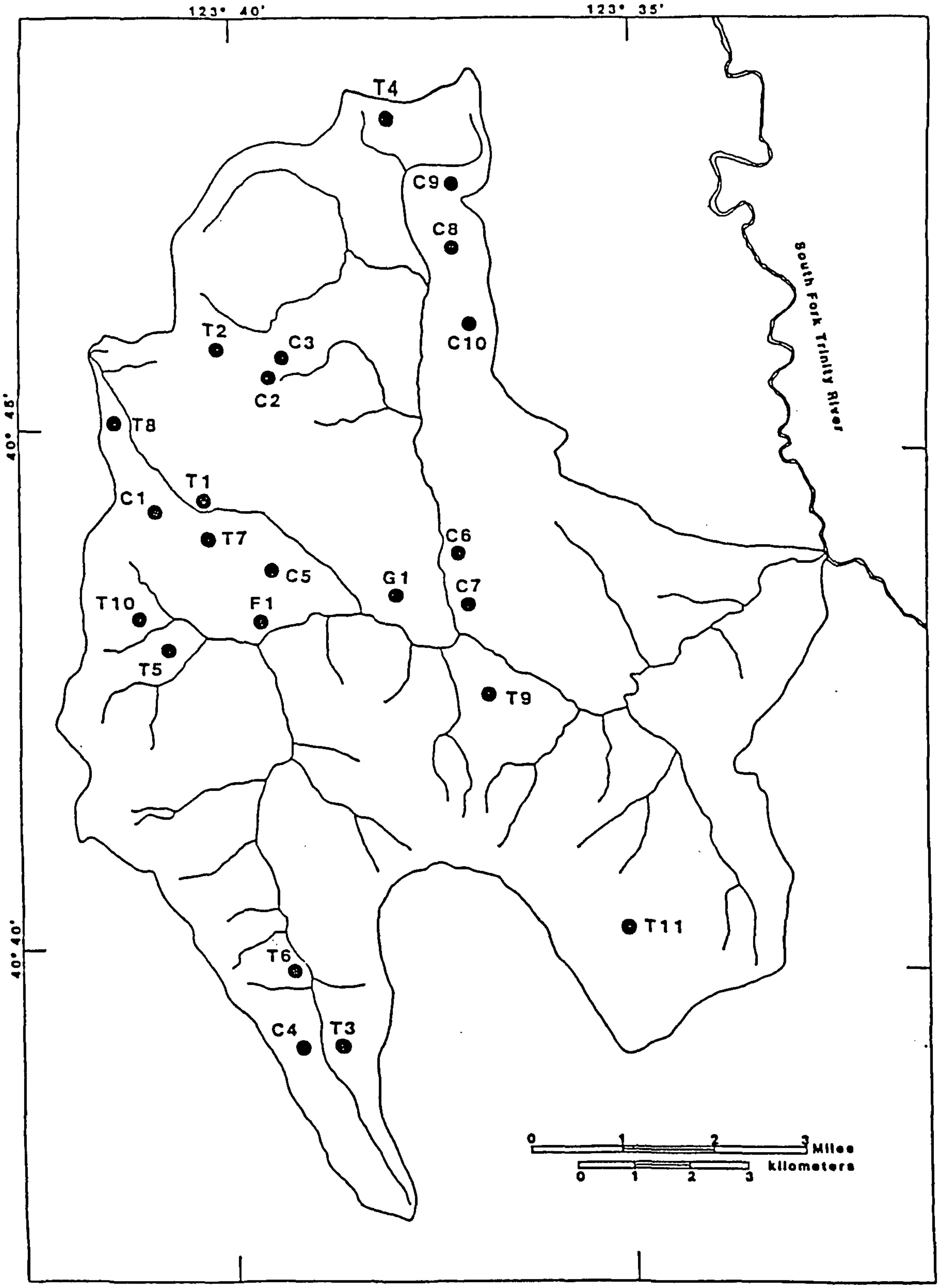


Figure 9. Location map of sites used for the slope erosion inventory. T = tractor-yarded sites; C = cable-yarded sites. Site numbers correspond to slope inventory locations in Table 13.

and is calculated by an equation designed to evaluate R in the western United States [Wischmeier and Smith, 1978]:

$$R = 27.38\ P^{2.17} \qquad (4)$$

where P is the 2-year, 6-hour rainfall in inches. P was calculated using data from a California North Coast rainfall study conducted to evaluate precipitation for Grouse Creek [Goodridge, 1989]. Using a mean annual precipitation for Grouse Creek of 70 inches, calculated by the isohyetal method [p.75, Dunne and Leopold, 1978], and the 6-hour storm recurrence data of Goodridge [1989], we determined that the 2-year, 6-hour rainfall is 2.40 inches (Figure 10). The R value for Grouse Creek is therefore 182.

Factor K reflects the erodability of the soil. Soil-survey-assigned K factors were not available for all hillslope erosion sites. We therefore averaged six K factor values from soil surveys in Grouse Creek covering the most intensely logged areas [Howell and Smith, 1989], and applied that average to all of the hillslope erosion sites. The average K factor, 0.22 ± 0.03, reflects the predominance of gravelly loam soils.

The length-of-bare-slope factor, L, is

$$L = (y/72.6)^m \qquad (5)$$

[Wischmeier and Smith, 1978] where y is the distance in feet from the point of origin of overland flow to the point at which sediment is deposited or the point at which runoff enters a well-defined channel. Variable y was measured in the field for each erosion site as the average slope distance over which there was evidence of uninterrupted sheetwash and rilling; y ranged from 0.5 to 23 meters and decreased with the age of revegetation. For slopes greater than 6°, m=0.5 in the above equation [Wischmeier and Smith, 1978].

The slope steepness factor, S, is a function of hillslope angle, which was measured on each erosion site (Table 12). For slopes greater than nine percent and y less than four meters in length,

$$S = 3.0 \sin^{0.8} b + 0.56 \qquad (6)$$

[McIsaac et al., 1987] where b is the hillslope angle. For slopes between 9 and 30 percent

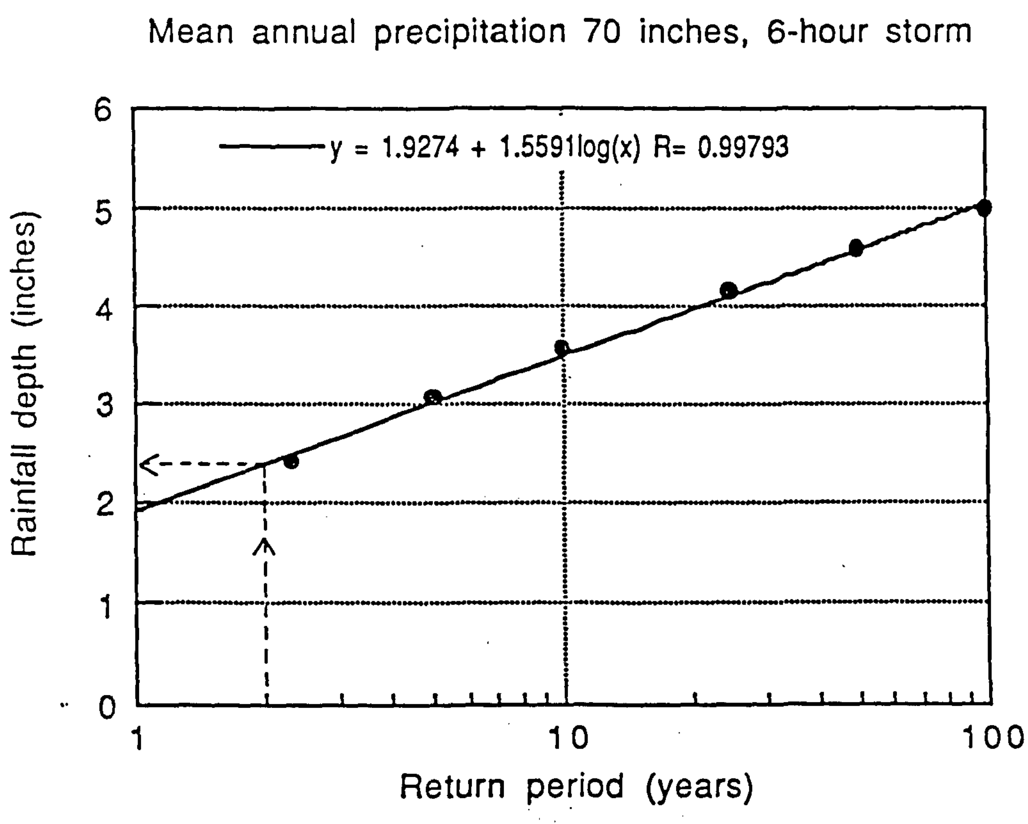


Figure 10. The relationship of rainfall depth to recurrence interval for a 6-hour storm in the northern California Coast Ranges in areas where the mean annual precipitation is 70 inches. Arrow indicates the value of P, the depth of rainfall with a recurrence interval of 2 years, used to calculate the rainfall and runoff factor R of the USLE for Grouse Creek.

Table 12. Field data and erosion yields for slope erosion sites.

Site No.	Site name	Area of sampled plot (ha)	Approx. year of harvest	Years since harvest	Slope (degrees)	Net gully yield to stream (m^3/ha)	Landslide yield to stream (m^3/ha)	L (length of bare slope)*	S (slope factor)*	C (cover management)*	USLE erosion rate w/o D factor (t/ha/yr)	D (mobilized sediment to stream)*	USLE erosion rate with D factor (t/ha/yr)
TRACTOR-YARDED HARVEST UNITS													
T1	Grouse Mtn	0.85	1987	2	30	21	0	0.795	5.92	0.0690	29.150	0.99	28.850
T2	Grouse lookout	4.76	1987	2	22	0	0	0.820	5.17	0.0620	23.630	0.05	1.180
T3	Whiting Ridge	7.54	1986	3	17	25	5.3	0.475	3.43	0.0390	5.690	0.20	1.140
T4	Ammon Ridge	3.54	1986	3	29	0	0	0.300	2.24	0.0210	1.267	0.01	0.013
T5	Greenwood	1.85	1984	5	23	82	8.1	0.820	4.61	0.0700	23.740	0.50	11.870
T6	1600 Road	6.00	1984	5	27	0.9	0	0.638	5.37	0.0200	6.140	0.24	1.480
T7	Mid Cow	2.82	1974	15	26	122	0	0.590	5.25	0.0029	0.807	0.34	0.274
T8	Upper Cow	6.05	1970	19	25	40	0	0.368	2.07	0.0064	0.437	0.05	0.022
T9	Blue Goo	10.05	1968	21	21	209	3.8	1.180	4.22	0.0120	5.360	0.80	4.290
T10	White Oak	0.73	1965	24	25	0	0	0.260	2.07	0.0070	0.338	0.02	0.007
T11	Upper Bear	3.75	1959	30	17	0.49	0	0.301	1.68	0.0110	0.499	0.01	0.005
CABLE-YARDED HARVEST UNITS													
C1	Powerline	1.97	1987	2	33	0	0	0.475	6.46	0.0200	5.520	0.01	0.055
C2	Grouse south	4.92	1987	2	31	9.3	0	0.475	6.20	0.0750	19.500	0.10	1.950
C3	Grouse north	4.64	1987	2	31	0	0	0.823	6.10	0.0510	22.980	0.01	0.230
C4	Headwaters	3.06	1985	4	29	0	0	0.425	2.24	0.0380	3.250	0.15	0.487
C5	Cow Cr Ridge	2.34	1986	3	35	0	0	0.165	0.24	0.0090	0.314	0.01	0.003
C6	Hot burn	1.56	1984	5	32	0	0	0.523	6.28	0.0240	7.080	0.25	1.770
C7	Above cabin	2.90	1984	5	35	0	0	0.582	6.81	0.0100	3.560	0.01	0.036
C8	Upper Mosq. 1	1.98	1973	16	27	0	0	0.150	2.15	0.0020	0.058	0.01	0.001
C9	Upper Mosq. 2	1.98	1964	25	27	0	0	0.150	2.15	0.0020	0.058	0.01	0.001
C10	Sugarloaf	2.93	1964	25	32	0	0	0.213	2.37	0.0020	0.091	0.01	0.001
PRAIRIE AND GRASS-OAK WOODLAND													
G1	Big Opening	23.80	NA	NA	28	4.7	11.3	0.301	2.20	0.0067	0.399	0.05	0.020
OLD GROWTH FOREST													
F1	Above confl.	3.70	NA	NA	35	0	0	0.213	2.48	2 E-06	1 E-04	0.01	1 E-06

* dimensionless

steepness (5-17°) and y greater than four meters in length,

$$S = (12 \pm 7)\sin(b) - 0.08 \tag{7}$$

[McIsaac et al., 1987].

The cover-management factor, C, uses nine subfactors: (1) amount of bare soil, or conversely, ground cover, (2) canopy, (3) soil reconsolidation, (4) high organic content, (5) fine roots, (6) residual binding effect, (7) onsite storage, (8) steps, and (9) contour tillage [Dissmeyer and Foster, 1984]. Contour tillage is also the P factor of the USLE (equation 3), but for forest lands it is combined with the cover-management factor (see below). Values for subfactors 1-8 in Grouse Creek were derived from field observations, published soil surveys, and from tables and figures for untilled soils in Dissmeyer and Foster [1984].

The P factor [Wischmeier and Smith, 1978] is used on agricultural sites to evaluate runoff reduction from contour tillage. Forest-site preparation by disking is similar to tillage but judged less effective [Dissmeyer and Foster, 1984]. Disking is not practiced in Grouse Creek, so P is assigned a value of 1.0 in all calculations.

Factor D is the fraction of sediment mobilized by sheetwash or rilling that enters a stream channel. A similar modification of the USLE has been applied by other investigators [Williams and Berndt, 1972; Holberger and Truett, 1976; Dissmeyer and Foster, 1981]. D was estimated on each slope erosion site by assessing the interconnectedness of bare areas and whether the bare areas drain directly to a stream. D is unity where bare areas at a site drain directly to a stream. If sediment delivery to streams appeared minimal, only one percent of mobilized sediment was assumed to enter a stream system each year (D=0.01) (Table 12). Values of D ranged from 0.01 to 0.34, with the exception of one 1987 tractor-yarded site where D=0.99 (Table 12). A high value of D indicates there was a gully system conveying sediment to the stream.

Soil yields from sheetwash and rilling for all logged sites over the duration of the budget period were calculated using the relation of yield versus time since logging (Figure 11) in conjunction with the logging history (Table 2). Table 13 shows these yields for different areas at different times in the budget period. All areas logged within an aerial photograph interval were

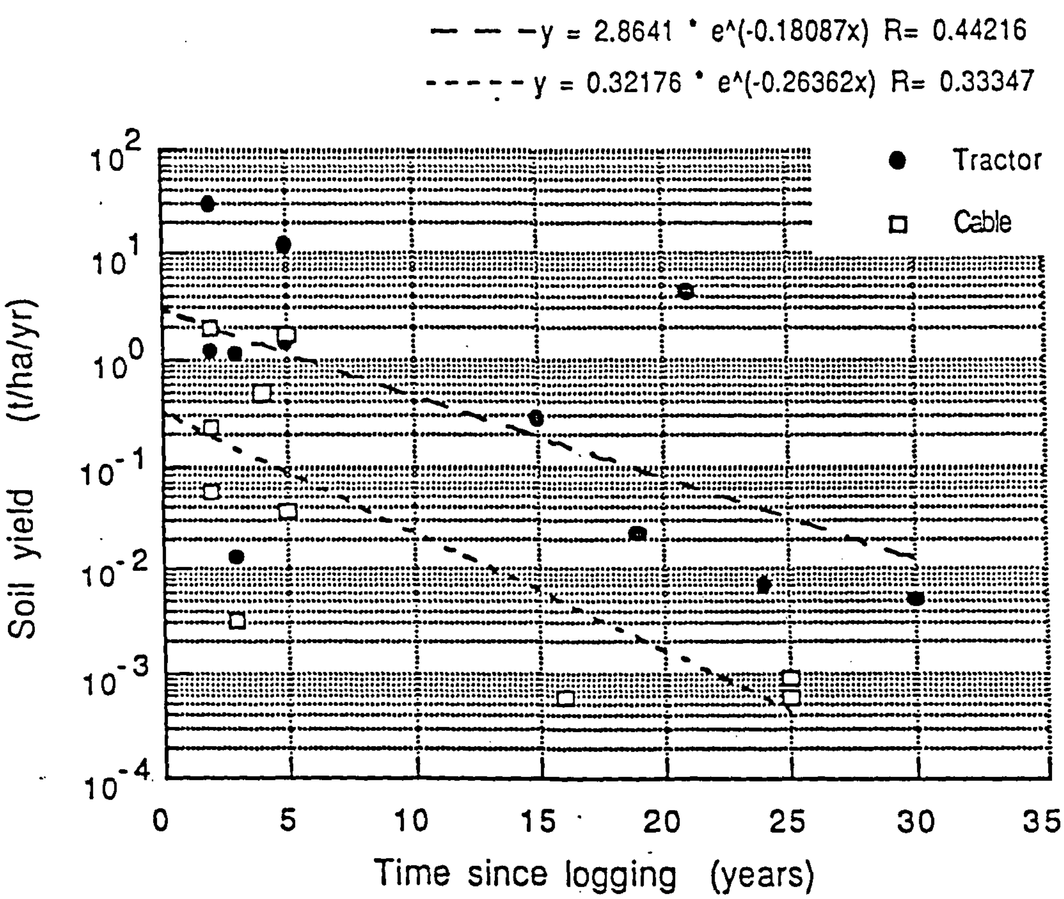


Figure 11. Semi-log plot of hillslope erosion sediment yields (m^3/ha) as a function of time since logging for two harvest methods. Closed circles are tractor-harvest units. Open squares are cable-yarded harvest units. Lines represent the best fit for the decrease in sediment production from sheetwash and rill erosion for both tractor and cable-yarded units.

Table 13. Time distribution of hillslope erosion (tonnes) by yarding mothod.

		Hectares reduced for		1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	
Tractor cut	Hectares	re-entry	age(x)→	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Totals
1960	953			2,277	1,900	1,586																											5,763
		851					1,182	987	823	687	573	479	399	333	278	232	194	162	135	113	94	78	65	55	46	38	32	26	22	18	15	13	7,081
1966	1,150						2,750	2,295	1,915	1,598	1,334	1,113	929	775	647	540	451	376	314	262	219	182	152	127	106	88	74	62	51	43	36	30	16,468
1970	709											1,695	1,414	1,180	985	822	688	573	478	399	333	278	232	193	161	135	112	94	78	65	55	46	10,014
1972	248														589	492	410	342	286	238	199	166	139	116	97	81	67	56	47	39	33	27	3,422
1975	608																	1,449	1,209	1,009	842	703	587	489	409	341	285	237					7,560
		561																											183	153	128	107	570
1980	276																					681	551	460	384	320	267	223	186	155	130	108	3,447
1982	102																								243	203	169	141	118	98	82		1,056
		49																														33	33
1985	235																											561	468	391	326	272	2,018
1988	352																														842	702	1,544
		Totals		2,277	1,900	1,586	3,932	3,281	2,738	2,285	1,907	3,287	2,743	2,289	2,499	2,088	1,741	2,902	2,421	2,021	1,686	2,068	1,728	1,440	1,445	1,206	1,007	1,401	1,154	963	1,648	1,337	58,976
Cable cut	hectares	ha adjusted for re-entry																															
1960	0			0																													0
1968	234						58	44	34	26	20	15	12	9	7	5	4	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0	249
1970	192											47	38	28	22	17	13	10	8	6	4	3	3	2	2	1	1	1	1	0	0	0	204
1972	137														34	26	20	15	12	9	7	5	4										132
		126																						3	2	2	1	1	1	1	0	0	11
1975	66																	16	13	10	7	8	4	3	3	2	2	1	1	1	1	0	69
1980	82																					20	15	12	9	7	5	4	3	2	2	1	82
1982	113																								28	21	16	13	10	7	6	4	105
1985	141																											35	27	21	16	12	110
1988	203																														50	38	89
		Totals		0	0	0	58	44	34	26	20	63	48	37	62	48	37	45	34	26	20	36	27	21	44	34	26	55	42	32	75	58	1,052
																													Total				60,028

Roads are subtracted by reducing measured areas by the average of 3%
Logged units that are re-entered are re-set to erosion rate at year 1

Tractor yarded erosion yield rate (t/ha/yr)= 2.8641*e^(-0.18087*age of cut x)
Cable yarded eroison yield rate (t/ha/yr)= .32176*e^(-0.26362*age of cut x)

assumed to be logged during the middle of that interval. Roaded areas were excluded by subtracting three percent of the logged area because road erosion is accounted for as a separate component of the budget.

The USLE erosion rate calculated for the grass-oak woodlands (Table 12) was multiplied by the length of the budget period and the area to obtain the sediment production total of 122 tonnes (Table 4).

Sediment production from hillslope erosion in old growth forest is essentially zero (Table 14). The cover management factor C in the USLE calculation is small (2.1×10^{-6}) because of the lack of bare soil, and the D factor is minimal. The only bare ground on hillslopes found in the old growth were discontinuous networks of game trails.

Gullying - Gullying is a significant erosion process on most tractor-yarded slopes because water is concentrated by skid roads. It is much less common on cable-yarded slopes and on grass and oak woodlands. The majority of gullies are associated with tractor yarding. No gullies occur within the old-growth forest.

Gullies are bare-walled channels that are at least 0.01 m^2 in cross-sectional area. Sediment yields from gullies were calculated from gully measurements on each slope erosion site (Table 12). Field work consisted of measuring cross-sectional areas and lengths of all gullies on the site, and assessing the fraction of sediment mobilized by gullies that was delivered to a stream system. Total gully volumes were divided by the area of the site and the fraction of stream delivery to calculate a unit yield.

Total sediment yield from gullying on lands logged between 1959 and 1987 ranges from 0 to 209 m^3/ha. Because gullying does not occur on all sites, there is not a clear correlation of cumulative gully yield with time (Figure 12). For this reason, gully erosion volumes were calculated as a fixed yield per hectare rather than assuming gully yield is dependent on time since logging. Cable-yarded sites were assigned a gully yield of 9.3 m^3/ha, which was applied to 10 percent of the total cable-yarded areas to reflect that portion of the sample with gullying.

Gully yields from tractor-yarded sites were first ranked, then stratified by order of

Table 14. Hillslope erosion from old-growth forest.

Aerial photo interval	Area (ha)	Total (tonnes)*
1960-1966	13,334	0.080
1966-1970	11,970	0.048
1970-1972	11,024	0.022
1972-1975	10,627	0.032
1975-1980	9,926	0.050
1980-1982	9,560	0.019
1982-1985	9,335	0.028
1985-1988	8,995	0.027
1988-1989	8,495	0.008
Total		0.314

* erosion rate is 1E-6 t/ha/yr

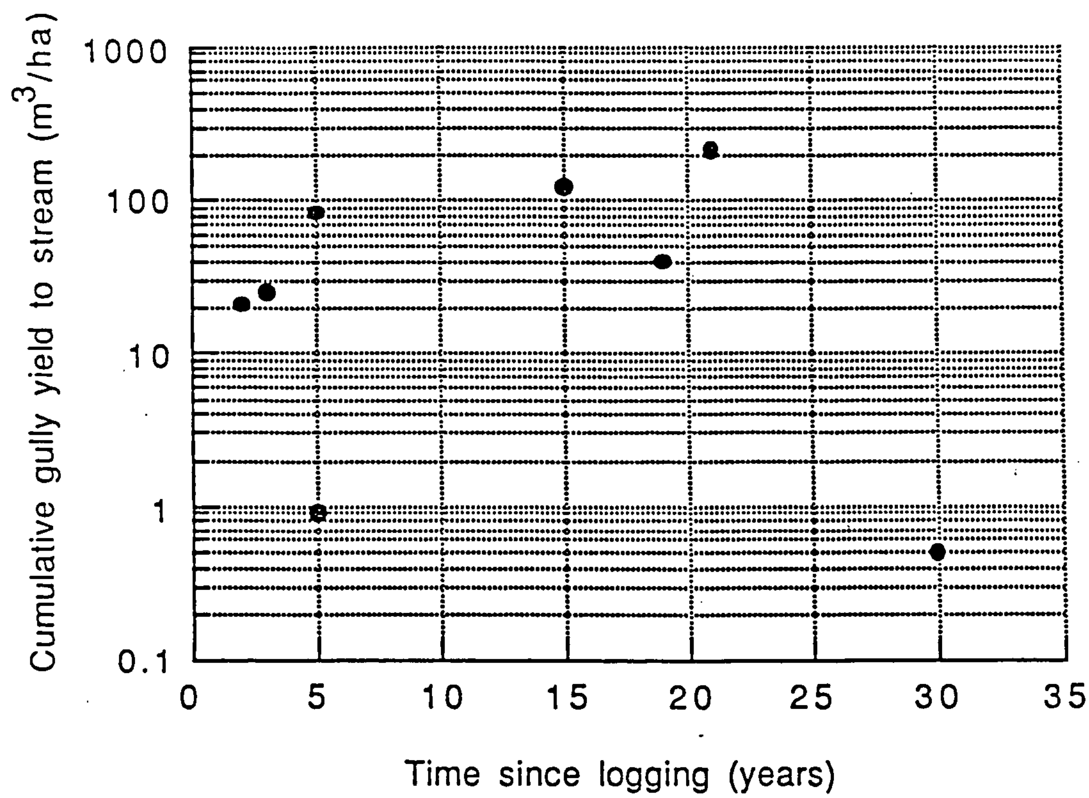


Figure 12. Semi-log plot of gully yields from tractor-yarded slope erosion sites (m^3/ha) as a function of time since logging. Sites in which no gullying was measured are plotted below the log axis.

magnitude. The yield in each magnitude class was then averaged, and the class averages were weighted in proportion to the percentage of the tractor-yarded sites in each range to produce a weighted average yield of 45.6 m^3/ha (Table 15). The weighted average yield was applied to the total of all tractor-yarded areas. The sediment produced from all gullying is listed in Table 16.

Road areas were not removed from the calculations for hillslope gullying. Gullies in roads are part of the gully network on the hillslope, so were included in the slope erosion surveys.

Mid-slope landsliding - Landsliding in Grouse Creek is infrequent on mid-slope locations not associated with roads, stream crossings, or other processes already inventoried. Sediment production from mid-slope landsliding was estimated from the slope surveys. No landslides were observed on cable-yarded sites and only 3 out of 11 tractor-yarded sites had landslides (Table 12). Based on the slope surveys, the average landslide yield of 5.7 m^3/ha (Table 12) was applied to 27 percent of all tractor-yarded areas to reflect that portion of sampled sites with landsliding (Table 16).

Both gullying and mid-slope landsliding contribute sediment from the entire soil column. An average soil density was computed from lab analyses of soils in the area [Howell and Smith, 1989]. Gully and mid-slope landslide erosion volumes were converted to tonnes using a density of 1.3 t/m^3 (Table 16).

Hillslope erosion discussion. Gullying accounts for 80 percent of all sediment from hillslope erosion processes and is mainly generated from tractor-yarded slopes. Sheetwash and rill erosion contribute approximately 17 percent and mid-slope landsliding approximately 3 percent of the total.

Sediment production by sheetwash and rilling from logged sites spans six orders of magnitude (Figure 11). This range reflects variability in sediment production as a consequence of different site conditions. The production estimates are also subject to error if factors are improperly evaluated.

The D factor spans 1.5 to 2 orders of magnitude (Figure 13) and accounts for most of the variability in sediment production. The D factor is the most dependent on site conditions, which

Table15. Gully yield rates applied by percentage from sample sites.

Order-of-magnitude class interval	Percent of field measure-ment within class interval	Average yield within order-of-magnitude class (m3/ha)	Weighted yield, adjusted for % of total number of samples (n=11) within class interval (m3/ha)
< 0.1	27.3	0	0
0.1 - 1.0	18.2	0.695	0.13
1.0 - 10	0	0	0
10 - 100	36.4	42	15.29
100 - 1000	18.2	166	30.21
		Total	45.63

Table 16. Total sediment yield from hillslope erosion.

Erosion process		Yield (m^3)	Yield (tonnes)
Sheetwash and rilling	*	60,028	60,028
Gullying - tractor	**	208,164	270,613
Gullying - cable	**	1,109	1,442
Mid-slope landslides	**	6,928	9,007
Total		276,229	341,090

* conversion factor of 1.0 t/m^3 used (avg. density of upper soil layer)
** conversion factor of 1.3 t/m^3 used (avg. density of entire soil column)

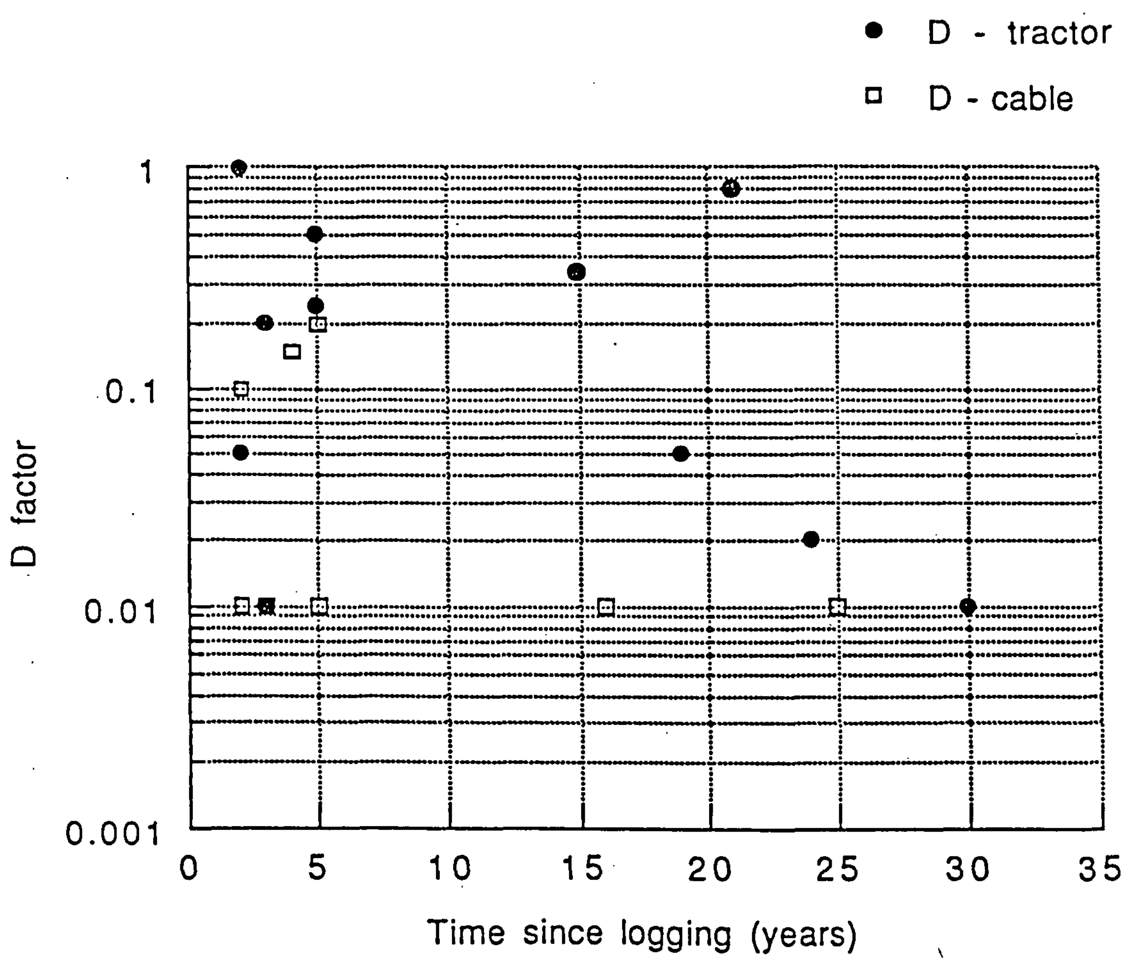


Figure 13. Variation in the value of the sediment delivery factor (D) as a function of time since logging for tractor-yarded sites (closed circles) and cable-yarded sites (open squares).

vary considerably as a function of slope stability, yarding methods, and land ownership. L and C factors each span about one order of magnitude (Table 12; Figures 14 and 15) and generally decrease with time since logging. Errors in L, C, and D could alter the relative magnitude of erosion among sites with different inherent site characteristics, management, and storm histories. Factor S depends on measurements of slope and is subject to small errors.

Factors R, K, and P are constants in the calculations, and therefore do not contribute to the range of sediment production. Uncertainty in R is likely to be less than a factor of two on the basis of an evaluation of R for the low and high ends of Grouse Creek precipitation isohyets (50 inches and 90 inches). Uncertainty in K is minimal because of the small differences in K values for Grouse Creek soils. Any errors in assigning values to R and K would affect all erosion rates uniformly. P is assigned a value of unity because no tillage occurs on Grouse Creek sites.

The following conclusions with regards to tractor-yarded sites are based mainly on sampling tractor-yarded clear cuts and not tractor-yarded partial cuts. However, limited sampling of tractor-yarded partial cuts (two sites) suggests that if geologic and topographic characteristics are similar, sediment yields from the partial-cut sites are similar to those from the clear-cut sites. Sediment yield from cable-yarded partial cuts is indistinquishable from sediment yield from cable-yarded clear cuts.

Sediment yield from sheetwash and rilling is most significant directly following logging and exponentially decreases with time (Figure 11; Table 12). Sediment yield also varies with type of logging. Because less bare ground is exposed by cable-yarding methods than by tractor yarding, sediment production from sheetwash and rilling after logging on cable-yarded slopes is much less (over an order of magnitude) than on tractor-yarded slopes (Figure 11). However, tractor-yarded cuts show the same rate of decreasing sediment yield as cable-yarded sites (Figure 11). This exponential decrease is primarily a function of decrease in the C-factor with time (Table 12).

Two tractor-yarded sites that are unrepresentative exert an influence on the relationship of sediment yield to age of logged slope (Figure 16). The Ammon Ridge site is a recently logged,

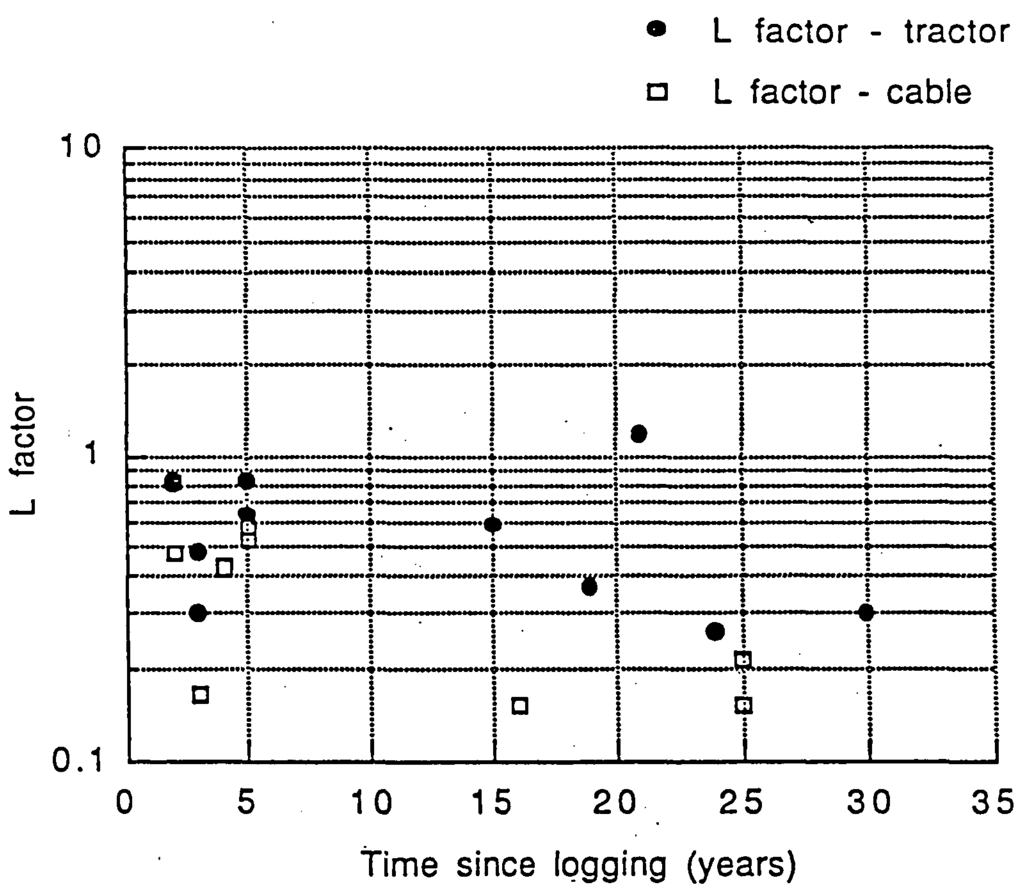


Figure 14. Semi-log plot of USLE L-factor for tractor and cable-yarded units as a function of time since logging.

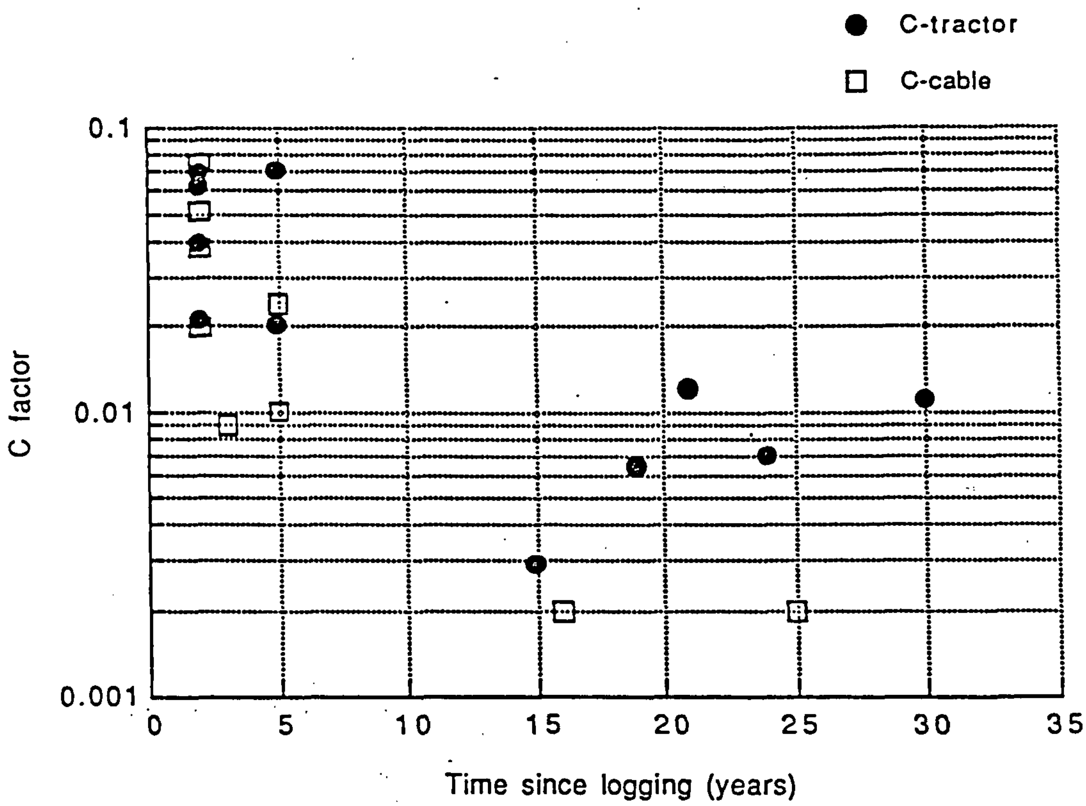


Figure 15. Semi-log plot of USLE C-factors for both tractor and cable-yarded units as a function of time since logging.

tractor-yarded partial cut with a very low rate of sediment production (Table 12). The Blue Goo site is an older logged slope with a high rate of sediment production (Table 12). Though measurements on these sites accurately reflect the local conditions, these sites are not representative of the erosional status of a tractor-yarded slope 3 and 21 years, respectively, after timber harvest. If these sites are eliminated, the best-fit relationship suggests erosion rates immediately following logging are a little more than a half order of magnitude greater but that erosion rates in the second and third decades following logging are less (Figure 16). Recalculating total sheetwash and rill erosion yields without these sites predicts twice as much sediment production from sheetwash and rilling of logged slopes. Relative to the sediment budget as a whole, however, these differences are minor and change the sediment contribution from sheetwash and rilling from one to two percent.

Total erosion on logged slopes in Grouse Creek is approximately 48 m^3/ha as compared to 19 m^3/ha from a recent study of logged slopes in the northern California Coast Ranges [Lewis and Rice, 1989]. The difference in erosion values reflects differences in logging practices and storm events between the two studies. The Lewis and Rice study included 357 sites logged during the one-year period of 1978-1979, a peak period of logging activity that provided a large study population. In contrast to most of the logging activity in Grouse Creek, timber harvesting of the 1978-1979 study sites complied with current California Forest Practice Regulations and occurred during a period without major storm activity. In addition, erosion values from the 1978-1979 study sites ranged from 0 m^3/ha on 40 percent of the sites to 1,270 m^3/ha on less than one percent of the sites, indicating that a minor portion of sites are producing the majority of sediment. Due to the unstable geology, Grouse Creek may contain a higher percentage of the high-erosion-yield sites than the large sample.

Road-related Erosion

Erosion from roads is a persistent source of sediment in logged basins [Reid and Dunne, 1984] because mobilization of fine-grained road-surface and cutbank sediments is not dependent

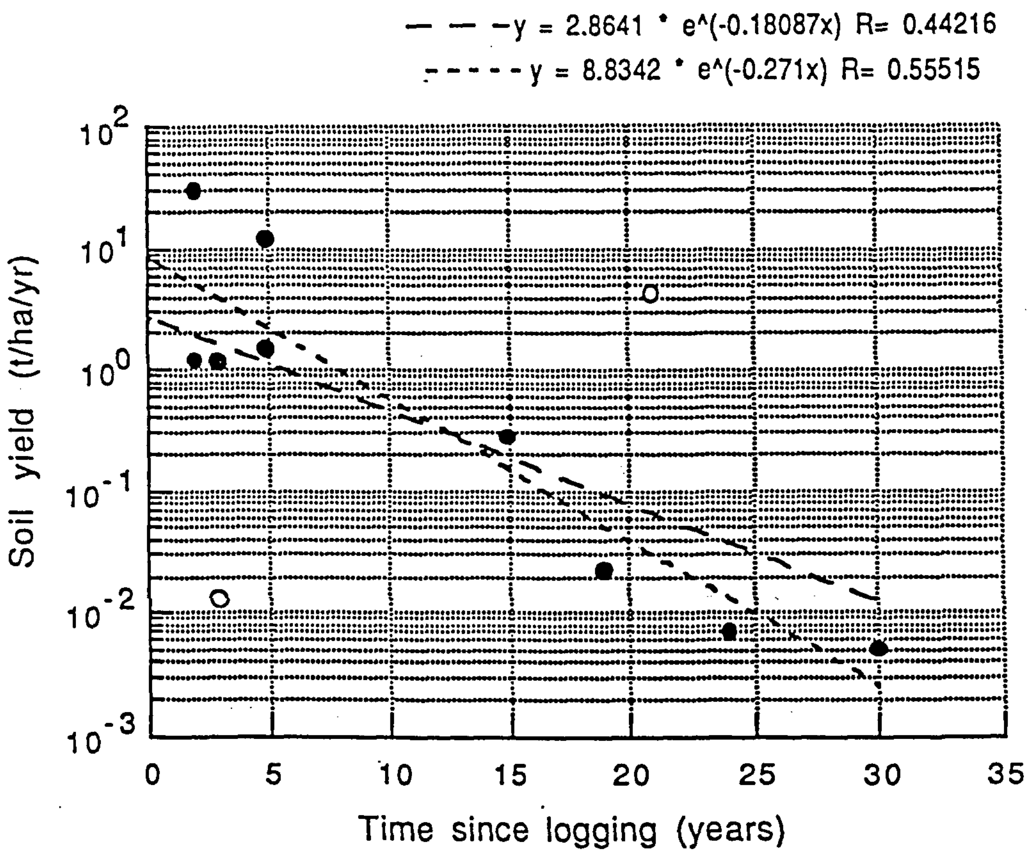


Figure 16. Semi-log plot of hillslope erosion sediment yields for tractor-yarded cuts. The long dash line represents the best fit through all data points; the short dash line represents the best fit through the data excluding the two points open-circle data points.

on major storm events. Processes included in road-related erosion are sheetwash and rill erosion from road surfaces; sheetwash, ravel, and rilling from road cutbanks; and failure of road fills at stream crossings. Although road-related erosion contributes the smallest percentage to the sediment production in Grouse Creek (Table 4), sediment introduced to streams from road surfaces and cutbanks is generally finer than 2 mm [Duncan et al., 1987; Reid, personal communication, 1989], which is the size fraction of sediment most harmful to fish and water quality [Cederholm et al., 1981].

Erosion from road surfaces. Erosion from road surfaces is extremely sensitive to traffic levels [Reid, 1981]. In the Clearwater basin on the Olympic Peninsula in Washington, Reid [1981] used precipitation records and measurements of runoff and sediment concentration from road segments to establish a relationship between road-surface sediment yield and road use. To estimate erosion from road surfaces, we applied data of Reid and Dunne [1984] to three categories of roads: moderate-use, light-use, and abandoned roads. Moderate-use roads carry one to four log trucks a day during the logging season, which in Grouse Creek is the dry, summer season. Light-use roads are traveled by cars and pickup trucks. Abandoned roads are unmaintained and most often are closed to traffic.

Even though haul-road traffic may be heavier than four trucks per day, the heavy-use road category of Reid and Dunne [1984] was not used for Grouse Creek because current California forest practices legislation discourages hauling during rainy periods. The moderate-use road category most appropriately reflects conditions during hauling in Grouse Creek.

Three adjustment factors were employed prior to applying Clearwater basin road-surface-sediment-yield rates to Grouse Creek. First, to account for the difference in precipitation, sediment yield rates were multiplied by 0.76, which is the ratio of the Grouse Creek R factor (see hillslope erosion section) to the Clearwater R factor [Reid, 1981]. R-factor differences better reflect differences in the erosion potential of rainfall between two basins than differences in mean annual precipitation. Second, average road width in Grouse Creek is 1.3 times the average width of Clearwater roads (5.2 meters vs 4.0 meters). Third, the fraction of Grouse Creek road culverts and waterbars contributing flow directly to streams (as determined from road surveys (Table 17)) is 0.32 times the direct sediment delivery for Clearwater roads.

Total sediment production from road-surface erosion was calculated using the adjusted road-surface yields (Table 18) and the length of road in each road-use category (Table 3) for each year during the budget period (Table 19). All sediment introduced into the stream channels from road surface erosion is assumed to be 2 mm or finer [Duncan et al., 1987; Reid, personal communication, 1989].

Sediment production from road cutbanks. Sediment production from road cutbanks was determined from road surveys. Road segments in the surveys represent different ages, uses, slope positions and locations in the basin. Road and cutbank properties were recorded every 0.1 mile by vehicle or every 50 paces by foot. Fourteen road segments were sampled (Table 17).

Road cutbanks are divided into an upper cut face and a debris apron that accumulates at the base of the cut face (Figure 17). The net erosion of cutbanks is the difference between the amount of material eroded from the cutface and the amount stored in the debris apron. The volume of eroded material available for fluvial transport from the road surface or ditches is the fraction of net eroded material that is 2 mm or finer.

Depth of erosion was determined by measuring cutbank retreat perpendicular to the cut face. Overhanging soil and root masses or the depth of exposed roots provided depth estimates. Slope and distance of the cut face and the debris mantle was measured. The fine fraction of the cut face and debris apron (< 2mm) was visually estimated using grain-size density cards.

Figure 17 shows the simplified geometry assumed in calculating the sediment lost from cutbanks. A factor of 0.71 accounts for the reduction in density of the material eroded from the cut face and redeposited in the debris apron [Reid, 1981]. Unit areas of erosion were converted to volumes of erosion by using a unit meter road length. Sediment delivery rates were computed by multiplying unit volumes by the fraction of the runoff that drains to a stream, and dividing this product by the age of the road (Table 17). The final rate was converted to units of mass using a density of 1 g/cm^3 [Reid, 1981].

Table 17. Road erosion survey data.

Road segment	Age (years)	Number of measurements	Length of survey (m)	Road use (below)	Slope position	% of cutbank vegetated	Average slope distance of cutbank (m)	Fraction of surveyed road length with cut bank	Average road width (m)	Fraction of road Insloped	Fraction of road with inboard ditches	Fraction of road with eroding in-board ditches	Fraction of road with an outside berm	Volume avail. for fluvial transport (m^3/m)	Net erosion rate (cm/yr)	Fraction of culverts & waterbars draining to streams	Sediment delivery rate to streams (m^3/km/yr)
Upper Cow Crk	2	10	860	L	Mid	-	4.2	1.00	6.8	0.20	0.10	0.00	0.90	.07 + .07	.09 +1.41	0.89	30.88
Champion 1700 *	5	9	900	A	Mid	-	7.1	0.90	4.8	0.56	0.40	0.10	0.30	.13 + .12	.84 + .75	0.44	11.80
x Sims Mtn. 4N40	11	14	2410	L	Up-mid	17	4.4	1.00	5.0	0.00	0.00	0.00	0.47	.21 + .14	.83 + .44	0.07	1.38
Brays Opening *	17	15	2250	L	Mid	5	9.0	1.00	5.3	0.47	0.27	0.07	0.67	3.58 + 6.67	2.45 + 2.45	0.48	**[101.21]
x Sims Mtn. 4N36F	17	11	800	L	Upper	8	2.0	0.64	4.0	0.09	0.00	0.00	0.00	.06 + .09	.22 + .27	0.09	0.34
x Grouse Mtn. 5N04	22	15	2410	A	Upper	14	6.5	1.00	5.3	0.00	0.00	0.00	0.20	.28 + .37	.36 + .39	0.11	1.46
Champion Spur	23	13	1020	A	Mid	-	7.4	0.92	4.0	0.31	0.00	0.00	0.62	.41 + .52	.61 + .72	0.14	2.53
x Champion 2000 Spur	25	12	1450	L	Mid	30	4.4	0.83	4.9	0.33	0.42	0.33	0.75	.42 + .78	.71 + .78	0.10	1.64
Cow Chip Springs	29	17	2570	L	Upper	41	5.6	0.88	5.6	0.29	0.59	0.06	0.94	.13 + .18	.08 + .24	0.35	1.52
x Devils Canyon	29	13	1090	A	Mid	7	9.1	0.98	5.8	0.54	0.08	0.00	0.77	.64 + .43	.49 + .45	0.64	14.03
Champion 1000 *	29	10	1600	M	Up-mid	17	11.8	0.96	5.4	0.10	0.50	0.20	0.80	1.37 + 3.68	.21 + .69	0.40	18.87
Champion 2000	30	28	1240	M	Up-mid	-	-	-	-	-	-	-	-	-	-	0.10	-
Upper Bear Crk	30	12	1600	L	Upper	-	1.7	0.75	-	-	-	-	-	.15 + .19	.24 + .25	***[.32]	1.60
Cow Crk. 4N06 *	34	24	3200	M	Up-low	28	4.6	0.96	5.7	0.21	0.29	0.04	0.54	.54 + .82	.47 + .70	0.32	5.14
Average						19	6.0	0.91	5.20	0.28	0.22	0.06	0.58			0.32	7.60
St dev						12	2.9	0.11	0.74	0.19	0.22	0.10	0.29			0.25	9.52
n=						9	13	13	12	12	12	12	12			13	12

* 1-3 cutbank slides in sample
** Brays Opening omitted from total average as an outlier; omission reduces the mean by a factor of 2 but reduces the median by less than .5.
*** Data not collected; averaged survey value used to compute delivery rate.

M - moderate use road
L - light use road
A - abandoned road

x Data from surveys used to compute sediment delivery rates to streams from other eight surveys where debris mantles were not separated from cut faces

Table 18. Unit sediment yields (t/km/yr) for three different road-use types and two different types of road-related erosion.

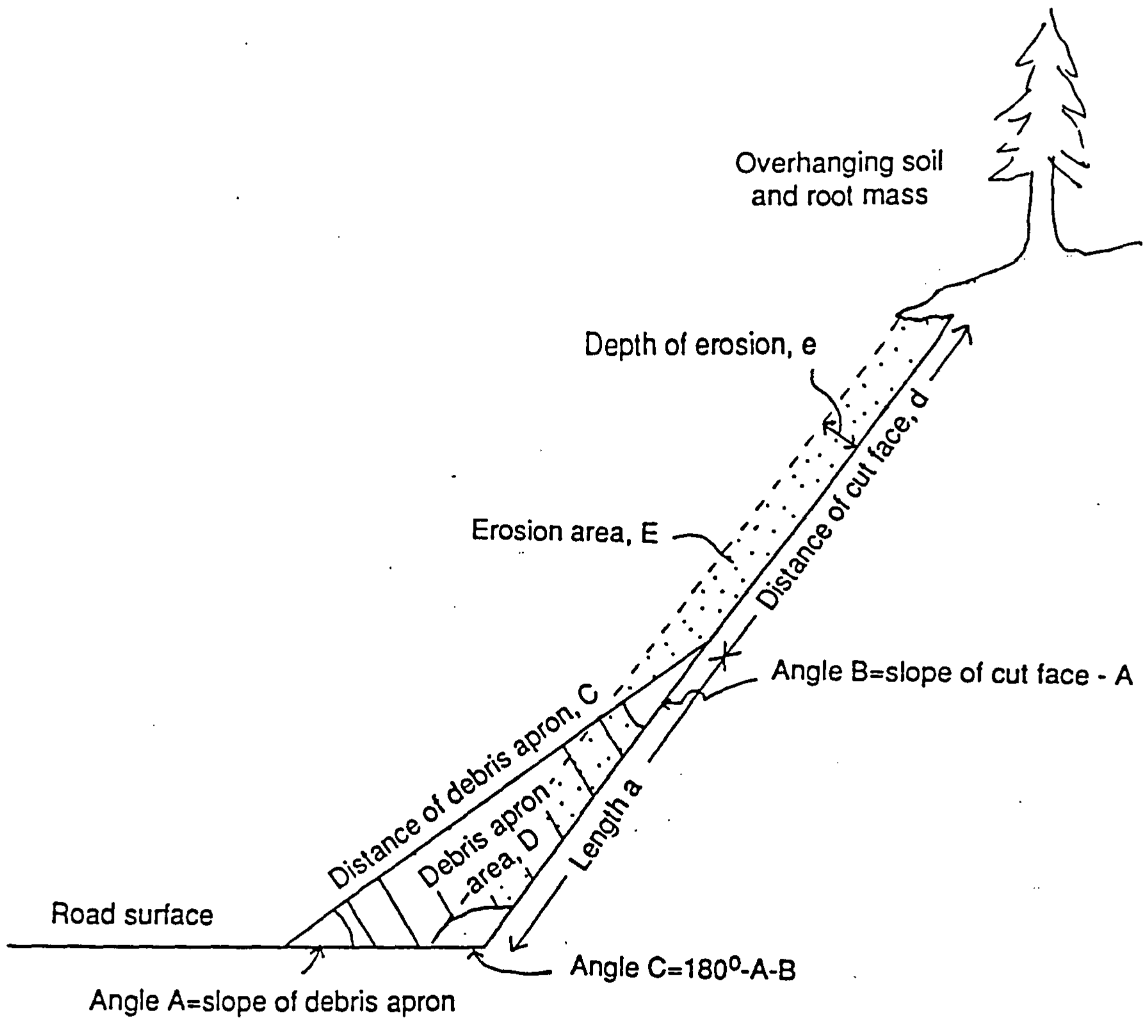
Type of erosion	Type of road use: Moderate use roads	Light use roads	Abandoned roads
Road surfaces *	42.0	3.80	0.51
Adjusted road surfaces **	13.4	1.22	0.16
Cutbanks	7.6	7.6	7.6

* unit sediment yield for road surfaces from Reid and Dunne(1984)

** Grouse Creek adjustment factors:
R factor ratio = .76
road width ratio factor = 1.3
road surface drainage to streams = .32
Total adjustment factor = (.76)(1.3)(.32) = .32

Table 19. Sediment production (tonnes) for road-related erosion, separated by road use and source of sediment.

Sediment source	1960	1961-1966	1967-1970	1971-1972	1973-1975	1976-1980	1982-1982	1983-1985	1986-1988	TOTAL
MODERATE USE ROADS										
Road-surface sediment yield	666	10,195	6,732	2,881	4,422	7,531	2,155	3,638	4,667	42,887
Cutbank sediment yield	378	5,782	3,818	1,634	2,508	4,271	1,222	2,063	2,647	24,324
LIGHT USE ROADS										
Road-surface sediment yield	4	73	188	152	283	448	224	318	311	2,001
Cutbank sediment yield	24	456	1,170	947	1,763	2,789	1,395	1,981	1,938	12,464
ABANDONED ROADS										
Road-surface sediment yield	0	2	14	10	22	55	29	47	44	224
Cutbank sediment yield	0	105	681	492	1,058	2,596	1,389	2,203	2,114	10,637
TOTAL	1,072	16,613	12,604	6,117	10,055	17,689	6,415	10,250	11,721	92,535



Erosion Area E = e(d+a)
Distance a = c/sin C(sin A)
Debris apron area D = 1/2 ac(sin B)
Net erosion = E - D(.71)
Fine fraction of net erosion = E(fraction of cut face fines) -
D(fraction of debris apron fines)(.71)

Figure 17. Cross-section diagram of a road cutbank showing the variables used to compute cutbank sediment yield.

Cutbank erosion rates for individual road segments are variable (Table 17). High erosion rates in some segments were due to cutbank slides. Erosion rates also vary with road age. Grouse Creek cutbank erosion rates trend from 0.8 cm/yr on a five-year-old cut to 0.2 cm/yr on 30-year-old cuts. A similar relation occurs in western Oregon where cutbank erosion rates vary from 2.1 cm/yr on one-year-old cuts to 0.58-1.12 cm/yr on five-year-old untreated cutbanks [Dyrness, 1970].

Although a trend in the rate of cutbank retreat with age of the road exists, it is not reflected in the final sediment yield rates. Sampled road segments in Grouse Creek show no systematic variation in cutbank yield rate among road use, age, or cutbank height. Therefore we assigned an average unit yield rate from all sampled road segments of 7.6 t km^{-1} yr^{-1}. Cutbank sediment production was calculated by multiplying the average annual sediment yield rate by the length of roads in each year (Table 3). Sediment production totals are summarized in Table 19.

A number of factors contribute to the yield-rate variability among road segments and include cutbank height, percentage of road length with inboard ditches, varying road construction and maintenance standards, and, most importantly, the proportion of road drainage to streams. The position of the road on the slope also effects cutbank sediment yield, as roads high on slopes or ridges will have fewer cut banks.

On the average, debris aprons cover 44 percent of the original cut-face areas. The fraction of the cut face covered by debris aprons showed no correlation with cutbank heights or slopes of the cut face.

Failure of road fills at stream crossings. A significant process by which roads deliver sediment to streams is through failure or gullying of earthen fill where roads cross stream channels. U.S. Forest Service personnel visited approximately 85 percent of all logging-road stream crossings in the Grouse Creek basin in the summer of 1989. In the course of evaluating the status of each crossing, they estimated the volume of crossing fill material that had entered the stream channel by either mass failure or gullying. These estimates are presented in Table 20.

Table 20. Sediment production by mass movement and gullying of road fills at stream crossings.

Sub-basin	Area (ha)	Number of failed road crossings	Sediment production (m^3)	Unit sediment production (m^3/ha)
Lower Grouse	1,515	1	14	0.01
Bear Cr	1,744	24	11,717	6.72
Lower mid Grouse	1,088	20	8,809	8.10
Mosquito Cr	3,880	6	767	0.20
Upper mid Grouse	1,038	17	2,892	2.79
Cow Cr	1,382	4	314	0.23
White Oak Cr	1,074	3	353	0.33
Upper Grouse	2,934	7	256	0.09
Total	14,655	82	25,122	

Estimates of sediment production from stream crossings (Table 20) are conservative because evidence of earlier stream-crossing erosion was obliterated by subsequent road reconstruction at many places. At several locations, two generations of culvert buried in the road fill allowed estimates of sediment production from more than one crossing failure at a single site. Estimates of sediment production due to stream crossing erosion are probably underestimated by a factor of two or more.

Road systems in some drainage sub-basins have a comparatively high volume of sediment production from stream crossings (Table 20). In the Bear Creek area and the lower portion of the middle Grouse area (Figure 3), where relatively high densities of abandoned roads are present, sediment production from stream crossings is one to two orders of magnitude greater than from other drainage sub-basins.

Road-related erosion discussion. Only 32 percent of culverts and waterbars drain directly to streams (Table 17). The low percentage of roads with direct drainage is probably a recent condition reflecting the current emphasis on construction of waterbars on less-traveled roads. With waterbars spaced more closely together, much of the water and sediment from roads is deflected onto side slopes and the forest floor. Though it would be difficult to estimate road drainage to streams under past maintenance practices, the overall road-surface and cutbank sediment production for the budget period is likely to be underestimated because of these changes. However, even if road-related erosion was doubled by assuming more road-crossing failures and a higher percentage of road drainage to streams, road-related erosion would still only account for 3.7 percent of total sediment production.

Berms are created on the outside of roads during regrading of the road surface. A large percentage of Grouse Creek basin roads are outsloped, and the berms effectively concentrate runoff on the road surfaces and defeat the purpose of outsloping the roads. Forty-eight percent of sampled roads in the basin are outsloped, 27 percent are level, and 25 percent are insloped. Forty-six percent of the outsloped roads have an outside berm. The lowest sediment delivery rate from cutbanks comes from a sampled road segment for which 91% of the surface is outsloped and there are no inboard ditches or outside berms.

Sediment Storage

Sediment storage is the amount of change in storage of sediment in the stream channel of Grouse Creek during the budget period. If sediment is removed from gravel bars and the stream bed at the same rate it is replaced, there is no net change. The large volume of sediment deposited in Grouse Creek channels between 1960 and 1975 exceeded the capacity of the stream to transport it out of the basin, and a net increase in stored sediment occurred. Measurements from sample reaches and from aerial photographs were used to evaluate change in sediment storage.

The relative stability of stored sediment was evaluated in the field or on aerial photographs using the storage classification of Madej [1984] (Figure 18). Active sediment (Figure 18) is transported during moderate flood flows with a one-to-five year recurrence interval. Deposits are unvegetated and generally of low relief. Semi-active sediment (Figure 18) is mobilized during higher, 5-to-20 year flood flows, and is covered with shrubs or young trees. Inactive sediment (Figure 18) is mobilized by floods of recurrence intervals between 20 and 100 years. Inactive sediment consists of coarse lag deposits, three-to-five-meter-high gravel berms, or material stored in log jams. Stable sediment (Figure 18) has not been mobilized historically and, in Grouse Creek, is vegetated with stands of old-growth Douglas fir and oak.

In Grouse Creek, semi-active and inactive sediment dominate post-1960 additions to storage. Grouse Creek aggraded in response to the 1964 flood, and the creek subsequently incised into these flood deposits. The remains of these deposits, which are inactive sediment, are easily identified on aerial photographs and in the field.

Sediment storage was measured by field survey for selected reaches of fifth and sixth-order channels of Grouse Creek (Table 21). Storage volumes were measured with a Jacob's staff, rangefinder, or by pacing. Where flood deposits covered pre-existing flood terraces, only

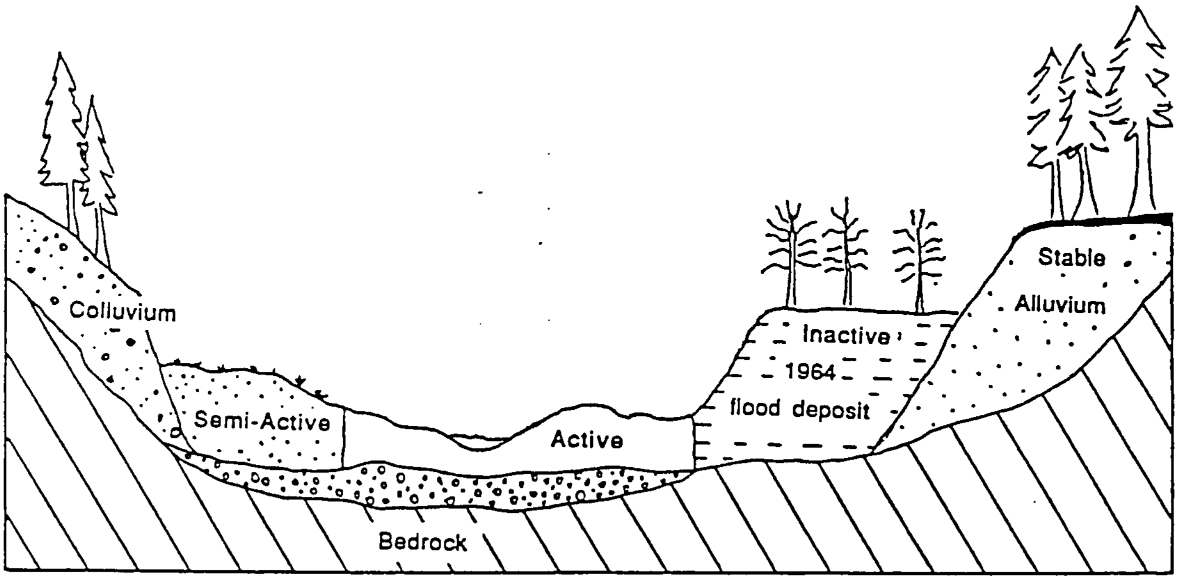


Figure 18. Cartoon of stream cross-section showing channel sediment storage classification of Madej [1984].

Table 21. Summary of field measurements of changes in sediment storage.

Reach	Stream order	Reach length (m)	Sediment in semi-active storage (m^3)	Sediment in inactive storage (m^3)	Sediment in wedges behind debris dams (m^3)	Total storage (m^3)	Unit semi-active storage (m^3/m)	Unit inactive storage (m^3/m)	Total unit storage (m^3/m)
Grouse Creek downstream from Mosquito Creek	6	1,200	4,302	52,642		56,944	3.6	43.9	47.5
Mosquito Creek below slide 3056 *	6	214	1,343	3,753		5,096	6.3	17.5	23.8
Grouse Creek upstream from Mosquito Creek	5	970	2,877	12,658		15,535	3.0	13.1	16.0
Grouse Creek downstream from Cow Creek	5	1,108	3,647	1,922		5,569	3.3	1.7	5.0
Grouse Creek between Cow & White Oak creeks	5	2,166	4,647	4,012	3,600	12,260	2.2	1.9	4.0
Grouse Creek between Carson & Brays Opening creeks *	4	832	233				0.3		0.3

* informal surveys done while mapping landslides
all storage compartments may not be measured

the veneer of post-1964 sediment was measured. These deposits were identified by buried stands of trees remaining on the aggraded surfaces. The volumes of the large deposits in the lower Grouse Creek channel were measured on aerial photographs. Depth was estimated from field reconnaissance.

For fourth-order channels, we assigned a change-in-storage volume to all reaches (Table 22) based on field observations (Table 21), gradient, width and condition of channel through time, and decreasing storage capacity in the lower-order streams. No storage was assigned to 5 of 12 fourth-order streams with gradients of 0.13 and higher and little evidence of channel disturbance.

Residence times of sediment in first through third-order streams are assumed to be short because of the steep gradients characteristic of these channels. Although logging activities increase sediment storage in lower-order streams, the effect is temporary. Data collected in Grouse Creek [J. McHugh, written communication, 1990] show an increase of 0.49 m^3/m in storage between a first-order stream in old growth and that same stream in a recently-logged unit. In Grouse Creek, the area of recently-logged land in 1960 is approximately equal to the area of recently-logged land in [illegible]9, and any temporary increase in sediment storage in lower-order streams due to logging activity should balance during the budget period.

Total storage volumes and methods of measurement by stream order are summarized in Table 23. The change in storage during the budget period is 1,121,000 m^3. Using an average density of 1.8 t/m^3 for water-deposited sediments [Gottschalk, 1964], sediment storage has increased by approximately 2,018,[illegible] tonnes (Table 23). The increase in stored sediment is equal to 27 percent of the sediment produced during the budget period. Approximately 70 percent of measured and estimated storage compartments are inactive storage, or remnant 1964 flood deposits.

The majority of sediment from landslides in Grouse Creek was also deposited directly into fourth through sixth-order streams, which are the same stream orders that showed significant increases in stored sediment. Approximately 45 percent of all landslide sediment was deposited into fifth and sixth-order channels, with 41 percent going directly into fourth-order channels.

Table 22. Aerial photograph measured changes in sediment storage in fourth-order channels.

Channel	Average gradient	Length (m)	Relative disturbance level*	Sediment storage estimate (m^3)
Upper Grouse (reach 2)	0.04	4,084	moderate	12,252
Bear Creek	0.08	3,901	severe	110,500
White Oak	0.10	670	moderate	1,005
Cow Creek	0.11	2,268	moderate-severe	13,177
Brays Opening	0.13	1,768	minor	0
Spike Buck	0.13	1,950	minor-moderate	0
Greenwood	0.15	1,280	severe	1,472
Upper Grouse (reach 1)	0.16	610	minor	0
Last Chance	0.17	1,950	severe	8,506
Sims	0.19	2,377	minor-none	0
Devil's Canyon	0.27	914	moderate-severe **	0

* disturbance level:
- minor - no debris flows, little if none vegetative disturbance
- moderate - debris flow track evident, storage dependent on gradient & measurable storage compartments
- severe - extensive vegetative disturbance, storage dependent gradient & measurable storage compartments

** no measured storage, no recent sliding

Table 23. Methods of measurement changes in channel-stored sediment (△S), classified by order of channel.

Stream order	Measurement procedure	Total change in storage volume (m^3)
First	Assume △S = 0 *	0
Second	Assume △S = 0 *	0
Third	Assume △S = 0 *	0
Fourth	Reconnaissance field measurement (see Table 21) in conjunction with aerial photograph measurements. Assume △S= 0 for 5 of 12 streams with high gradient and/or negligible impact from management.	147,000
Fifth	Storage measured along 36% of streams. The calculated storage per unit length was applied to remaining 64%.	118,000
Sixth	Storage field measured for a 1200 m lenth of channel below Mosquito Creek (Table 21), aerial photograph measurements of storage along 3,060 m of stream, and calculated storage per unit length applied to remaining 4,744 m.	856,000
	Total	1,121,000
	Equivalent in tonnes**	2,018,000

* △S assumed to be negligible in lower-order streams because the steep gradients and wide discharge ranges result in short sediment residence time. Any actual values of △S would be small compared to higher order channels.

** Average density of water-deposited sediments is 1.8 t/m3 (Gottschalk, 1964).

An inability to assess the change in the amount of sediment stored in wedges behind debris dams is a source of error for the storage component. Although the scale and resolution of the 1960 aerial photographs are excellent, the dense streamside canopy in most channel reaches precluded the mapping of debris dams as of 1960. In the 1989 channel survey of fourth, fifth, and sixth-order streams, only three debris dams were mapped in the upstream reaches of the fifth-order stream (Table 21). Debris dams do not persist where valley widths are greater. The change in sediment storage behind small debris dams in the lower-order streams will be minor compared to the additional sediment stored in flood deposits in the higher-order streams with few debris dams.

Sediment Discharge

Sediment discharge cannot be measured directly because the Grouse Creek basin is ungaged. Sediment discharge is therefore calculated as the difference between the total sediment production (I) and the change in sediment storage (ΔS) (equation 1). Subtracting the estimated amount of additional stored sediment from the sediment produced in the last 29 years yields a sediment discharge of 5,409,000 tonnes for the budget period (Table 4).

An independent approximation of the sediment discharge can be calculated from measured sediment discharges on the South Fork Trinity River upstream and downstream from the confluence of Grouse Creek [Knott, 1974]. Grouse Creek comprises 42 percent of the drainage area for this reach of the South Fork Trinity River and is the only major tributary (Figure 19). Assuming 42 percent of the increase in sediment discharge along this reach of the South Fork Trinity River comes from Grouse Creek, the resulting sediment discharge (3,596,000 tonnes) equals 67 percent of the sediment discharge calculated from the sediment budget (Table 24).

The computation of sediment discharge using data from the South Fork Trinity River is a minimum value for sediment discharge because the effect of the 1964 flood has been averaged

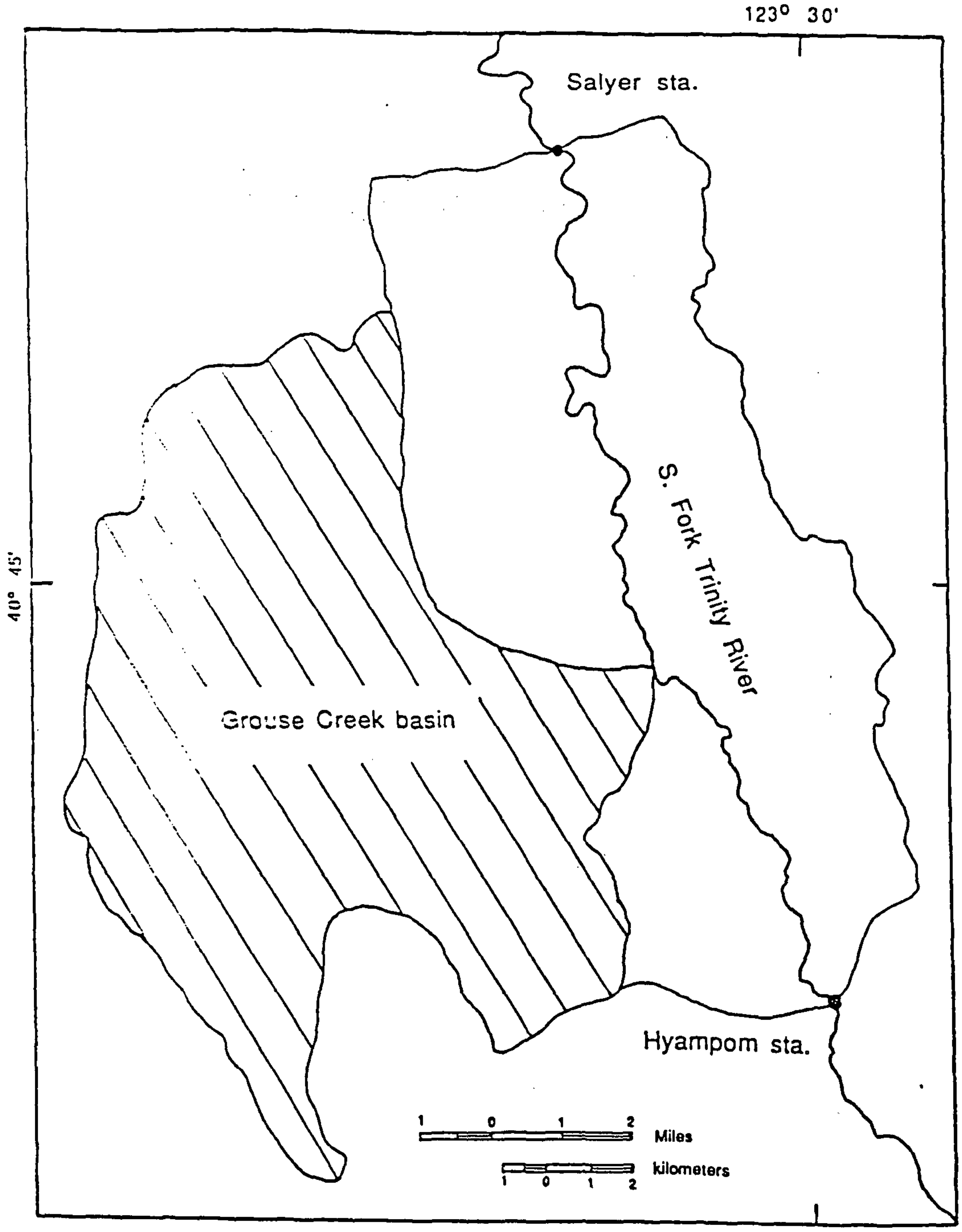


Figure 19. Map showing the drainage area (solid bold line) between the USGS gaging station at Salyer and the USGS gaging station at Hyampom on the South Fork Trinity River. The diagonal striped pattern represents the Grouse-Creek-basin portion of this drainage area.

Table 24. Sediment discharge data for South Fork Trinity River.

	Relative river km	Drainage area (km2)	Annual suspended sediment discharge (tonnes)	Annual bedload sediment discharge (tonnes)	Total annual sediment discharge (tonnes)	Total sediment discharge during budget period (n=29 years) (tonnes)
S. Fork Trinity R. near Salyer *	0	2,326	948,000	353,000	1,301,000	
S. Fork Trinity R. below Hyampom *	26.5	1,979	741,000	265,000	1,006,000	
Difference in area and sediment discharge between stations		347	207,000	88,000	295,000	
Grouse Creek (42% of difference in sediment discharge)	16.7	147	87,000	37,000	124,000	
Grouse Creek sediment discharge using S. Fork Trinity R. data						3,596,000
Sediment budget calculated sediment discharge						5,409,000

* Data from Knott [1974].

into the 59-year period of the study. The relative contribution from Grouse Creek may also be larger because it is the only major tributary draining the area between the two gaging stations.

DISCUSSION

The Grouse Creek sediment production rate of 1,750 $t/km^2/yr$ is among the highest of published and available rates for disturbed, forested watersheds in the Pacific Northwest (Table 25). Errors due to limitations in data collection discussed above all tend to underestimate sediment production, so the actual sediment production rate may be higher. Sediment production is concentrated during periods of major storms (Table 26), in proximity to roaded areas, and in zones of geologic instability (Figures 6a-g), indicating that unstable geology, logging, and frequency of major storms are the dominant controls on rates of sediment production.

A comparison of cumulative landsliding and logging in Grouse Creek (Figure 20) shows an increase in landsliding out of proportion to an increase in logging at the end of 1966. The disproportionate increase in landsliding relative to logging indicates the 1964 storm and resulting flood are probably the major cause of landsliding during that period. However, a logging-related component to erosion also exists for the 1964 storm and flood. A storm in 1955 produced a flood event of slightly lesser magnitude than the December 1964 flood [Coghlan, 1984], but produced insignificant channel changes on 1960 aerial photographs of Grouse Creek compared to channel changes evident in 1966 and 1970 photographs due to flooding.

The Bear Creek tributary was the most severely modified by the 1964 flood. Headwater slopes in Bear Creek were heavily logged just prior to the flood. Although major faults parallel the stream channel, renewed slide activity in Bear Creek is uncommon after 1966 relative to other unstable reaches of the basin that show renewed sliding during later storm periods (Figures 6b-g). Logging impacts are implicated as the major cause of landslide erosion in Bear Creek.

Table 25. Sediment production rates to streams in disturbed watersheds in the Pacific Northwest.

Watershed	Drainage area (km^2)	Years of record	Sediment production rate (t/km^2/yr)	Source
Big Beef Creek W. Washington	38	9	110	Madej, 1982
Lone Tree Creek N. California	1.74	3	903	Lehre, 1981
Armentieres Creek Queen Charlotte Is.	4	19	1,019 *	Roberts & Church, 1986
Garrett Creek N. California	10.8	25	1,179	Best et al., in press
Deer Creek W. Washington	137	48	1,408 *	Eide, 1989
Van Duzen River N. California	1,111	35	1,597	Kelsey, 1980
Grouse Creek N. California	147	29	1,750	

* Rate converted from m^3/km^2/yr using density factor of 1.8 t/m^3

Table 26. Sediment production (tonnes) by aerial photograph interval and sediment source.

Sediment source	1960-66	%	1967-70	%	1971-75	%	1976-80	%	1981-85	%	1986-89	%
Landslides												
Old growth *	3,166,188	62.1	368,767	41.9	378,155	39.2	21,960	13.0	58,037	22.4	8,299	14.1
Managed lands**	753,387	14.8	184,552	21.0	249,189	25.8	6,842	4.0	83,347	32.2	4,458	7.6
Roads ***	639,439	12.6	195,870	22.3	189,334	19.6	85,278	50.4	49,472	19.1	739	1.3
Streambank erosion	353,151	6.9	57,861	6.6	63,348	6.6	8,978	5.3	14,964	5.8	1,047	1.8
Hillslope erosion												
Logged areas												
Sheetwash & rilling	15,850	0.3	10,378	1.2	11,746	1.2	10,065	5.9	7,089	2.6	6,463	9.0
Gullying	109,638	2.2	42,168	4.8	49,514	5.1	16,867	10.0	27,750	10.7	26,117	44.5
Mid-slope landsliding	3,630	0.1	1,396	0.2	1,639	0.2	558	0.3	919	0.4	865	1.5
Grass and oak woodlands												
Sheetwash & rilling	25	0.0	17	0.0	21	0.0	21	0.0	21	0.0	17	0.0
Gullying	909	0.0	149	0.0	163	0.0	23	0.0	38	0.0	3	0.0
Landslides	3,078	0.1	504	0.1	552	0.1	89	0.0	117	0.0	9	0.0
Old-growth forest												
Sheetwash & rilling	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Road erosion												
Road surfaces	10,940	0.2	6,934	0.8	7,770	0.8	8,034	4.7	6,411	2.5	5,022	8.6
Cutbanks	6,745	0.1	5,669	0.6	8,402	0.9	9,656	5.7	10,253	4.0	6,699	11.4
Fill failures	32,016	0.6	5,245	0.6	5,743	0.6	927	0.5	1,221	0.5	95	0.2
TOTALS	5,053,891		883,164		968,105		197,686		263,292		62,363	

* Land use classifications 1 and one half of 6 (see Table 5)
** Land use classifications 3,5, and one half of 6 (see Table 5)
*** Land use classifications 2 and 4 (see Table 5)

Streambank erosion and fill failures were distributed in the same proportion of the total as landsliding.
Gullying and mid-slope landsliding were distributed in proportion to the growth of logging.

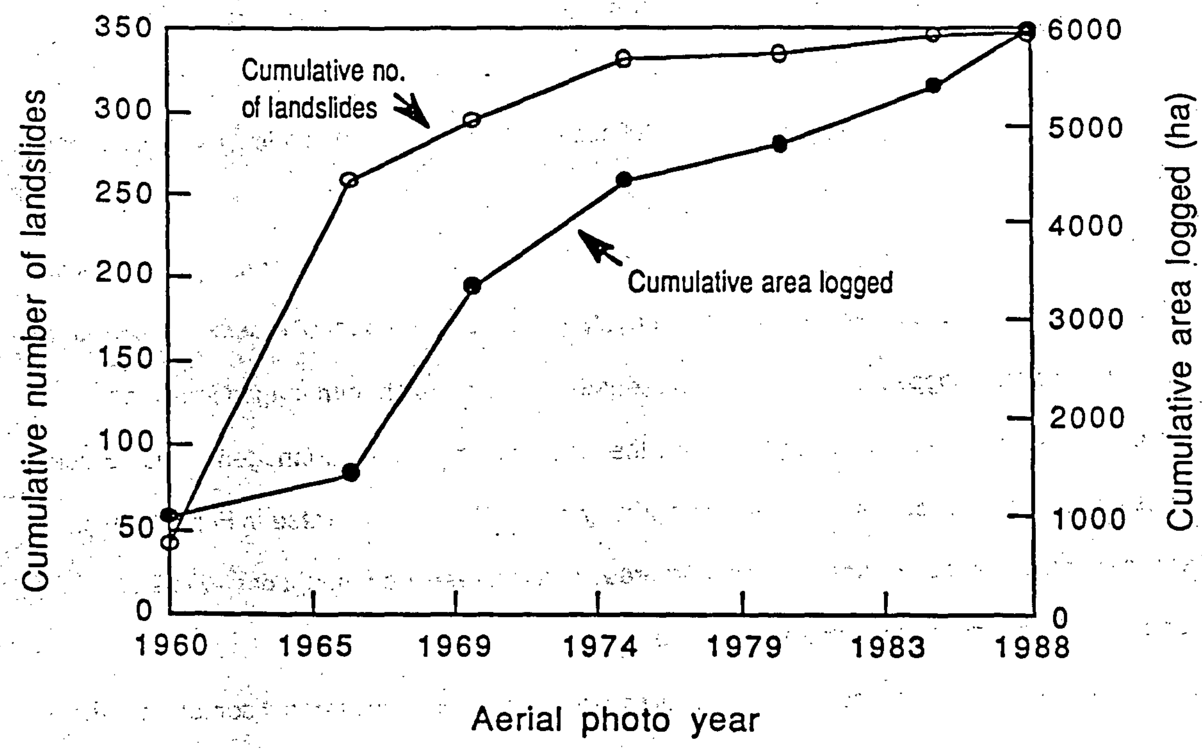


Figure 20. Comparison of cumulative number of landslides to cumulative area logged, Grouse Creek.

Grouse Creek is the most turbid tributary to the South Fork of the Trinity River [State of California, 1979], despite the fact that Grouse Creek has one of the lowest percentages of logged area. Assuming logging practices within the rest of the South Fork Trinity basin are not substantially different from those in Grouse Creek, the inherently unstable terrain and multiple fault zones probably accounts for most of the discrepancy.

Sediment production in the basin is dominated by mass wasting, but the relative sediment contributions from hillslope erosion and roads increase as landsliding decreases between 1976 and 1989 (Table 26). Slopewash, road surface, and cutbank erosion contribute only fines, so the proportion of fines in the total sediment delivery to channels during this period also increased.

A comparison of erosion rates calculated by land use (Table 27) indicates that roads and landslides directly associated with roads contribute the greatest amount of erosion per unit area. Erosion rates from logged areas are one to six times those rates on unmanaged land, and erosion rates from roads are 20 to 140 times the erosion rates in the unmanaged areas. Erosion rates for all three categories decrease dramatically after 1975. As illustrated in Figures 6a-g, sediment produced from logged and roaded areas can increase the amount of streamside landsliding in downstream, unmanaged areas.

An additional contribution to the suspended-sediment load in streams comes from the attrition of particles during fluvial transport and storage. Fluvial attrition for Grouse Creek is estimated from the sediment production and discharge components of the sediment budget. From the South Fork Trinity River sediment discharge data (Table 24) [Knott, 1974], we estimate that 30 percent of sediment discharged from the Grouse Creek basin is bedload-size particles (> 2 mm). The proportion of bedload-size particles estimated for the sediment production component is 61 percent (Table 4). The difference between the bedload proportion of the production and discharge components suggests that roughly 50 percent of bedload-size particles introduced into Grouse Creek break down to suspended-load size before leaving the basin. In Grouse Creek, Franciscan siltstones and schist are particularly susceptable to abrasion,

Table 27. Changes in erosion rate over time for managed, unmanaged, and roaded areas.

Aerial photograph interval	Erosion rate (t/ha/yr)		
	Unmanaged lands *	Managed lands *	Total road-related **
1960-66	48.2	61.1	915.6
1967-70	9.5	18.9	316.7
1971-75	8.7	14.8	200.1
1976-80	0.6	2.7	90.7
1981-85	1.6	4.8	54.5
1986-89	0.3	1.8	11.8

* includes streamside landslides

** includes erosion from road surfaces, cut banks, road fills and road-related landslides.

fragmentation, and weathering. Rocks that break down during fluvial transport and storage will add significantly to the amount of fine-grained sediment available for transport.

Follow-up monitoring of turbitity measurements [State of California, 1979] would allow a qualitative comparison of water quality with earlier values. Since landslide sediment production rates have decreased dramatically in the last 15 years, a comparable decrease in suspended-load discharge may exist. If not, then stored sediment and sediment from persistent processes are likely sources.

The rate of logging and road building in Grouse Creek has decreased since 1975. Storm events also have been minimal in the last 15 years. The next major storm will be a test of the effectiveness of changing forest management practices and the decrease in the rate of road building and logging on sediment production. Following such an event, an updated landslide inventory can be conducted to assess the management-related contribution to erosion. Such an inventory could be constructed using aerial photographs and the area-to-volume relationships for debris slides described in the sediment budget.

A more in-depth study on channel storage and width, similar to studies by Madej [1984] or Lisle [1982], would provide an assessment of the state of recovery to pre-flood conditions in Grouse Creek channels. If the time required for recovery from the 1964 through 1975 storms exceeds the recurrence interval of the storms, changes in sediment storage will persist and recovery of the system will be prolonged. Using the sediment budget information, investigators may be able to dete[illegible] management-related sediment production, although greatly reduced from the first half of the budget period, is delaying recovery to pre-flood morphology.

CONCLUSIONS

The sediment production rate in Grouse Creek of 1,750 t km^{-2} yr^{-1} (4,130 tons mi^{-2} yr^{-1}) for the last 29 years is among the highest of published rates in the Pacific Northwest. Using an average bedrock density of 2.5 g/cm^3, the sediment production rate is equivalent to a bedrock lowering rate of 0.7 mm/yr.

The timing of sediment production in the Grouse Creek basin is episodic due to storms and logging. Sixty-nine percent of the total sediment produced during the 29-year budget period occurred in the six-year interval that includes the December 1964 storm. Ninety-three percent of all sediment was produced during the first half of the budget period (1960-1975), which coincides with four major storm events (1964, two in 1972, and 1975) with recurrence intervals of 10 to 50 years. In addition, 75 percent of logging and 80 percent of the road construction was completed by 1975, prior to the enactment of revised forest practice regulations.

Sediment production is dominated by streamside landsliding that accounts for over 86 percent of all sediment delivered to Grouse Creek during the period 1960-1989. Landsliding is concentrated in logged and roaded areas, immediately downstream from logged areas, and in areas of unstable geology. Slopes underlain by unstable rock units or fault zones are most vulnerable to mass wasting and renewed erosion activity, especially where faults parallel stream channels, and respond quickly to climatic events.

The remainder of sediment produced from all other sources is less than 14 percent of the total sediment production. Streambank erosion accounts for about seven percent of sediment. Hillslope erosion on managed land and road-related erosion exclusive of large landslides account for approximately five percent and two percent of sediment production, respectively. As landsliding decreased after 1975, the relative importance of hillslope erosion and road-related erosion increased.

Dominant erosion processes in Grouse Creek differ according to stream order. Second and third-order channels in Grouse Creek are most vulnerable to debris torrents and streambank erosion. Fourth through sixth-order streams are most susceptible to channel aggradation and lateral corrasion. Streamside landslides are concentrated along these same high-order channels; 85 percent of landslide sediment was deposited directly into higher-order streams.

Channel-stored sediment increased by approximately 2,018,000 tonnes during the 29-year budget period. The increase in stored sediment accounts for 27 percent of the sediment delivered to streams during 1960 to 1989. The increase in storage occurred in fourth, fifth, and sixth-order channels in the Grouse Creek basin; remnant 1964 flood deposits account for roughly 70 percent of the increased volume of alluvial storage.

Continued monitoring of sediment production and transport processes will provide valuable information on the state of channel conditions and the relative contributions to sediment production from management activities.

REFERENCES

Aalto, K. R., W. P. Irwin, and H. M. Kelsey, Reconnaissance geologic map of the Pilot Creek quadrange, Humboldt and Trinity Counties, California, scale 1:62,500, Open-File Report 88-363, U.S. Geol. Surv., Menlo Park, CA, 1988.

Best, D. W., H. Kelsey, D. K. Hagans, M. Alpert, Role of fluvial hillslope erosion and road construction in the sediment budget of Garrett Creek, Humboldt County, California, in Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California, edited by K. M. Nolan, H. M. Kelsey, and D. Marron, Prof. Paper 1454, U.S. Geol. Surv., in press.

Cederholm, C. J., L. M. Reid, and E. O. Salo, Cumulative effects of logging road sediment on salmonid populations in the Clearwater River, Jefferson County, Washington, in Salmon-Spawning Gravel: A Renewable Resource in the Pacific Northwest?, Rep. 39, pp. 38-74, Wash. Water Res. Cent., Pullman, WA, 1981.

Coghlan, M., A climatologically-based analysis of the storm and flood history of Redwood Creek: Tech. Rep. 10, 47 pp., Redwood Natl. Park, Arcata, CA, 1984.

Dietrich, W. E., T. Dunne, N. Humphrey, and L. M. Reid, Construction of sediment budgets for drainage basins, in Sediment budgets and routing in forested drainage basins, Edited by F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanson, Gen. Tech. Rep. PNW-141, pp. 5-23, U.S.D.A. For. Serv., 1982.

Dissmeyer, G. E., and G. R. Foster, Estimating the cover-mangement factor (C) in the universal soil loss equation for forest conditions, J. of Soil and Water Cons., 235-240, July-August, 1981.

Dissmeyer, G. E., and G. R. Foster, A guide for predicting sheet and rill erosion on forest land, Tech. Pub. R8-TP 6, 40 pp., U.S. Dept. of Agric., Atlanta, GA, 1984.

Duncan, S. H., R. E. Bilby, J. W. Ward, and J. T. Heffner, Transport of road-surface sediment through ephemeral stream channels, Wat. Res. Bull., 23, 113-119, 1987.

Dunne, T., and L. B. Leopold, Water in Environmental Planning, 818 pp., W. H. Freeman and Co., New York, 1978.

Dyrness, C. T., Stabilization of newly constructed road backslopes by mulch and grass-legume treatments, Research Note PNW-123, 5 pp., USDA For. Serv., Pac. N.W. Forest and Range Exp. Sta., Portland, OR, 1970.

Eide, J., A 48-year sediment budget (1942-1989) for Deer Creek basin, Washington, M.S. thesis, 122 pp., West. Wash. Univ., Bellingham, 1989.

Goodridge, J. D., California North Coast design rainfall, Grouse Creek Study Technical Report No. 2, 12 pp., USDA For. Serv. R5 SRNF, Eureka, CA, 1989.

Gottschalk, L. C., Sedimentation, in Handbook of Applied Hydrology, edited by Ven Te Chow, p. 18, McGraw-Hill Book Co., New York, 1964.

Goudie, A. (Ed.), Geomorphological Techniques, 395 pp., George Allen and Unwin, Boston, 1981.

Harden, D. R., R. J. Janda, and K. M. Nolan, Mass movement and storms in the drainage basin of Redwood Creek, Humboldt County, California--A progress report, Open-File Report 78-486, 161 pp., U.S. Geol. Surv., Menlo Park, CA, 1978.

Holberger, R. L., and J. B. Truett, Sediment yield from construction sites: Proc. Third Inter-Agency Sedimentation Conference, pp. 1-47 to 1-58, 1976.

Howell, D. W., and D. W. Smith, Soil and vegetation survey, South Fork Mountain Area, Humboldt and Trinity Counties, California, Interim publication, Calif. Dept. of For. and Fire Prot. and U.S.D.A. S.C.S., May, 1989.

Kelsey, H. M., A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941-1975: Summary, Geol. S. of Amer. Bulletin, Part 1, v. 91, pp. 190-19, 1980.

Knott, J. M., Sediment discharge in the Trinity River basin, California, Water-Resources Investigations 49-73, 56 pp., U.S. Geol. Surv. Menlo Park, CA, 1974.

Kojan, E., Mechanics and rates of natural soil creep, pp. 233-253, U.S. Forest Service Experiment Station Report, Berkeley, CA, 1967.

Lehre, A. K., Sediment budget of a small California Coast Range drainage basin near San Francisco, in Erosion and sediment transport in Pacific Rim steeplands, I.A.H.S. Publ. No. 132, Christchurch, pp. 123-139, 1981.

Leopold, L. B., W. W. Emmett, and R. M. Myrick, Channel and hillslope processes in a semiarid area, New Mexico, Prof. Pap. 352-G, pp. 193-253, U.S. Geol. Surv., 1966.

Lewis, J., and R. Rice, Site conditions related to erosion on private timberlands in northern California, in Critical Sites Erosion Study, v. II, 95 pp., Calif. Dept. of For. and Fire Prot. and U.S.D.A. For.Serv. PSW Forest & Range Exp. Sta., Arcata, 1989.

Lisle, T. E., Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California, Wat. Resources Res., 18:6, 1643-1651, 1982.

Madej, M. A., Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington, in Sediment budgets and routing in forested drainage basins, Edited by F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanson, Gen. Tech. Rep. PNW-141, pp. 97-108, U.S.D.A. For. Serv., 1982.

Madej, M. A., Recent changes in channel-stored sediment, Redwood Creek, California, 54 pp., Redwood Natl. Park, Arcata, CA, 1984.

McIsaac, G. F., J. K. Mitchell, and M. C. Hirschi, Slope steepness effects on soil loss from disturbed lands, Transactions of the ASAE, 30(4), pp. 1005-1013, 1987.

Reid, L. M., Sediment production from gravel-surfaced forest roads, Clearwater Basin, Washington, M.S. thesis, 247 pp., U.W. College of Fisheries, Fisheries Research Institute FRI-UW-8108, 1981.

Reid, L. M., and T. Dunne, Sediment production from forest road surfaces, Water Resources Res., 20(11), pp. 1753-1761, 1984.

Roberts, R. G., and M. Church, The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia, Can. J. of Forest Res., 16:5, 1092-1106, 1986.

State of California, South Fork Trinity River Watershed Erosion Investigation, 83 pp., Dept. of Water Resources N. District, 1979.

Strahler, A., Quantitative analysis of watershed geomorphology, Trans. Amer. Geophy. U., 38, 913-920, 1957.

Swanston, D. N., R. R. Ziemer, and R. J. Janda, Influence of climate on progressive hillslope failure in Redwood Creek Valley, Northwest California, Open-file report 83-259, 49 pp., U.S. Geol. Surv., Menlo Park, CA, 1983.

Varnes, D. J., Slope movement types and processes, in Landslides: Analysis and Control, edited by R. L.Schuster and R. J. Krizek, Special Report 176, pp. 11-33, Natl. Acad. of Sciences, Wash. D.C., 1978.

Williams, J. R., and H. D. Berndt, Sediment yield computed with universal equation, pp. 2087-2098, Proc. American Soc. of Civ. Engr., HY 12, v. 98, 1972.

Wischmeier, W. H., and D. D. Smith, Predicting rainfall erosion losses - A guide to conservation planning, Agriculture Handbook No. 537, 58 pp., U.S. Dept. of Agric., Wash. D.C., 1978.

Young, J. C., Geologic map and sections of the Willow Creek 15' quadrangle, Humboldt and Trinity Counties, California, scale 1:62,500, Map sheet 31, Calif. Div. of Mines and Geol., 1978.

Appendix A. Grouse Creek streamside landslide inventory.

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measurement method*	Photo year first appears	Landslide classification**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
LG	3023	R	60	DS	RT	2	35	NE	15970	56627	8833	47994	
LG	3024	R	66	DS	RT	1		SW	1069	2419	185	2234	
LG	3083	A	60	IF	RT	1	35	SE	54630		152010	90392	Stream erosion of lg. talus cone, renewed
LG	3085	A	60	IF	RT	1	39	SE	44146			283	Persistent feature-est. budget period cont
LG	3086	F	66	CS	RT	1	22	SW	5004	24083	4420	19663	
LG	3087	F	66	CS	RT	1		NNW	20600			135077	
LG	3088	F	60	SE	RT	6	22	NW	15077		1600	2031	Budget period contribution - pre 60 slide
LG	3089	F	60	CS	RT	6	39	N	31462		612	4070	Budget period contribution - pre 60 slide
LG	4001	R	66	DS	RT	1		NW	6300	15900	1091	13989	
LG	4002	R	66	DS	RT	1		SE	1788	4412	407	4005	
LG	4003	A	60	CS	RT	1		SW	17418			7064	Shallow failure
LG	4004	A	66	DS	RT	1		NW	6178			2824	Shallow failure
LG	4005	R	66	DS	RT	3		SE	2276	5845	580	5265	Stream cut slope slide on PGE right of way
LG	4006	A	66	DS	RT	3		SE	5202			31717	Large stream cut slope slide
LG	4007	R	70	DS	RT	1		NW	6015	18171	2322	15849	
LG	4008	R	66	DS	RT	1		SE	3888	10920	8987	1933	80% of eqn amt stored on slope
LG	4009	R	66	DS	RT	1		SE	1561	3765	332	3433	
LG	4010	R	66	DS	RT	1		NW	1569	3788	334	3454	
LG	4011	R	66	DS	TZ	1		NE	2912	7794	831	6963	
LG	4275	A	60	SE	RT	1,3		SE	512760			210251	Devastation slide
							LG Totals		763521	154004	184442	621090	
BC	3002	R	66	DS	TZ	1	37	NE	5560	16578	2080	14497	
BC	3017	R	66	DS	TZ	1	35	NE	9517	27758	3379	24378	
BC	3018	R	60	DS	TZ	1	35	NE	6440			3425	20% enlargement of pre 60 slide
BC	3019	R	66	DS	TZ	1	45	NE	7674	24144	3253	20891	
BC	3020	R	66	DS	TZ	1	39	NE	3811	10668	1222	9446	
BC	3021	R	66	DS	TZ	1	31	W	3846	10782	1238	9545	
BC	4012	R	66	DS	TZ	1		NE	6029	18221	2330	15892	
BC	4013	A	66	DT	TZ	1		NE	3901			2379	Small tributary debris torrent
BC	4014	R	66	DS	TZ	1		SW	2090	5293	512	4781	
BC	4015	R	66	DS	TZ	1		SW	4418	11562	1192	10370	
BC	4016	R	66	DS	TZ	1		NE	1905	4749	446	4302	
BC	4017	R	66	DS	TZ	1		SW	1632	3966	355	3611	
BC	4018	R	66	DS	TZ	1		SW	3201	8702	952	7750	
BC	4019	A	66	DT	TZ	1		NE	6561			2000	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
BC	4020	R	66	DS	TZ	1		E	976	2176	161	2015	
BC	4021	R	66	DS	TZ	1		E	1463	3491	300	3190	
BC	4022	R	66	DS	TZ	1		W	3317	9072	1002	8070	
BC	4023	R	66	DS	TZ	1		W	4148	11776	1378	10399	
BC	4024	R	66	DS	TZ	1,3		SE	7205	22431	2982	19449	
BC	4025	R	66	DS	TZ	1,3		NE	2276	5845	580	5265	
BC	4026	R	66	DS	TZ	1,3		SW	513	1028	56	973	
BC	4027	R	66	DS	TZ	1,3		SW	5808	17445	2211	15234	
BC	4028	R	66	DS	TZ	1,3		SW	5761	17278	2186	15092	
BC	4029	R	66	DS	TZ	1,3		NE	6391	19504	2526	16978	
BC	4030	R	66	DS	TZ	1		NE	3900	10958	1262	9696	
BC	4031	R	66	DS	TZ	3		E	2613	6867	710	6157	
BC	4032	R	66	DS	TZ	4		NE	3381	9278	1030	8248	
BC	4033	R	66	DS	TZ	3		NE	7782	24544	3317	21227	
BC	4034	R	66	DS	TZ	4		NE	2369	6124	615	5509	
BC	4035	R	66	DS	TZ	3		E	2211	5650	557	5094	
BC	4036	R	66	DS	TZ	3		SW	2150	5469	534	4934	
BC	4037	R	66	DS	TZ	3		W	1633	3968	355	3613	
BC	4038a	R	66	DS	TZ	4		NW	5226	15420	1908	13513	
BC	4038b	R	66	DS	TZ	4		NE	5847	17580	2232	15348	
BC	4039	R	66	DS	TZ	3		NE	4849	14133	1718	12415	
BC	4040	R	66	DS	TZ	3		E	3001	8071	868	7204	
BC	4041	R	66	DS	TZ	4		E	6689	10283	1345	8938	Shallow slide - regression eqn/2
BC	4042	R	66	DS	TZ	3		W	4421	12688	1508	11179	
BC	4043	A	66	DT	TZ	5		N	25779	23573	0	23573	
BC	4044	R	66	DS	TZ	4		NW	5017	14702	1801	12901	
BC	4045	R	66	DS	TZ	4		NW	1812	4479	414	4065	
							BC Totals		193122	600262	50515	403546	
LM	3003	F	66	DS	TZ	2	40	SW	83067	90483	35769	54713	
LM	3004	F	66	DS	TZ	2	60	SW	1497	6350	306	6044	
LM	3006	R	66	DS	TZ	1,3	45	SE	3711	10344	1177	9167	
LM	3007	R	66	CS	TZ	1		SW	8974	28983	4035	24949	
LM	3008	R	66	DS	TZ	1,3	45	N	3916	11013	1270	9743	
LM	3009	A	66	DS	TZ	1,3	42	NE	24985	67800	17781	50019	
LM	3010	A	66	DS	TZ	1,3	45	NE	14056	29990	15087	14903	
LM	3011	F	66	DS	TZ	1,3	40	NE	18311	130198	9939	120259	
LM	3012	R	66	DS	TZ	1,3	22	NE	14715	51619	7905	43714	
LM	3013	A	60	DS	TZ	1	35	SW	18840	42062	0	42062	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
LM	3016	R	66	DS	TZ	1,3	33	NE	7838	24751	3350	21401	
LM	3022	R	75	DS	TZ	1,3	39	NE	2717	7189	752	6437	
LM	4046	A	66	DT	TZ	5		N	43039	54032	0	54032	
LM	4047	R	66	DS	TZ	5		W	17140	61675	9707	51968	
LM	4048	R	66	DS	TZ	1,3		E	6912	21371	2816	18556	
LM	4049	R	66	DS	TZ	1,3		N	4285	12232	1443	10789	
LM	4050	A	66	SE	TZ	1,3		NE	11810	27365	10946	16419	
LM	4051	R	66	DS	TZ	1,3		NE	3414	9383	1044	8338	
LM	4052	A	66	DT	TZ	5,4		NE	73153	44595	0	44595	
LM	4053	A	66	DT	G	1,3		SW	12374	3772	1775	1996	
							LM Totals		374756	735207	125102	610105	
MC	3056	F	80	CS	TZ	4	31	NE	51634			33495	Vol. from debris slide portion
MC	3090	F	66	DS	G	1,3	43	W	3832	5981	0	5981	
MC	3091	R	66	DS	G	1,3		W	6331	19290	2493	16797	
MC	3092	F	66	DS	G	1,3	40	SE	1366	4248	0	4248	
MC	3093	R	66	DS	G	1,3	27	E	14258	49752	7575	42176	
MC	3094	R	66	DS	TZ	1,3	45	E	9977	32799	4665	28135	Original slide larger than field mapped
MC	3095	F	66	DS	TZ	1,3	42	SW	1181	2438	0	2438	
MC	3107	F	66	DS	G	2	45	N	8964	17829	1852	15977	
MC	3108	F	66	DS	G	2	45	S	4772	6258	0	6258	
MC	3109	F	75	DS	G	4	44	N	1793	1703	1362	340	
MC	3110	F	75	DS	G	2	40	S	974	388	235	153	
MC	3111	F	66	DS	G	2	42	SE	3165	3742	975	2768	
MC	4055	A	66	DT	G	4		S	18191	8130	0	8130	
MC	4056	A	66	DT	G	4		NW	6954	2960	0	2960	
MC	4057	R	66	DS	G	3		NE	7246	22583	3006	19577	
MC	4058	R	66	DS	G	5		NW	3298	9010	994	8017	
MC	4059	A	66	DT	G	2		S	27632	22751	0	22751	
MC	4060	R	66	DS	G	1		NW	2759	7318	768	6549	
MC	4061	R	66	DS	G	1		W	4052	11459	1333	10126	
MC	4062	R	66	DS	G	1		SE	1212	2801	226	2576	
MC	4063	R	66	DS	G	1		SW	4642	13429	1615	11815	
MC	4064	A	66	CS	G	4		E	4323	5375		5375	
MC	4065	R	66	DS	G	2		NE	2857	7622	808	6814	
MC	4066	A	66	DT	G	2		E	9269	6062	0	6062	
MC	4067	R	70	DS	G	3		SE	1380	3259	274	2984	
MC	4068	R	66	.DS	G	3		E	1207	2789	224	2565	
MC	4069	A	75	DS	G	3		E	7556	4572	0	4572	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
MC	4070	R	70	DS	G	4		SE	7427	23242	3110	20131	
MC	4071	A	66	DT	G	1		E	11020	3359	0	3359	
MC	4072	A	66	DT	TZ	1		SE	23978	15994	0	15994	
MC	4073	A	66	DT	TZ	1		SE	8187	7064	0	7064	
MC	4074	A	60	DT	G	1,2		N	5337	2149	0	2149	
MC	4075	A	66	DT	G	1		NE	15491	2361	0	2361	
MC	4076	R	75	DS	G	1		NE	2211	5650	557	5094	
MC	4077	A	66	DT	G	2		SE	13531	4124	0	4124	
MC	4078	A	66	DT	G	1		E	20903	6371	0	6371	
MC	4079	R	66	DS	G	1		S	2090	5293	512	4781	
MC	4080	R	66	DS	G	1		S	4181	11885	1393	10492	
MC	4081	R	66	DS	G	1		N	1881	4681	438	4242	
MC	4082	R	66	DS	G	1		W	1338	3144	262	2882	
MC	4083	R	66	DS	G	1		SE	1941	4856	459	4396	
MC	4084	R	66	DS	G	1		W	2369	6124	615	5509	
MC	4085	R	66	DS	G	1		W	12138	41229	6091	35138	
MC	4086	R	66	DS	G	1		E	2197	5610	551	5059	
MC	4087	R	66	DS	G	1		W	1289	3012	248	2764	
MC	4088	R	66	DS	G	1		E	815	1764	121	1643	
MC	4089	R	66	DS	G	1		E	2276	5845	580	5265	
MC	4090	A	66	DT	G	1		SW	14708	10078	0	10078	
MC	4091	A	66	DT	G	1		W	3553	4333	0	4333	
MC	4092	A	66	DT	G	1,3		E	4947	4031	0	4031	
MC	4093	R	66	DS	G	1,3		E	5644	16869	2124	14745	
MC	4094	A	66	DT	G	1		W	34817	22397	0	22397	
MC	4095	R	66	DS	G	1,3		W	854	1863	130	1733	
MC	4096	R	66	DS	G	1,3		W	1069	2419	185	2234	
MC	4097	R	66	DS	G	1,3		W	2620	6888	713	6175	
MC	4098	R	66	DS	G	1,3		W	2508	6548	669	5879	
MC	4099	A	80	SE	TZ	3		NE	13094	16616	11631	4985	
MC	4100	A	66	DT	G	3		N	2601	1430	0	1430	
MC	4101	R	66	DS	G	1		N	4752	13800	1669	12131	
							MC Totals		442591	545576	60464	518605	
UM	3005	F	66	DS	G	3	40	NW	1165	4158	349	3809	
UM	3025a	A	66	CS	TZ	1	31	SE	5446			3306	Used debris slide portion area to est. vol. t
UM	3025b	F	66	DS	TZ	1	35	NW	870	3125	0	3125	
UM	3026	R	66	DS	CF	1	45	NW	3066	8276	895	7382	
UM	3030	F	66	DS	CF	1	50	NW	838	1988	0	1988	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
UM	3031	R	66	DS	CF	1	37	NE	1149	2632	207	2425	
UM	3032	F	66	DS	CF	1	33	NW	2513	2429	0	2429	
UM	3033	F	60	CS	S	2	27	SW	4160	7454	1491	5963	Very sm. in 60-using all of field volume in
UM	3034	R	70	DS	TZ	4	39	NE	3168	8599	938	7661	
UM	3035	F	75	CS	CF	1	31	SE	2628			2161	
UM	3036	F	66	DS	CF	1	42	SW	2486	3058	0	3058	
UM	3037	F	66	DS	CF	1	45	SE	532	567	59	508	
UM	3039	F	66	DS	CF	1	42	SE	1519	2675	285	2390	Combined slides a & b from field measurem
UM	3040	A	66	DS	CF	1	35	SE	2524	9113	765	8349	
UM	3042	R	66	DS	S	3	33	NW	1176	2704	215	2489	
UM	3114	F	75	DS	CF	3	55	NE	267	567	0	567	
UM	4054	R	66	DS	G	3		NW	10282	33970	4859	29109	
UM	4102	R	66	DS	TZ	3		W	1145	2621	206	2415	
UM	4103	R	66	DS	TZ	4		SW	2787	7404	780	6624	
UM	4104	R	66	DS	TZ	4		W	6979	21613	2853	18760	
UM	4105	R	66	DS	TZ	1		NE	829	1800	124	1676	
UM	4106	R	66	DS	TZ	1		SW	2323	5986	598	5388	
UM	4107	R	66	DS	TZ	1		E	1303	3048	252	2796	
UM	4108	R	66	DS	TZ	1		SW	1854	4600	429	4171	
UM	4109	R	66	DS	TZ	1		SW	1219	2821	227	2593	
UM	4110	R	66	DS	TZ	1		SW	926	2047	148	1900	
UM	4111	R	66	DS	CF	1		W	2732	7233	758	6475	
UM	4112	R	66	DS	CF	1		W	1073	2430	187	2243	
UM	4113	R	66	DS	CF	3		NW	2829	7533	797	6736	
UM	4114	A	66	DT	CF	4		SW	11812	5774	0	5774	
UM	4115	R	66	DS	CF	3		SE	1368	3227	271	2956	
UM	4116	R	66	DS	CF	3		SE	613	1265	75	1189	
UM	4117	R	66	DS	CF	3		NW	1737	4265	389	3876	
UM	4118	A	66	DT	CF	1		E	5210	1594	0	1594	
UM	4119	A	66	DS	CF	1		E	4947	5727	0	5727	
UM	4120	A	66	DT	CF	4		NW	22575	6881	0	6881	
UM	4121	R	66	DS	IF	3		W	962	2138	157	1982	
UM	4122	R	66	DS	IF	3		NW	1347	3169	265	2905	
UM	4123	R	66	DS	IF	3		NW	1816	4492	416	4076	
UM	4124	R	66	DS	IF	3		SW	1161	2666	211	2455	
UM	4125	R	66	DS	IF	3		W	594	1220	71	1149	
UM	4126	R	66	DS	IF	3		W	1496	3582	311	3271	
UM	4127	R	66	DS	IF	1		SE	752	1606	106	1501	
UM	4128	R	66	DS	IF	3		SW	2885	7707	820	6888	
UM	4129	R	66	DS	IF	1		NE	1263	2941	240	2701	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measurement method*	Photo year first appears	Landslide classification**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
UM	4130	R	66	DS	IF	1		NE	1463	3491	300	3190	
UM	4131	R	75	DS	IF	3		N	1482	3426	294	3132	
UM	4132	R	66	DT	CF,IF,S	6		N	48169	14682	0	14682	
UM	4133	R	66	DS	CF	1		N	662	1384	86	1298	
UM	4134	R	66	DS	CF	1		N	836	1817	125	1691	
UM	4135	R	66	DS	CF	1		N	1903	4744	446	4298	
UM	4136	R	75	DS	CF	1		SW	711	1503	96	1407	
UM	4137	A	66	DT	CF	1		N	4923	2180	0	2180	
UM	4138	R	66	DS	CF	1		S	464	914	47	868	
						UM Totals			190935	252850	22147	236168	
CC	3055	F	75	CS	TZ	2		NE	15851		1680	560	Field measured vol-aerial photo measured
CC	3057	F	66	CS	TZ	1	39	NE	14246	45314	14021	31293	
CC	3058	F	66	DS	TZ	1	45	NE	443	1295	0	1295	
CC	3059	F	66	DS	TZ	1	31	N	3227	14651	0	14651	
CC	3061	F	75	DS	TZ	1	45	NE	394	510	0	510	
CC	4139	R	66	DS	TZ	1		SW	864	1887	132	1755	
CC	4140	R	66	DS	TZ	1		SW	2555	6691	687	6003	
CC	4141	R	66	DS	TZ	1		SW	1227	2841	229	2612	
CC	4142	R	66	DS	TZ	1		SW	1040	2344	177	2167	
CC	4143	R	66	DS	TZ	1		W	1737	4265	389	3876	
CC	4144	R	66	DS	TZ	1		SW	2290	5888	586	5302	
CC	4145	A	66	CS	TZ	1		SW	8175	4438	0	4438	
CC	4146	R	60	DS	TZ	1		SW	251	432	0	432	Renewed portion only-60 scar revegetated
CC	4147	R	75	DS	TZ	1		S	813	1758	120	1638	
CC	4148	R	66	DS	TZ	1		N	3219	8760	960	7801	
CC	4149	R	60	DS	TZ	1		SW	2559	6704	689	6014	Major enlargement in budget period
CC	4150	R	66	DS	TZ	1		NE	1742	4278	391	3887	
CC	4151	R	66	DS	TZ	1		SW	4766	13848	1676	12172	
CC	4152	R	60	DS	TZ	1		SW	13317	45943	6907	39036	Major enlargement in budget period
CC	4153	R	66	DS	TZ	1		SW	4666	13512	1627	11884	
CC	4154	R	66	DS	CF	1,3		NW	1254	2916	238	2678	
CC	4155	R	75	DS	CF	3		NE	1219	2821	227	2593	
CC	4156	R	66	DS	CF	3		SW	1382	3266	275	2990	
CC	4157	R	66	DS	CF	3		SW	794	1711	115	1596	
CC	4158	R	66	DS	CF	3		SW	1317	3087	256	2831	
CC	4159	R	66	DS	CF	4		NW	4441	12752	1518	11234	
CC	4160	R	66	DS	CF	2		NW	3168	8599	938	7661	
CC	4161	A	66	DT	CF	2,4		NE	3446	2101	0	2101	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
CC	4162	R	66	DS	CF	3		NE	1540	3706	325	3381	
CC	4163	R	66	DS	CF	4		SW	1463	3491	300	3190	
CC	4164	R	66	DS	CF	3		NE	696	1468	93	1375	
CC	4165	R	66	DS	CF	4		NE	6369	19424	2514	16910	
CC	4166	R	66	DS	CF	4		NE	1219	2821	227	2593	
CC	4167	R	66	DS	CF	4		NE	1073	2430	187	2243	
CC	4168	R	66	DS	F	4		SW	1549	[illegible]732	328	3404	
CC	4169	R	66	DS	F	2		NE	3902	[illegible]	1264	9703	
CC	4170	R	66	DS	F	3		NE	297	543	20	523	
CC	4171	R	66	DS	F	3		NE	441	862	43	820	
CC	4172	R	66	DS	F	3		NE	520	1044	57	987	
CC	4173	R	60	DS	Z	1		SW	5095	7486	921	6565	Vol. of regres. eqn./2 for sed del. during bu
CC	4174	R	66	DS	.Z	1		SW	920	2031	146	1885	
CC	4175	R	66	DS	:Z	1		SW	4311	12318	1455	10863	
CC	4176	R	66	DS	TZ	1		NW	2090	2646	256	2390	Vol. of regres. eqn./2 for sed del. during bu
CC	4177	R	66	DS	TZ	1		NW	2696	7124	743	6381	
CC	4178	R	60	DS	CF	1		S	1097	1247	96	1151	Vol. of regres. eqn./2 for sed del. during bu
CC	4179	A	60	DT	TZ	1	39	S	26913	8204	0	8204	Renewed debris torrent
CC	4180	R	70	DS	CF	4		SW	1479	3535	306	3229	
CC	4181	R	70	DS	CF	4		SW	1635	3975	356	3619	
CC	4182	R	75	DS	CF	4		NE	1236	2866	232	2634	
CC	4183	R	70	DS	CF	4		SW	3953	11134	1287	9847	
CC	4184	R	75	DS	CF	4		SW	2357	6089	611	5478	
CC	4185	R	75	DS	CF	4		SW	1138	2603	204	2399	
CC	4186	R	70	DS	CF	4		W	2297	5908	589	5320	
CC	4187	R	70	DS	CF	3		E	943	2091	152	1939	
CC	4188	R	70	DS	CF	4		W	5149	15156	1869	13287	
CC	4189	R	70	DS	CF	3		W	943	2091	152	1939	
CC	4190	R	75	DS	CF	3		W	455	893	45	848	
CC	4191	R	70	DS	CF	3		SW	1347	3169	265	2905	
WO	3028	F	70	DS	CF	4	39	NE	6326	13953	4396	9580	Material stored on road and flood terrace
						CC Totals			191853	387617	53278	336602	
WO	3065	F	60	SE	CF	1,3	29	SW	6585			688	
WO	3067	F	75	CS	IF	3	37	SE	11389	38284	8155	30129	
WO	3068a	F	70	DT	IF	4	33	SE	3056	5798	0	5798	
WO	3068b	F	70	DS	IF	3	35	SE	543	1417	0	1417	Age uncertain-sm. feature hard to locate
WO	3069	R	75	DS	IF	4	33	S	6633	20368	2659	17708	Treated as debris slide to bedrock
WO	3070	R	70	DS	IF	4	37	N	4487	12909	1540	11369	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measurement method*	Photo year first appears	Landslide classification**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
WO	3071	F	70	DS	IF	3	30	N	2507	9832	3104	6728	Debris sliding to bedrock scion on slope
WO	3071a	F	70	IF	IF	3	35	S	481	359	207	72	
WO	3071b	F	70	IF	IF	3	35	S	356	132	117	15	
WO	3072	F	70	DS	IF	3	40	NE	1193	2848	937	1911	
WO	3073	F	70	DS	IF	3	40	NW	2615	5204	0	5204	
WO	3074	F	75	DS	IF	4	34	NE	385	609	37	572	
WO	3075	F	75	CS	IF	4	35	NE	2233	7574	765	6810	
WO	3076	F	70	CS	IF	4	35	SE	4758	8849	4129	4720	
WO	3077	R	75	DS	IF	4	42	NW	1833	3884	323	3382	
WO	3078	A	70	DT	IF	4	36	NW	6140	1812	0	1812	
WO	3079	F	65	DS	IF	4	37	NW	9114	5640	956	4684	
WO	3080	R	75	DS	IF	4	39	NW	4292	12264	1448	10808	
WO	3081	F	70	DS	IF	3	40	SE	8168	40042	1950	38092	
WO	3082a	F	75	DS	IF	4	40	S	773	922	0	922	
WO	3082c	F	85	DS	IF	1	20	N	732	1529	306	1223	
WO	3082d	F	85	DS	IF	3	27	N	1730	5352	1338	4014	
WO	3082e	F	75	DS	IF	3	27	NW	621	1486	0	1486	
WO	3122	F	75	DS	CF	3	40	NE	324	713	0	713	
WO	3124	F	70	DS	CF	3	35	SW	615	1242	115	1128	
WO	3125	F	66	DS	CF	3	35	S	691	927	84	843	
WO	4192	R	66	DS	CF	1,3		SW	1003	2248	167	2080	
WO	4193	R	66	DS	CF	1,3		NE	1115	2541	198	2343	
WO	4194	R	70	DS	CF	3		SW	585	1198	70	1128	
WO	4195	R	66	DS	CF	1,3		S	1129	2579	202	2377	
WO	4196	R	75	DS	CF	4		NE	2090	5293	512	4781	
WO	4197	R	70	DS	CF	4		NE	1630	3960	354	3606	
WO	4198	R	66	DS	CF	4		NE	6650	20427	2669	17759	
WO	4199	A	70	DS	IF	4		NW	2397	6210	626	5584	
WO	4200	R	70	DS	IF	3		NW	1003	2248	167	2080	
WO	4201	R	70	DS	IF	4		SE	2439	6337	642	5694	
WO	4202	R	66	DS	IF	1		N	2520	6584	674	5909	
WO	4203	R	75	DS	IF	4		NE	3077	8311	900	7411	
WO	4204a	R	70	DS	IF	4		NW	2341	6041	606	5436	
WO	4204b	A	66	DT	IF	6		N	26681	8133	0	8133	
WO	4205	A	75	DT	IF	4		NE	14901	5944	0	5944	Debris torrent assoc. with 3082 slides
WO	4206	R	66	DS	IF	1,3		NW	3693	10284	1168	9116	
							WO Totals		147212	289032	37200	252518	
UG	3027	A	60	CS	IF	1	27	NE	34907			11467	Regres. eqn used for debris slide portion po

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
UG	3043	F	60	DS	IF	1	39	SW	2283	4698	281	4418	70% of vol. from eqn. est. during budget per
UG	3044	F	60	CS	IF	1	29	NE	9824	24934	8601	16332	Est. 80% of field measured vol. during budg
UG	3045	F	70	DT	IF	5	25	NE	5965	11124	260	10864	
UG	3046	A	60	CS	IF	1	31	NE	5435			7998	Regres. eqn used for debris slide portion po
UG	3047	A	60	DS	IF	1	31	NE	39115			50986	Budget period enlargemt 20158yd^2 in eqn.
UG	3048	R	66	DS	IF	1	26	SW	4142	11757	1375	10382	Debris block sliding above debris slide
UG	3049	R	66	DS	IF	1	42	NE	1600	3876	344	3531	
UG	3050	A	60	CS	IF	1	25	SW	8884			2065	
UG	3051	A	60	CS	IF	1	35	W	19621			2389	
UG	3052	R	60	DS	IF	1	39	SW	9011			15040	60% of eqn. vol on total area during budget
UG	3053	R	66	DS	IF	1	37	E	6752	20793	2726	18068	
UG	3084	F	70	DT	IF	5	31	NE	15810	64475	19342	45133	
UG	3096	F	85	DS	CF	4	31	NW	1376	2936	294	2642	
UG	3099	F	66	DS	CF	1	39	W	564	1263	159	1104	
UG	3100	R	66	DS	CF	1	35	NW	1568	3784	333	3450	
UG	3102	R	66	DS	CF	1	37	SW	2257	5790	573	5217	
UG	3103	F	66	CS	CF	1	35	SE	2825			1871	
UG	3104	F	85	DS	CF	1	44	W	257	435	0	435	
UG	3105	F	60	DS	CF	1	35	NW	4888	9175	0	9175	
UG	3106	F	60	DS	CF	1	35	W	1118	1902	283	1619	
UG	3126	F	89	DS	CF	4	40	SE	253	446	42	404	
UG	4207	R	70	DS	IF	1		E	669	1400	87	1313	
UG	4208	R	66	DS	IF	1		SW	3066	8276	1308	7382	
UG	4209	R	75	DS	IF	1		E	486	964	50	914	
UG	4210	R	75	DS	IF	1		SE	648	1349	83	1267	
UG	4211	A	60	DT	IF	1		SW	18210			2775	Budget period contribution estimation
UG	4212	R	66	DS	IF	1		SE	1359	3201	268	2933	
UG	4213	R	66	DS	IF	1		SE	2144	5451	532	4919	
UG	4214	R	60	DS	IF	1		N	2921			5590	80% of eqn. vol on total area during budget
UG	4215	R	60	DS	IF	1		SW	5769			8314	55% of eqn. vol on total area during budget
UG	4216	R	75	DS	IF	1		SE	1368	3227	271	2956	
UG	4217	R	60	DS	IF	1		E	9812			16566	60% of eqn. vol on total area during budget
UG	4218	R	66	DS	CF	1		SE	1365	3220	271	2950	
UG	4219	R	70	DS	IF	1		SW	683	1435	90	1345	
UG	4220	A	60	DT	IF	1		W	38502	7968		7968	Budget period contribution estimation
UG	4221	R	66	DS	IF	1		SW	6502	19900	2587	17314	
UG	4222	R	75	DS	IF	1		NE	1839	4559	424	4135	
UG	4223	R	66	DS	IF	1		SW	2160	5499	537	4961	
UG	4224	R	66	DS	IF	1		SW	1812	4479	414	4065	
UG	4225	R	66	DS	IF	1		NE	2796	7432	784	6649	

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measure-ment method*	Photo year first appears	Landslide classifi-cation**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
UG	4226	R	66	DS	IF	1		NE	3270	8922	982	7941	
UG	4227	R	66	DS	IF	1		SW	2926	7838	837	7001	
UG	4228	R	66	DS	IF	1		E	911	2007	144	1863	
UG	4229	A	66	DT	IF	1		NW	21720	4576	0	4576	
UG	4230	R	66	DS	CF	1		W	662	1384	86	1298	
UG	4231	A	70	DS	CF	1		W	2038	1556	0	1556	
UG	4232	R	66	DS	CF	1		SE	1533	3684	323	3362	
UG	4233	R	66	DS	CF	1		NE	3089	8347	904	7443	
UG	4234	R	60	DS	CF	1		SE	1188			1259	50% of regr. eqn vol to chl in budget period
UG	4235	R	66	DS	CF	1		SE	1253	2914	237	2677	
UG	4236	R	70	DS	CF	1		NW	1541	3708	325	3383	
UG	4237	R	66	DS	CF	1		NE	3010	8100	872	7229	
UG	4238	R	66	DS	CF	1,3		NE	6912	21371	2816	18556	
UG	4239	R	66	DS	CF	1		SW	3094	8363	907	7457	
UG	4240	R	66	DS	CF	1		NW	2201	5623	553	5070	
UG	4241	A	60	DS	CF	1		SW	4273	260	0	260	Budget period contribution estimation
UG	4242	A	60	CS	CF	1		SW	13022			476	Budget period contribution estimation
UG	4243	R	66	DS	CF	1		NE	836	1817	125	1691	
UG	4244	R	66	DS	CF	1		S	1031	2320	175	2145	
UG	4245	R	66	DS	CF	1		NW	1505	3607	313	3294	
UG	4246	R	66	DS	CF	1		N	3902	10966	1264	9703	
UG	4247	R	66	DS	CF	1		S	1171	2690	213	2477	
UG	4248	R	60	DS	CF	1		S	3808			2548	27% of regr. eqn. vol.of total area during bu
UG	4249	R	85	DS	CF	4		N	2671	7045	733	6311	
UG	4250	R	80	DS	CF	4		N	4668	13517	1628	11890	
UG	4251	R	66	DS	CF	1		W	1570	3791	334	3456	
UG	4252	R	66	DS	CF	1		SW	1932	4829	456	4372	
UG	4253	R	66	DS	CF	1		SW	1819	4499	417	4082	
UG	4254	R	66	DS	CF	1		SW	2617	6880	712	6168	
UG	4255	R	66	DS	CF	1		W	1816	4492	416	4076	
UG	4256	R	66	DS	CF	1		SW	1932	4829	456	4372	
UG	4257	A	66	DS	CF	1		SW	2861	2129	0	2129	
UG	4258	A	66	DT	CF	1		SW	4273	929	0	929	
UG	4259	A	66	CS	CF	1		W	3888			2893	
UG	4260	R	66	DS	CF	1		NW	520	1044	57	987	
UG	4261	R	66	DS	CF	1		SE	562	1142	65	1077	
UG	4262	A	85	DT	CF	1		SW	836	510	0	510	
UG	4263	R	85	DS	CF	4		NE	3526	9743	1093	8649	
UG	4264	R	66	DS	CF	1,3		NW	1568	3784	333	3450	
UG	4265	A	60	DS	CF	1,3		SW	9290	5530	0	5530	Budget period contribution

Drainage sub-basin (Fig. 3 caption)	Landslide inventory number	Volume measurement method*	Photo year first appears	Landslide classification**	Geologic unit (Fig. 2 caption)	Land use ***	Slope (deg)	Aspect	Landslide map area (m^2)	Volume mobilized (m^3)	Volume stored on slope (m^3)	Volume delivered to channel (60-88) (m^3)	Comments
UG	4266	R	75	DS	CF	1,3		NE	390	747	34	713	
UG	4267	R	75	DS	CF	1,3		SW	785	1688	113	1575	
UG	4268	R	66	DS	CF	1,3		NE	1568	3784	333	3450	
UG	4269	R	66	DS	CF	1,3		NE	3005	8084	869	7215	
UG	4270	R	66	DS	CF	1,3		NE	1254	2916	238	2678	
UG	4271	R	66	DS	CF	1,3		SW	1003	2248	167	2080	
UG	4272	R	66	DS	CF	1,3		W	1380	3259	274	2984	
UG	4273	R	66	DS	CF	1,3		SW	1449	3451	296	3155	
UG	4274	R	70	DS	CF	1,3		SW	5853	17601	2235	15366	
						UG Totals			428496	474274	64657	542268	
						Watershed totals			2732486	3438822	597805	3520901	

* Volume measurement methods:
- F=field
- A=aerial photograph
- R=regression eqn.

** Landslide classification
- D=debris slide
- CS=complex slide
- RF=rock fall
- DT=debris torrent
- SE=slump earthflow

***Land use classifications:
- 1 = Occurs in unmanged land - not road related
- 2 = Occurs in unmanaged land - road or landing related
- 3 = Occurs in managed land - not road related
- 4 = Occurs in managed land - road or landing related
- 5 = Occurs in unmanaged land - clearly related to upslope managed land
- 6 = Occurs in both managed and unmanaged land

Appendix B. Landslide activity inventory (see end of table for activity classifications).

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
3002		I					
3003		I					
3004		I					
3005		I		Mi			
3006		I					
3007		I					
3008		I		Mi			Mi
3009		I		Ma			
3010		I				Mi	
3011		I		Mi		Mi	
3012		I					
3013	I	Ma					
3016		I		R			
3017		I	Mi			R	
3018	I	Mi					
3019		I					
3020		I					
3021		I					
3022				I		R	
3023	I	Ma					
3024		I					
3025a		I					
3025b		I					
3026		I					
3027	I			Ma			
3028			I				
3030		I					
3031		I				R	
3032		I					
3033	I			Ma			
3034			I	Ma			
3035				I			
3036		I					
3037		I					
3039		I					
3040		I		Mi			
3042		I	Mi	Mi			
3043	I	Ma					
3044	I	Ma					
3045			I				
3046	I	Ma		Mi			
3047	I	Ma					
3048		I		Mi		Mi	
3049		I					
3050	I	Ma					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
3051	I	Mi				Ma	
3052	I	Ma					
3053		I		Mi			
3055				I		Ma	
3056					I		
3057		I	Ma				
3058		I		R			
3059		I					
3061				I			
3065	I						
3067				I			
3068			I	Mi			
3068a			I				
3069				I			
3070			I				
3071			I				
3071a			I				
3071b			I				
3072			I				
3073			I				
3074				I			
3075				I			
3076			I				
3077				I			
3078			I				
3079						I	
3080				I	Mi		
3081			I	Mi			
3082a				I			
3082c						I	
3082d						I	
3082e				I			
3083	I			Ma			
3084			I	Ma			
3085	I	Mi					
3086		I					
3087		I	Ma				
3088	I	Mi					
3089	I	Mi					
3090		I					
3091		I				Mi	
3092		I		Mi		Mi	
3093		I		Mi			
3094		I					
3095		I					
3096						I	
3099		I	Mi			Mi	
3100		I					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
3102		I	Mi			Mi	
3103		I		M			
3104						I	
3105	I	Mi	Mi	M			
3106	I			M		Ma	
3107		I		M			
3108		I					
3109				I			
3110				I			
3111		I					
3114				I			
3115						I	
3122				I			
3124			I				
3125		I	Mi				
3126							I
4001		I			R		
4002		I					
4003	I	Ma					
4004		I				R	
4005		I					
4006		I					
4007			I			R	
4008		I			R		
4009		I					
4010		I					
4011		I					
4012		I					
4013		I			R		
4014		I					
4015		I				R	
4016		I					
4017		I					
4018		I				R	
4019		I			R		
4020		I					
4021		I					
4022		I					
4023		I					
4024		I					
4025		I			R		
4026		I					
4027		I					
4028		I					
4029		I		Mi			
4030				I			
4031		I				R	
4032		I				R	

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
4033		I			R		
4034		I					
4035		I					
4036		I				R	
4037		I				R	
4038		I			R		
4039		I					
4040		I					
4041		I					
4042		I					
4043		I					
4044		I					
4045		I					
4046		I				R	
4047		I					
4048		I				R	
4049		I					
4050		I			R		
4051		I		R			
4052		I				R	
4053		I			R		
4054	I	Ma		Mi			
4055		I				R	
4056		I			R		
4057		I					
4058		I			R		
4059		I				R	
4060		I					
4061		I			R		
4062		I			R		
4063		I				Ma	
4064		I					
4065		I					
4066		I				R	
4067			I				
4068		I			R		
4069				I		R	
4070			I	Ma		R	
4071		I				R	
4072		I					
4073		I					
4074	I	Mi					
4075		I				R	
4076				I			
4077		I					
4078		I				R	
4079		I				R	
4080		I					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
4081		I			R		
4082		I					
4083		I					
4084		I					
4085		I					
4086		I				R	
4087		I					
4088		I				R	
4089		I				R	
4090		I					
4091		I					
4092		I				R	
4093		I				R	
4094		I				R	
4095		I					
4096		I					
4097		I					
4098		I					
4099					I	Mi	
4100		I				R	
4101		I			R		
4102		I			R		
4103		I		R			
4104		I	Mi	Mi			
4105		I			R		
4106		I				R	
4107		I			R		
4108		I				R	
4109		I				R	
4110		I				R	
4111		I					
4112		I			R		
4113		I				R	
4114		I		R			
4115		I					
4116		I					
4117		I					
4118		I			R		
4119		I					
4120		I					
4121		I					
4122		I					
4123		I					
4124		I					
4125		I					
4126		I					
4127		I					
4128		I					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
4129		I					
4130		I					
4131				I			
4132		I					
4133		I		R			
4134		I		R			
4135		I					
4136				I		R	
4137		I			R		
4138		I			R		
4139		I		Mi			
4140		I				Mi	
4141		I			R		
4142		I			R		
4143		I			R		
4144		I			R		
4145		I			R		
4146	I			Mi			
4147				I			
4148		I			R		
4149	I	Ma					
4150		I		Ma		R	
4151		I					
4152	I	Ma		Ma		R	
4153		I				R	
4154		I			R		
4155				I			
4156		I				R	
4157		I					
4158		I			R		
4159		I					
4160		I			R		
4161		I			R		
4162		I				R	
4163		I					
4164		I					
4165		I				R	
4166		I			R		
4167		I			R		
4168		I			R		
4169		I					
4170		I					
4171		I					
4172		I					
4173	I	Ma	Mi				
4174		I				R	
4175		I					
4176	I	Ma					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
4177		I			R		
4178	I	Mi					
4179	I	Ma					
4180			I		R		
4181			I		R		
4182				I			
4183			I	Mi			
4184				I			
4185				I			
4186			I	Mi			
4187			I			R	
4188			I	Ma			
4189			I				
4190				I			
4191			I				
4192		I					
4193		I	Mi				
4194			I				
4195		I					
4196				I			
4197			I				
4198		I	Ma	Ma			
4199		I			R		
4200			I		R		
4201			I			R	
4202		I					
4203				I			
4204			I				
4204		I	Mi				
4205				I	Mi	Mi	
4206		I					
4207			I			R	
4208	I				R		
4209				I		R	
4210				I		R	
4211	I						
4212		I		Mi			
4213		I		Mi			
4214	I		Mi		R		
4215	I	Mi					
4216				I		Mi	
4217	I	Mi		Mi		R	
4218		I				R	
4219			I	Mi			
4220	I	Mi		Mi		Mi	
4221		I				R	
4222				I		R	
4223		I					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
4224		I					
4225		I		Mi	R		
4226		I				R	
4227		I		Mi			
4228		I					
4229		I		Mi			
4230		I					
4231			I		R		
4232		I				R	
4233		I				R	
4234	I						
4235		I					
4236			I				
4237		I					
4238		I				R	
4239		I					
4240		I					
4241	I					R	
4242	I					R	
4243		I					
4244		I	Mi				
4245		I	Mi				
4246		I					
4247		I					
4248	I	Mi					
4249						I	
4250					I	Mi	
4251		I					
4252		I					
4253		I					
4254		I				R	
4255		I					
4256		I					
4257		I					
4258		I					
4259		I				R	
4260		I					
4261		I					
4262						I	
4263						I	
4264		I			R		
4265	I	Mi				Mi	
4266				I		R	
4267				I		R	
4268		I				R	
4269		I		Mi			
4270		I					
4271		I					

Landslide number	Aerial photo year 1960	Aerial photo year 1966	Aerial photo year 1970	Aerial photo year 1975	Aerial photo year 1980	Aerial photo year 1985	Aerial photo year 1988+
4272		I					
4273		I					
4274			I				
4275	I	Ma	Mi	Mi	Mi	Mi	Mi
Total I	41	258	37	36	3	12	1
Total Mi	-	13	14	33	3	12	2
Total Ma	-	16	3	11	-	4	-
Total R	-	-	-	7	46	63	-

Landslide activity classifications:
I = Initial appearance of slide in aerial photograph year
Mi = Minor enlargement of slide
Ma = Major enlargement of slide
R = Revegetated

March 4, 1991

Mr. Mike Furniss, Hydrologist
Six River National Forest
507 F Street
Eureka CA 95501

Dear Mike:

Enclosed is the final report of the Grouse Creek sediment budget. The final report is much refined and contains a number of changes and additions to the preliminary draft submitted in December, 1990. Major changes are summarized below.

For the final report, all sediment volumes were converted to units of mass (tonnes) to facilitate comparison of sediment production and storage volumes of different densities. The need for the preliminary draft discussion on double-counting of sediment volumes was eliminated.

A significant change is the percentage contribution from landsliding from 77 to 87 percent. This adjustment stems from the volume-to-mass conversion and additional analysis of the hillslope and road-related erosion components rather than changes to landslide volumes. Changes in hillslope erosion figures are due mainly to fine-tuning empirically-derived USLE factors using updated, local data on rainfall and soils. Additional field work allowed revision of road-related erosion estimates, specifically cutbanks yields and road drainage to streams. Road-surface erosion estimates were modified using the revised USLE R factor and field-sampled road drainage percentage. More detailed discussion of these components of the sediment budget are found in the text.

A rainfall analysis using the Kneeland precipitation data sent to us in late December is not included in the final report. The data show a weak trend between

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landsliding and annual precipitation and no significant trend between storms greater than 75 or 100 mm and landsliding, which may be significant in itself; however, without comparing Kneeland precipitation to other nearby stations, it is difficult to determine if any Kneeland data is missing. We were hesitant to include a precipitation analysis based on the Kneeland data alone.

Data disks containing copies of the report text, data tables, and graphs have been mailed under separate cover. We will be glad to answer any questions regarding the data or final report. We would like to thank you again for the excellent field and office support extended to us during this project.

Sincerely,

Mary

Mary Raines
Harvey Kelsey