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Magnitude and Causes of Gully Erosion in the Lower Redwood Creek Basin, Northwestern California

By WILLIAM E. WEAVER, DANNY K. HAGANS, *and* JAMES H. POPENOE

GEOMORPHIC PROCESSES AND AQUATIC HABITAT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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MAGNITUDE AND CAUSES OF GULLY EROSION IN THE LOWER REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

By WILLIAM E. WEAVER,[1] DANNY K. HAGANS,[1] and JAMES H. POPENOE[2]

ABSTRACT

Gullying was found to be a major process of erosion on roaded prairies and logged lands in the 197-km^2 lower Redwood Creek basin. Detailed mapping of over 2,200 hectares of disturbed terrain revealed that 90 percent of the 329,500 m^3 of measured gully erosion on nine study sites was caused by the diversion of first-order and second-order streams. Plugged culverts, failure to install culverts at logging-road stream crossings, and bulldozing of soil and logging slash into shallow hillslope stream channels were the leading causes of stream diversions and consequent gullying.

On all study sites, logging and related practices and the degree of ground disturbance were similar, yet gully yields were highly variable. The highest amounts of postharvest gully erosion were typically associated with lengthy, unmaintained logging road systems in areas underlain by incoherent bedrock and soils low in clay or in rock fragments. In contrast, thin rocky soils or thicker soils having high clay content tended to retard gully development. Although land use, geology, and soils controlled the susceptibility of a site to gullying, areas that had not had a major rainfall and runoff event (recurrence of 10 to 12 years, or more) since logging showed very little gully erosion.

Most gully erosion from areas of similar land use occurred in certain high-yield terrain types, of restricted areal extent, which were characterized by thick, erodible soils. In the lower Redwood Creek basin, these terrains occupy 31 percent of the roaded prairies and tractor-logged land and have contributed an estimated 70 percent of the total volume of material eroded by gullies. In contrast, 16 percent of the lower basin area, making up the low yield category, was estimated to account for less than 1 percent of the total volume of soil eroded by gullies. Fluvial sediment production from rills and gullies on steep, logged, or roaded terrain similar to that of the lower Redwood Creek basin may be reliably estimated by (1) limiting sediment source inventories to gullies produced by stream diversions at logging road and skid-trail stream crossings and (2) restricting actual field measurements to the largest gullies. Small gullies, those 0.1 to 1.1 m^2 in cross-sectional area, were numerous on study sites but relatively unimportant as contributors to sediment production. They made up nearly 60 percent of the cumulative 76 km of gullies measured but yielded only 6 percent of the recorded volume of eroded soil. In contrast, gullies larger than 4.5 m^2 in cross-sectional area were the source of over 80 percent of the sediment production, yet they constituted less than 25 percent of the gully network by length.

Gully erosion in the lower Redwood Creek basin is estimated to account for 25 percent less sediment production than streamside landsliding over the last three decades. Careful land management practices and preventive erosion control following logging and related activities could have eliminated approximately 85 percent of the gully erosion through improved road construction, road maintenance, and road abandonment practices.

[1] Pacific Watershed Associates, Arcata, CA 95521.
[2] Redwood National Park, Arcata, CA 95521.

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INTRODUCTION

A significant problem commonly associated with timber harvesting and road building in mountainous terrain is increased rates of soil erosion and sediment yield (Anderson, 1979; Kelsey, 1980; Swanson, 1981). Few places in North America display this more graphically than the Redwood Creek basin where physiographic, geologic, and climatic factors, together with certain land use patterns, have contributed to exceptionally high rates of erosion (Janda and others, 1975). For example, during 6 years of record beginning in 1971, Redwood Creek at Orick, Calif., transported a mean annual suspended sediment load of 2,619 mg/km^2, 32 percent higher than the Eel River at Scotia, Calif. (Janda, 1978), which has been characterized as the most rapidly eroding, nonglaciated basin of comparable size in North America (Brown and Ritter, 1969). Although Redwood Creek's suspended sediment discharge has been estimated to be 8.6 times greater than the expected normal rate of delivery (Anderson, 1979), synoptic storm sampling indicates that some tributary basins displaying severe ground disruption from recent timber harvesting have yielded as much as 17 times the suspended sediment, per unit area, as nearby unharvested basins (chap. L, this volume).

As a result of a congressionally authorized watershed rehabilitation program in the lower Redwood Creek basin (fig. 1), cutover forested areas and prairie grasslands have been studied to locate active and potential sources of erosion for eventual erosion control. To achieve this, Redwood National Park geologists have completed detailed erosional inventories and geomorphic maps, at a scale of 1:1,200, on approximately 4,000 hectares (ha) of logged land within the lower one-third of the Redwood Creek basin. This mapping, which began in 1978, has included both the location and dimension of hillslope gullies, landslides, enlarged natural stream channels, and a variety of other erosional features.

Fluvial erosion on cutover lands in the Redwood Creek basin has been significantly increased in relation to erosion under undisturbed conditions, probably to a greater degree than erosion from mass-movement processes (Janda and others, 1975). Nolan and others (1976) noted an increase in the basinwide abundance of gullies from 1947 to 1974. In addition, preliminary data from sediment budget studies suggest that fluvial erosion from hillslopes contributed nearly 70 percent of the sediment input to the upper 175 km^2 of the Redwood Creek basin between 1956 and 1980 (Kelsey and others, 1981). Locally intense gully erosion has also been recorded in several tributary basins (Weaver and others, 1981; chap. M, this volume).

Gullies have been qualitatively defined as distinct, narrow channels that are larger and deeper than rills and that usually carry water only during or after storms or snowmelt (Bates and Jackson, 1980). Considerable effort has been expended to study gully formation and growth (Leopold and Miller, 1956; Schumm and Hadley, 1957; Graf, 1979) and gully control (Ramser, 1932; Heede, 1976, 1978). However, the magnitude of steepland gully erosion and the extent to which various causes of gullying on logged or roaded hillslopes have contributed to elevated sediment yields have not been closely analyzed elsewhere in the literature. Because gullies are widely spaced on the landscape, sediment yields from fluvial hillslope erosion in large mountainous drainage basins have been difficult to determine quantitatively. As a result, sediment budget studies have typically left fluvial erosion as the unmeasured, least well defined term in the budget equation (Kelsey, 1980).

To help reveal the importance of fluvial erosion on logged land, a study was designed to determine the magnitude and causes of gully erosion on selected areas in the lower Redwood Creek basin. For this investigation, gullies were defined as newly formed channels greater than 0.1 m^2 in cross-sectional area. Specific objectives of the study were (1) to quantify the magnitude of gully erosion on a variety of sites where detailed geomorphic mapping had previously been completed, (2) to identify those land use and site variables most responsible for causing the formation of hillslope gullies, and (3) to suggest simplified sampling procedures, based on an analysis of the identified causes and magnitude of gully erosion, which could aid in quantifying fluvial hillslope erosion in large cutover drainage basins elsewhere. Study areas were not specifically selected to be representative of other portions of the Redwood Creek basin. However, as described below, inventoried sites were not atypical either in pedologic and geomorphic conditions or in the style and intensity of land use disturbances.

Results of this investigation indicate that gully formation promoted by land use practices is a principal cause of soil erosion from roaded and tractor-logged hillslopes. Because most gullies are caused by stream diversions, improved logging, road construction, and road maintenance practices could have greatly reduced postharvest fluvial erosion. In addition, several site factors, including both land use and natural variables, were found to exert strong control on the dimensions and volumetric contribution of gully systems on cutover terrain within the study areas.

STUDY SITES

GEOLOGY AND SOILS

Throughout most of the lower watershed, Redwood Creek follows the trace of the Grogan fault, a major geologic structure that divides the basin into two different terranes. Three of the study sites, constituting 805 ha situated west of the fault (fig. 1), are underlain by intensely sheared, well-foliated, mica-quartz-feldspar schist of the Franciscan assemblage of Late Jurassic to Cretaceous age (Harden and others, 1981); these sites generally have steeper hillslopes, a more clay-rich soil, and a higher drainage density than areas on the east slope. In contrast, the remaining six study sites, encom-

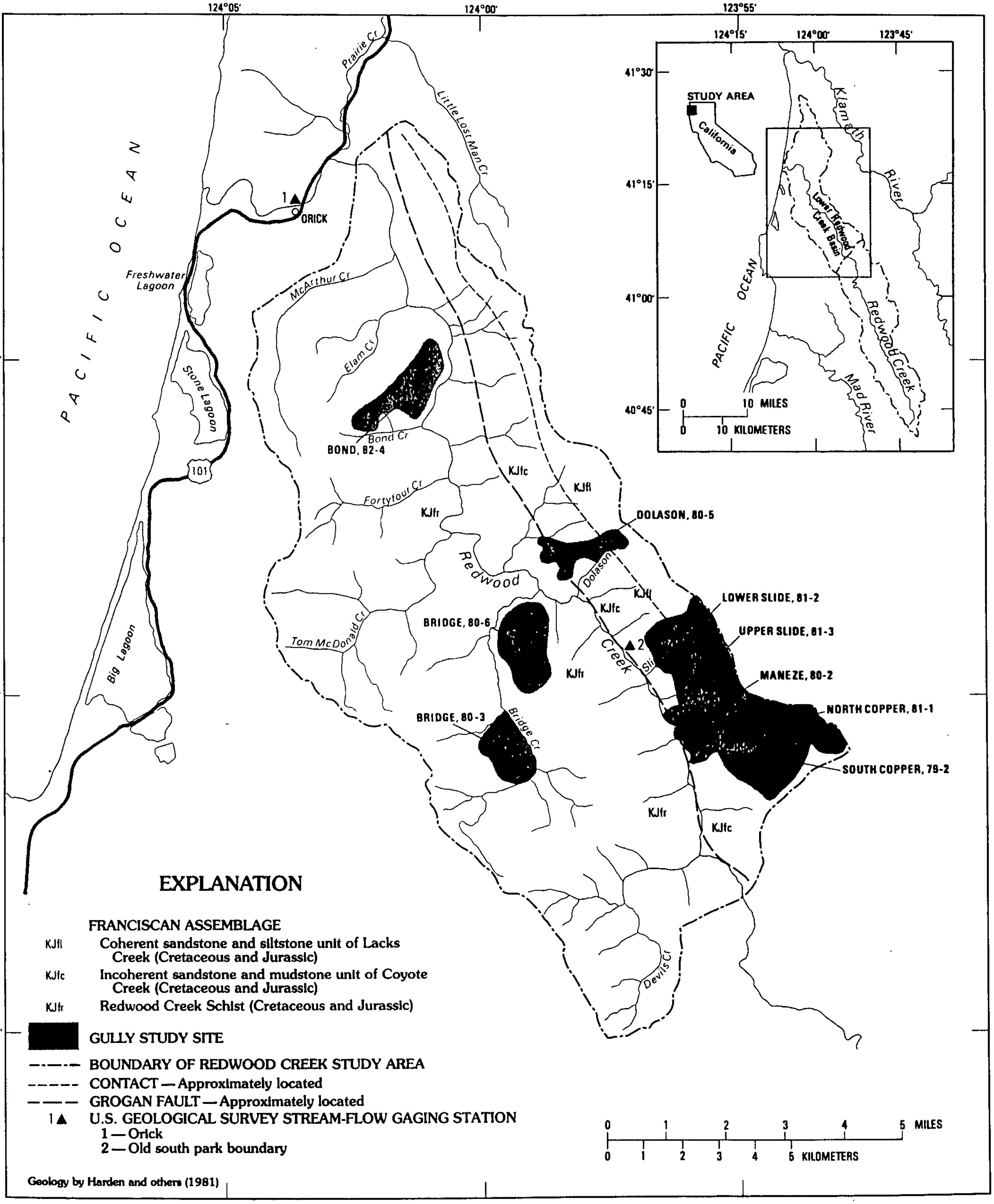


FIGURE 1.—Lower Redwood Creek basin, nine study sites (shaded areas), and generalized bedrock geology. For this study, the lower Redwood Creek basin encompasses all lands within the Redwood Creek unit of Redwood National Park, excluding the Prairie Creek drainage basin and areas downstream from the confluence of Prairie Creek and Redwood Creek.

TABLE 1.—*Classification of principal soils in the lower Redwood Creek basin*

[From Popenoe and Lewis (1983, unpublished). These newly proposed soil names have not yet been approved or reserved by the National Cooperative Soil Survey]

Soil order	Subgroup	Family description	Proposed soil name
Alfisol	Typic Tropudalfs	Fine, mixed, isomesic	Atwell.
Inceptisols	Typic Humitropepts	Loamy-skeletal, mixed, isomesic	Lack, Slidecreek.
Do.	....do....	Fine loamy, mixed, isomesic	Coppercreek, Devilscreek.
Ultisols	Typic Tropohumults	Clayey, oxidic, isomesic	Fortyfour.
Do.	Orthoxic Tropohumults	Clayey, oxidic, isomesic	Trailhead.

TABLE 2.—*Setting and characteristics of principal soils in the lower Redwood Creek basin*

[From Popenoe and Lewis (1983, unpublished) and Harden and others (1981)]

Soil name	Bedrock characteristics	Slope gradient (percent)	Slope morphology	Depth to bedrock contact (cm)	Clay content by horizon (percent)		Rock fragment content by horizon[1] (percent)	
					A	B	A	B
Trailhead	Coherent schist	10–50	Broad ridges, uniform upper slopes.	>150	28–36	40–60	1–25	1–20
Fortyfour	Coherent schist	10–50	Rounded upper slopes and ridges.	50–100	28–32	38–48	10–35	10–35
Devilscreek	Sheared schist	30–70	Steep, uniform to concave slopes.	>150	25–32	27–35	15–35	5–35
Lack	Massive sandstones, mudstones, and coherent schist.	30–75	Steep or strongly convex slopes.	50–100	20–30	24–32	10–45	35–75
Coppercreek	Sheared mudstones, sandstones, and schist.	15–70	Moderate to steep slopes	100–>150	20–30	27–35	1–35	10–35
Slidecreek	Massive sandstone, mudstones	30–75	....do....	>100	20–28	27–35	15–75	5–60
Atwell	Sheared shales, sandstones	15–50	Moderate, concave irregular slopes.	>150	27–32	35–50	2–25	5–35

[1] Gravel- and cobble-sized rock fragments.

passing 1,409 ha east of the Grogan fault, are underlain primarily by unmetamorphosed, pervasively sheared and folded sandstones and siltstones of the Coherent unit of Lacks Creek and the Incoherent unit of Coyote Creek, two units of the Franciscan assemblage (Harden and others, 1981).

Lower hillslope positions, which are underlain by the more brecciated, sheared, and argillaceous rocks of the Incoherent unit of Coyote Creek, have a rolling, subdued topography similar to that formed elsewhere in north coastal California on Franciscan mélange. Drainage networks are less deeply incised than those formed on the coherent unit. In contrast, much of the upper half of the hillslopes east of the Grogan fault is underlain by more resistant sandstone and mudstone turbidite sequences of the Coherent unit of Lacks Creek. Here, hillslopes are steeper and straighter, and major tributary drainages are confined to incised V-shaped canyons.

Differing bedrock lithologies and weathering stages have resulted in the development of several different soil units on study sites in the lower Redwood Creek basin. Durgin and Tackett (1982) used observations made during the original soil surveys (Alexander and others, 1962) together with several quantitative erosion indexes to evaluate the relative erodibility of soils found within the study sites. These evaluations do not indicate a unique relationship between observed erodibility and erosion indexes derived from laboratory analyses of the various soils. Therefore, susceptibility to erosion was inferred to be dependent on such factors as hillslope gradient, soil disturbance, and other site characteristics (Durgin and Tackett, 1982). More recent, detailed remapping, description, and classification of soils within the study sites (table 1) have been initiated by Popenoe and Lewis (National Park Service, unpub. reports, 1983). As will be described in a later section, new data on the distribution and properties of soils specifically found within the lower Redwood Creek area provide useful correlations with erosion rates and gully dimensions as measured at the nine study sites evaluated in this paper.

Five major soil series that developed on the schist of Redwood Creek (Redwood Creek schist) of the Franciscan assemblage have been identified and named (table 2); these soil series occur on study sites west of the Grogan fault. The Trailhead and Fortyfour soils occur together on upper to middle slopes having gradients in the range of 10 to 50 percent. These are well-drained Ultisols whose red-clay argillic horizons are high in iron oxides and gibbsite. The Coppercreek and Lack soils occur together mostly on middle slope positions. These are well-drained Inceptisols having yellowish-brown, gravelly clay loam cambic horizons and mixed clay mineralogy. The poorly to moderately drained Devilscreek soils occur in hillslope hollows and near drainages, primarily on the lower slope positions.

Four major soil series that developed on the Coherent unit of Lacks Creek and the Incoherent unit of Coyote Creek, two units of the Franciscan assemblage, have been identified (table 2); these soil series occur on study sites east of the Grogan fault. Soil patterns are influenced by variation in relief and bedrock lithology. Relief is generally higher and steeper on the coherent sedimentary units. On the whole, soils formed on the sandstone turbidites of the Coherent unit of Lacks Creek (Harden and others, 1981) are thinner and have higher concentrations of rock fragments than soils formed on the Incoherent Coyote Creek mudstones. The Lack, Slidecreek, and Coppercreek soils occur on the Coherent unit of Lacks Creek. These are all well-drained Inceptisols. Coppercreek and Atwell soils predominate on the Incoherent unit of Coyote Creek. The Atwell soils are most common in drainage amphitheaters, which exhibit high drainage density and areas of slope instability. Atwell soils are poorly to moderately drained Alfisols having gray, mottled clay argillic horizons.

LAND USE AND STORMS

Most of the study sites on the east side of the basin are dominated by conifer forests. However, four of the six sites on the east side contain grasslands and oak woodlands ranging from 31 to 66 percent of their upland areas. For example, prior to timber harvesting, 59 percent (445 ha) of the Copper Creek drainage was covered with a conifer forest dominated by coastal redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*). The remainder of the basin consisted of Oregon White oak (*Quercus guarryana*) woodlands on the middle and upper slopes and prairie grasslands along the ridgetop areas. In contrast, two other sites east of the Grogan fault and all three study sites west of the fault consist entirely of cutover coniferous forests.

With the exception of several small, cable-yarded areas on four of the study sites, all of the logging on each site was done by tractors. Felled trees were yarded downhill to the nearest logging road and loaded on trucks. In the process, yarding tractors constructed a network of interconnecting skid trails that crossed nearly every hillslope stream channel at frequent intervals (fig. 2). Typically, upon completion of clearcut operations, from 80 to 85 percent of the total ground surface had been disrupted, and roughly 40 percent of the site was covered by areas of severe ground disturbance; the disturbances included roads, landings, and skid trails (Janda and others, 1975).

The effect is a nearly total disruption of the microtopographic features of the site and obliteration of all but the major channels of the original drainage network. Compacted areas (roads, trails, and landings) promote rapid surface runoff during winter storms, and diverted streams find new paths over the disrupted landscape (fig. 3).

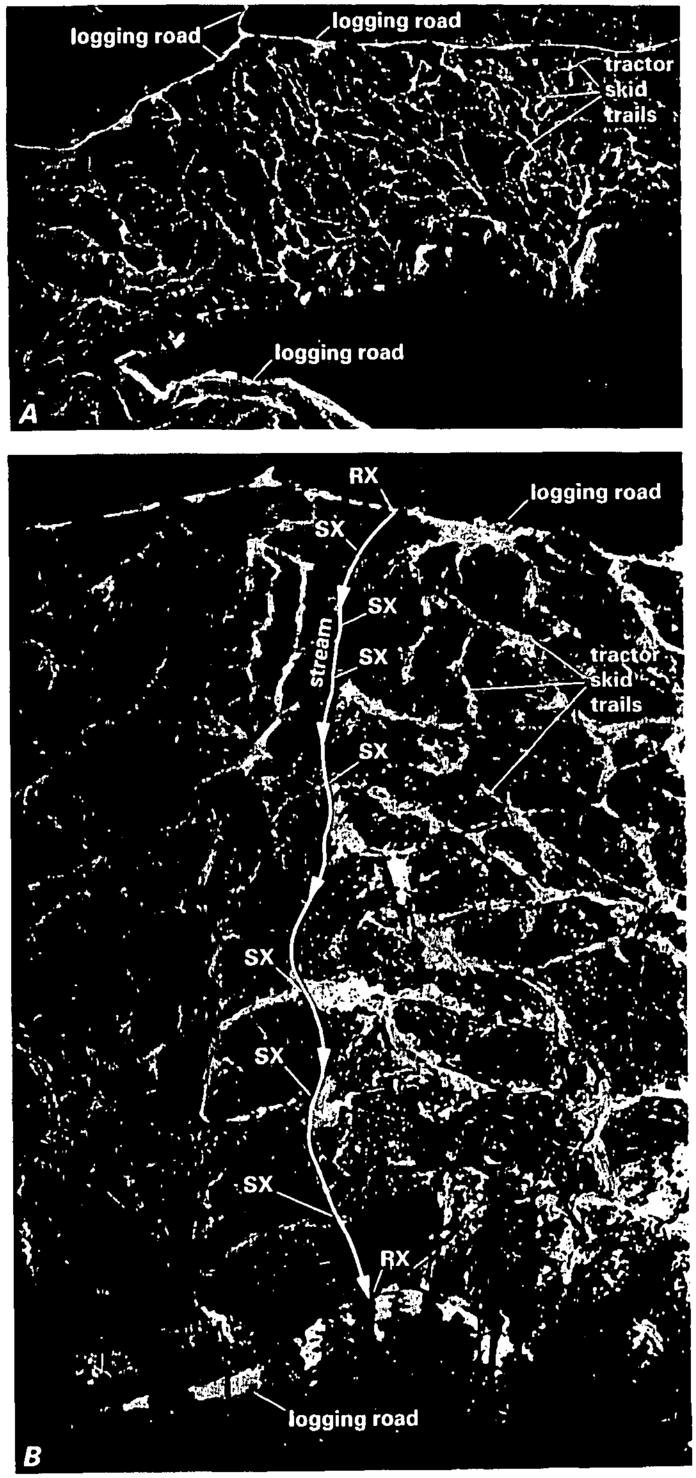


FIGURE 2.—Oblique aerial photographs of a portion of the Bond Creek study site (82–4). *A*, Top photograph taken in 1978, shows intricate web of tractor skid trails and associated haul roads on hillslope that was clearcut in 1975 and 1976. Areas between trails had already begun to revegetate. In contrast, the area at top of photograph was last logged in 1970. Old-growth forests remain at the base of the hill. *B*, Lower photograph shows two road crossings (RX) and at least seven skid-trail crossings (SX) of the intermittent stream that flows from top-center to bottom-center of the photographs.

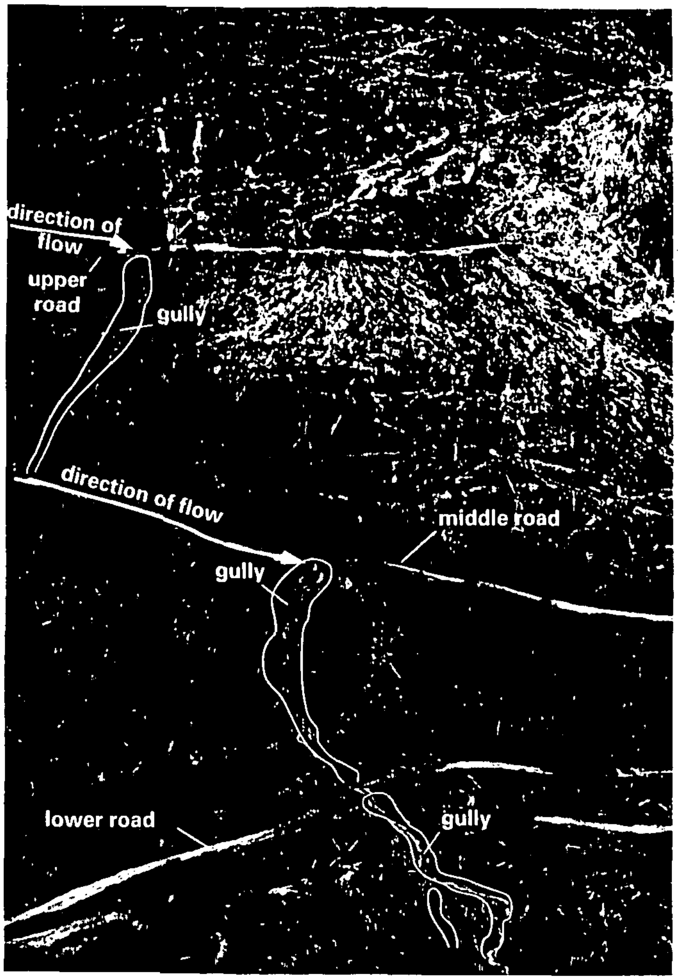


FIGURE 3.—Oblique aerial photograph of a roaded, clearcut hillslope in the lower Redwood Creek basin. Lack of culverts on the upper road resulted in large gully that extended from the end of switchback down to the middle road. The lack of a culvert at the stream crossing on the middle road caused diversion of flow down the ditch and across a road prism near center of the photograph, creating a large, visible gully extending down to and across the lower road system. Photograph was taken soon after the March 1972 storm.

FIGURE 4.—Vertical aerial photograph taken March 7, 1972, of the western portion of the South Copper Creek study site. Note the degree of ground disturbance and the complex pattern of skid trails associated with clearcut tractor-yarding completed in 1971. Old-growth forest (upper right, outside study site) was logged the following year.

The sequence of harvesting in each of the nine study sites has generally consisted of (1) pioneer road construction and limited selective harvesting in the late 1950's and early 1960's and (2) reentry in the early 1970's (table 3), after a period of no activity, for additional road construction and clearcut tractor-yarding over virtually the entire forested portion of each site. For example, in South Copper the conifer forests were logged between 1959 and 1971, with 5 years of intermittent selective tractor logging from 1959 to 1963. The remaining residual timber was clearcut and tractor-yarded from 1970 to 1971. On all sites, this final phase of logging was marked by extreme ground disturbance that left approximately 80 percent bare soil in place of the forested portion of the study site (fig. 4). Road construction history paralleled harvesting operations. In general, 35 to 65 percent of the road network at each site was established during the early periods of selective harvesting. Each road system was then reopened and lengthened in the final period marked by widespread clearcutting.

Dendrochronological evidence not presented in this report (W.E. Weaver, U.S. National Park Service, unpub. data) suggests that timing of the four major storms correlates well with the most active periods of gully development on the study sites. Based on long-term precipitation records from Orick, Calif., and on records from within the Redwood Creek basin since 1974, annual precipitation in the lower one-third of the Redwood Creek basin between 1938 and 1980 averaged approximately 2,000 mm. Four major storms (one in

TABLE 3.—*Physical characteristics and logging history of the nine study sites*

Site name and number (from fig. 1)	Area (ha)	Area upslope from site (ha)	Hillslope position[1]	Mean slope length[2] (m)	Mean slope gradient (percent)	Percent of site steeper than 30 percent gradient	Years logged (19XX)	Logging roads (No.)	Logging roads (km)	Roads upslope from site (No.)	Roads upslope from site (km)	Bedrock characteristics	Principal soils [3]
South Copper (79–2).....	246	84	U,M,L	1,340	37	73	59–63,70–71	3	10.8	1	0.6	Sheared mudstone, minor sandstone.	Coppercreek.
North Copper (81–1).....	[4]410	0	U,M,L	1,280	32	66	55,62,70	4	6.3	0		....do....	Do.
Maneze (80–2)..........	172	0	U,M,L	1,620	38	72	58,62,66,71,73	4	5.3	0		....do....	Coppercreek, Atwell.
Lower Slide (81–2)......	[5]198	239	M,L	1,830	40	82	59,64,71,76	3	6.1	3	4.5	....do....	Do.
Bridge (80–6)..........	304	0	U,M,L	1,370	36	77	69,71,73,75	5	11.8	0		Sheared and coherent schist.	Coppercreek, Devilscreek.
Upper Slide (81–3)......	[6]239	0	U,M	910	33	59	62,66,71	3	4.5	0		Massive sandstone, minor mudstone.	Lack, Slidecreek, Coppercreek.
Dolason (80–5).........	[7]144	11	U,M	1,770	29	54	[8]55,71,77	2	7.7	1	.6	Sheared mudstone, minor sandstone.	Coppercreek, Atwell.
Bridge (80–3)..........	275	123	M,L	1,830	38	77	71,76	3	5.0	2	4.0	Sheared schist	Coppercreek, Devilscreek.
Bond (82–4)............	226	0	U,M	910	24	30	66,71,76	1	2.7	0		Coherent schist	Trailhead, Fortyfour.

[1] U=upper third, M=middle third, L=lower third.
[2] Distance from bottom of unit to drainage divide.
[3] Soils are listed in order of decreasing areal extent; soil characteristics are described in table 2.
[4] Includes 270 ha of grasslands.
[5] Includes 64 ha of grasslands.
[6] Includes 74 ha of grasslands.
[7] Includes 81 ha of grasslands.
[8] 50 percent of site roaded and harvested in 1977; 25 percent of site has been cable-yarded.

1964, two in 1972, and one in 1975) have occurred since logging began on several of the study sites. However, most harvesting and road construction on the nine sites occurred after 1964 but prior to or immediately after the storms of 1972. While the rainfall intensities and durations of the 1972 storms were probably less than for either the 1964 or 1975 storms (Harden and others, 1978), the erosional impact appears to have been greater, perhaps because clearcutting and tractor-yarding on many of the sites had been just completed.

SITE SELECTION

Nine study sites totaling 2,214 ha were selected (fig. 1). Study sites were limited to those that had been mapped in sufficient detail to allow accurate determination of gully volumes as well as the causes of each newly developed gully system. Several sites were specifically chosen because of their apparent low rate of fluvial hillslope erosion. Most of the sites described in this investigation, however, displayed widespread and intense ground disturbance from recent road construction and timber harvesting. These activities had resulted in locally severe gullying and landslide erosion. The study sites covered a variety of bedrock types, soil materials, hillslope positions, and slope gradients (table 3).

As a prerequisite to erosion control activities, detailed geomorphic maps (scale=1:1,200) of each site were compiled. Active and inactive erosion sources, including gullies with cross-sectional areas greater than 0.1 m^2, were located in the field and plotted on enlarged aerial photographs. On eight of the study sites, totaling 1,968 ha, gully widths and depths were estimated at least every 21 m. Volumes were then computed by multiplying the measured cross-sectional area by the corresponding length of gully reach. On the 246-ha South Copper Creek study site, all gullies were carefully measured with tape and survey rod. Cross sections were measured at 6-m intervals or more frequently if a significant change in gully size or shape occurred. Because more frequent measurements and more accurate methods of field measurement were used on the South Copper Creek site, results for that site are discussed in more detail than the other eight less intensively sampled study sites. Analysis of data on these sites reveals similar relationships and confirms conclusions drawn from the South Copper data.

CAUSES OF GULLY FORMATION

Locating and determining causes for gully erosion were often the most difficult aspects of the study. Causes were sometimes obscure, and commonly a single erosional feature could be attributed to more than one cause. Primary and secondary causes were determined for each gully in the South Copper Creek study site. This paper presents only the primary causes. In a few cases, where two causes seemed to have equal influence on a gully, both causes were listed as primary, and the volume was divided between them. Gully volumes in the South Copper Creek site were related to six principal causes:

(1) Plugged culverts at stream crossings on logging roads resulted either in gullying of the road fill at the

crossing site or in diversion of the stream down the road with subsequent gullying of the road prism and adjacent hillslopes (fig. 5).

(2) Lack of culverts at logging road stream crossings resulted in the same mechanism of gully formation as described for plugged culverts (fig. 6). Some ephemeral and intermittent streams were not fitted with culverts during summer road construction. These were comparatively smaller than culverted streams, and the gullies attributed to lack of culverts were shown to be smaller than gullies attributed to plugged culverts.

(3) Channel obstructions, which caused hillslope stream diversions, occurred almost exclusively at locations where tractors had crossed streams or bulldozed soil and logging slash into shallow channels. Streamflow was then diverted across adjacent logged hillslopes and produced gullies that generally followed the network of skid trails (fig. 7).

(4) Misplaced culverts were those installed some distance from the actual stream crossing. Streamflow was diverted along the inside ditch and usually discharged onto the hillslope within 100 m of the crossing. Gullies developed below the culvert outlet and extended downslope until the diverted flow rejoined the natural stream channel (fig. 8).

(5) Interception and concentration of road surface runoff resulted in minor enlargement of inside road ditches and the development of small gullies where culverts released this flow onto bare hillslopes. Sloughing at cutbanks also blocked ditches and diverted runoff across the road surface and onto downslope areas.

(6) Increased surface runoff resulted from soil exposure and compaction and from the interception of near-surface ground water and throughflow in deep skid-trail cuts. Concentration of increased hillslope runoff from roads, landings, and skid trails on bare areas created shallow and narrow, but lengthy, gully systems (fig. 9).

Ninety-four percent of the total volume of gully erosion in the South Copper Creek study site was caused by stream diversions. Given the overriding importance of stream diversions as a cause of gullying, determinant analyses for the remaining study sites were restricted to the three mechanisms by which streams were diverted: culvert plugging, lack of culverts, and channel obstructions at skid-trail stream crossings.

In the following sections, detailed information is presented on gully erosion on South Copper and the other eight study sites in the lower Redwood Creek basin. The South Copper data set consisted of approximately 3,200 cross-sectional measurements from which the total volume of soil eroded by gullies was computed. In the remaining eight study sites, over 2,600 gully cross sections were measured. In all, cross-sectional measurements were taken along a cumulative gully length of nearly 76 km on the nine study sites.

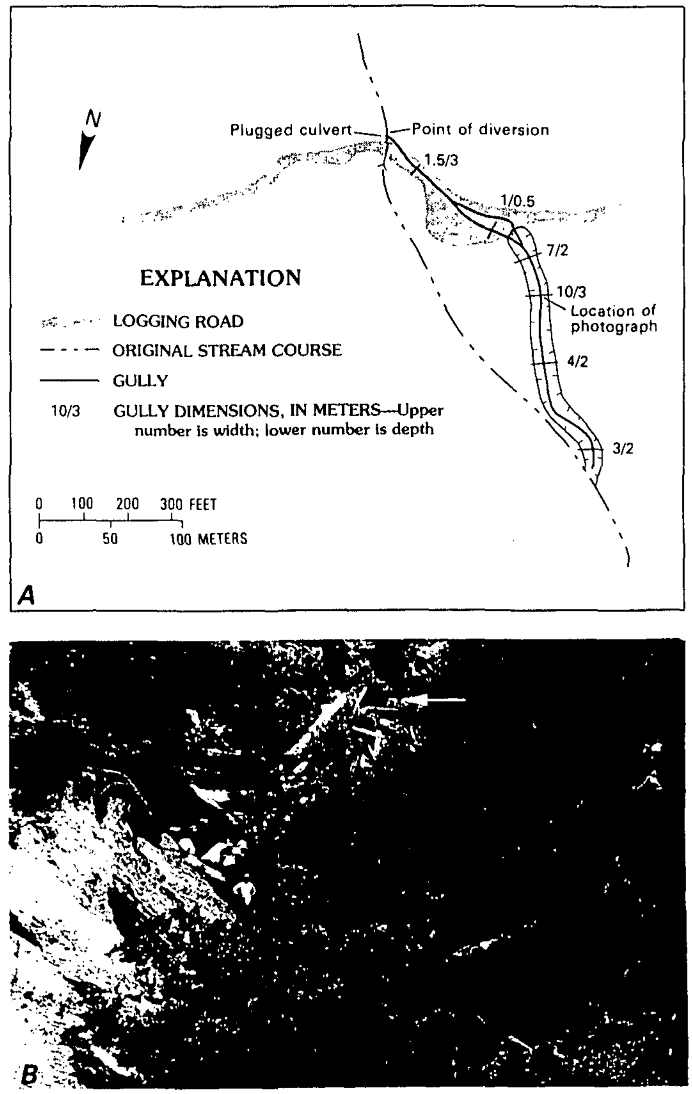
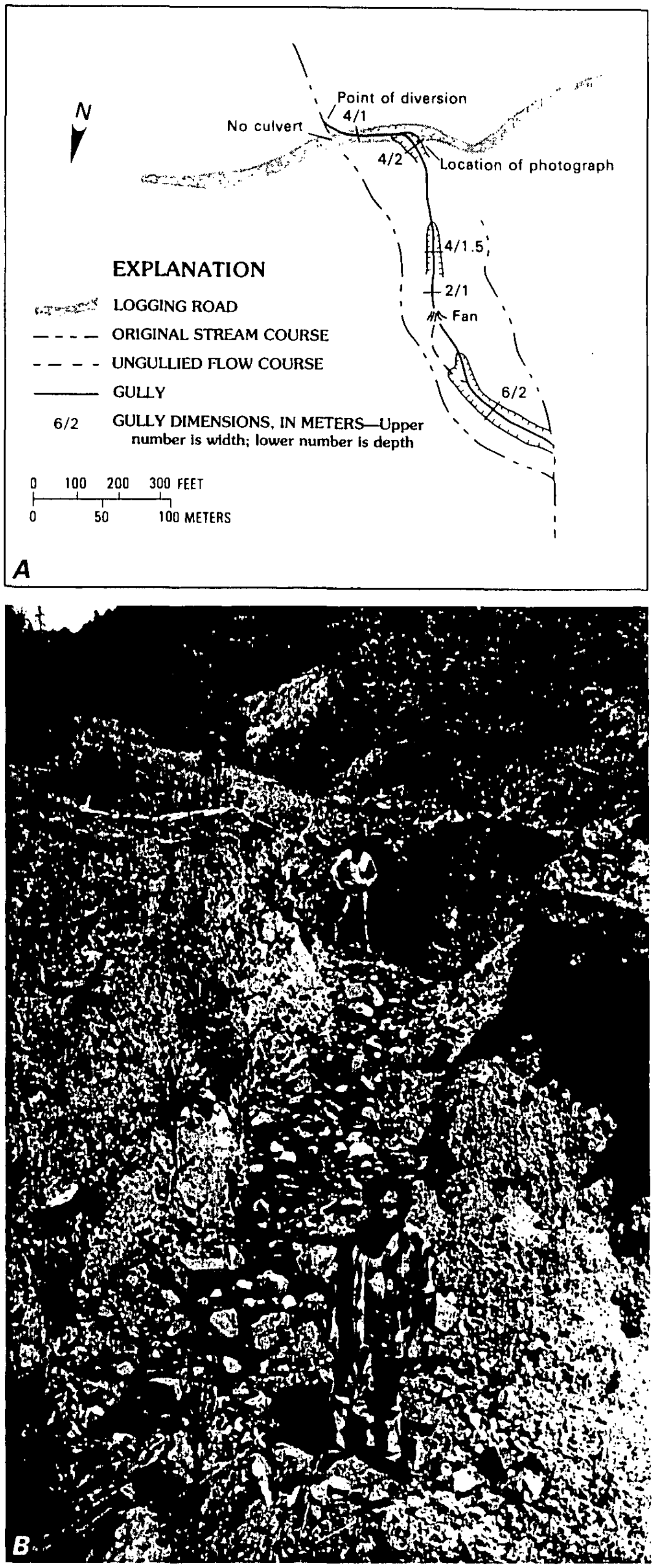


FIGURE 5.—Large gully created when a plugged gully diverted a perennial stream. *A*, Planimetric map of gully showing selected cross-sectional dimensions. Total measured volume of gully is 2,800 m^3. *B*, Photograph of same gully. Scale is indicated by person standing in gully. Arrow indicates logging road at prominent headcut.

RESULTS

INCREASED EROSION IN THE SOUTH COPPER CREEK STUDY SITE

Gully systems on the 246-ha tractor-yarded clearcut area south of the main channel of Copper Creek are widespread and complexly interconnected, and they represent the dominant source of eroded material



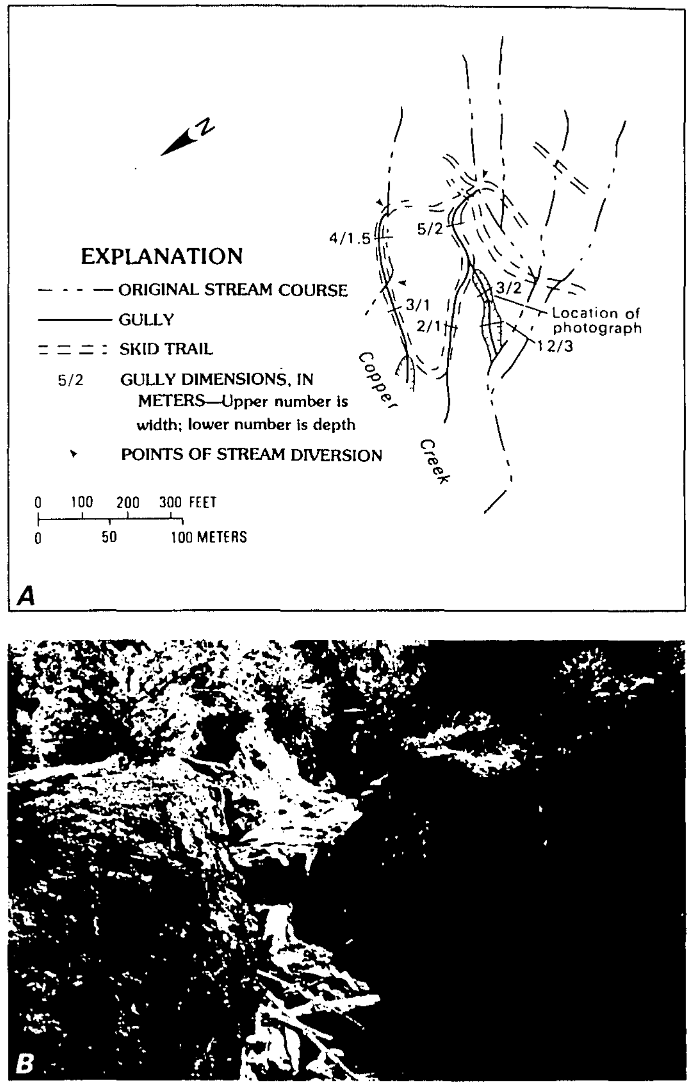
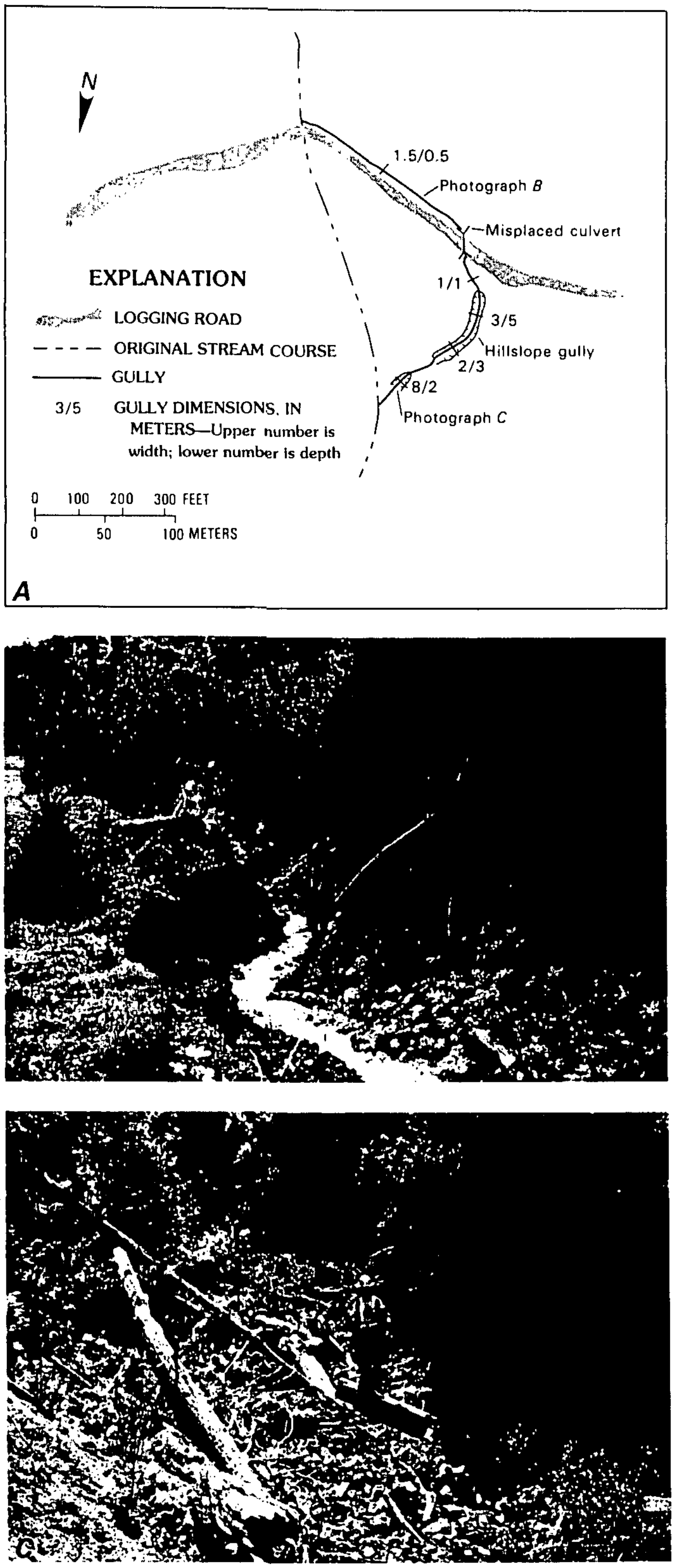


FIGURE 7.—Gullies created by channel obstruction where tractors crossed streams. *A*, Planimetric map of gully system showing selected cross-sectional dimensions. Most diverted streams followed skid trails. Total volume of gully erosion shown on the map is 4,700 m^3. *B*, Photograph of typical gully in the system.

◄ FIGURE 6.—Gully attributed to lack of culvert on logging road. *A*, Planimetric map of gully showing diversion of stream down the roadside ditch, across road, and then down several hundred meters of hillslope before entering another stream channel. Total volume of gully system on map is 2,000 m^3. *B*, Photograph taken where gully headcut has migrated across the road prism to a roadside ditch. Note coarse lag deposit that has accumulated in the bed of the gully.



◄ FIGURE 8.—Gully attributed to misplaced culvert on logging road. *A*, Planimetric map showing diversion of a perennial watercourse down the roadside ditch for a distance of 150 m to the misplaced culvert, downslope from which a larger gully was formed. Cross-sectional dimensions of the gully are shown at selected intervals, and the computed gully volume is 1,200 m^3. *B*, Photograph of a gullied roadside ditch on a logging road. *C*, Photograph of gully, which is much larger than gully in *B* above, on hillslope. Note the increase in the cross-sectional area of the gully as slope steepens.

contributing to increased sediment yield in the study site (Weaver and others, 1981) (fig. 10). Most gullies were caused by diversions of low-order stream channels on the clearcut hillslopes (table 4). These diversions resulted from (1) widespread tractor disturbance in and adjacent to the natural channel system, (2) lack of maintenance of the 9.3-km logging road system between the initial selective harvest and subsequent reharvesting in the early 1970's, and (3) the lack of maintenance of the dead-end logging road system after clearcutting activities were completed in 1972. Culvert blockages led to either road washouts or stream diversions and the creation of large hillslope gullies. Water was also diverted onto adjacent bare hillslopes where logging roads and skid trails crossed ephemeral and intermittent streams without culverts. These diversions resulted in the development of extensive gully networks.

Volumetrically, 70 percent of the 124,400 m^3 of eroded material measured from all sources in the South Copper Creek study site can be attributed to newly formed gullies (table 4). An additional 13 percent was derived from gullied, or enlarged, natural stream channels. Although not described in this paper, stream diversions from one channel to another resulted in substantial morphologic adjustments to watercourses that received increased discharges and sediment loads. The remaining 17 percent of eroded material was associated with mass-movement processes, such as landslides and slumps, on unstable logging roads, hillslopes, and cutbanks primarily on lower hillslope positions of the study site. Apparently as a combined result of increased stream discharges, steeper hillslopes and channels, and highly erodible soils, 90 percent of the soil eroded by newly formed gullies, and 96 percent of the sediment generated from the enlargement of natural stream channels, was derived from the lower half of the hillslopes (table 4).

MAGNITUDE AND CAUSES OF GULLY EROSION IN SOUTH COPPER CREEK

Within the South Copper Creek study site, 89 percent of the postharvest gully erosion was attributable to three principal causes (table 5):

(1) Culvert plugging and subsequent stream diversion along logging roads (38 percent);

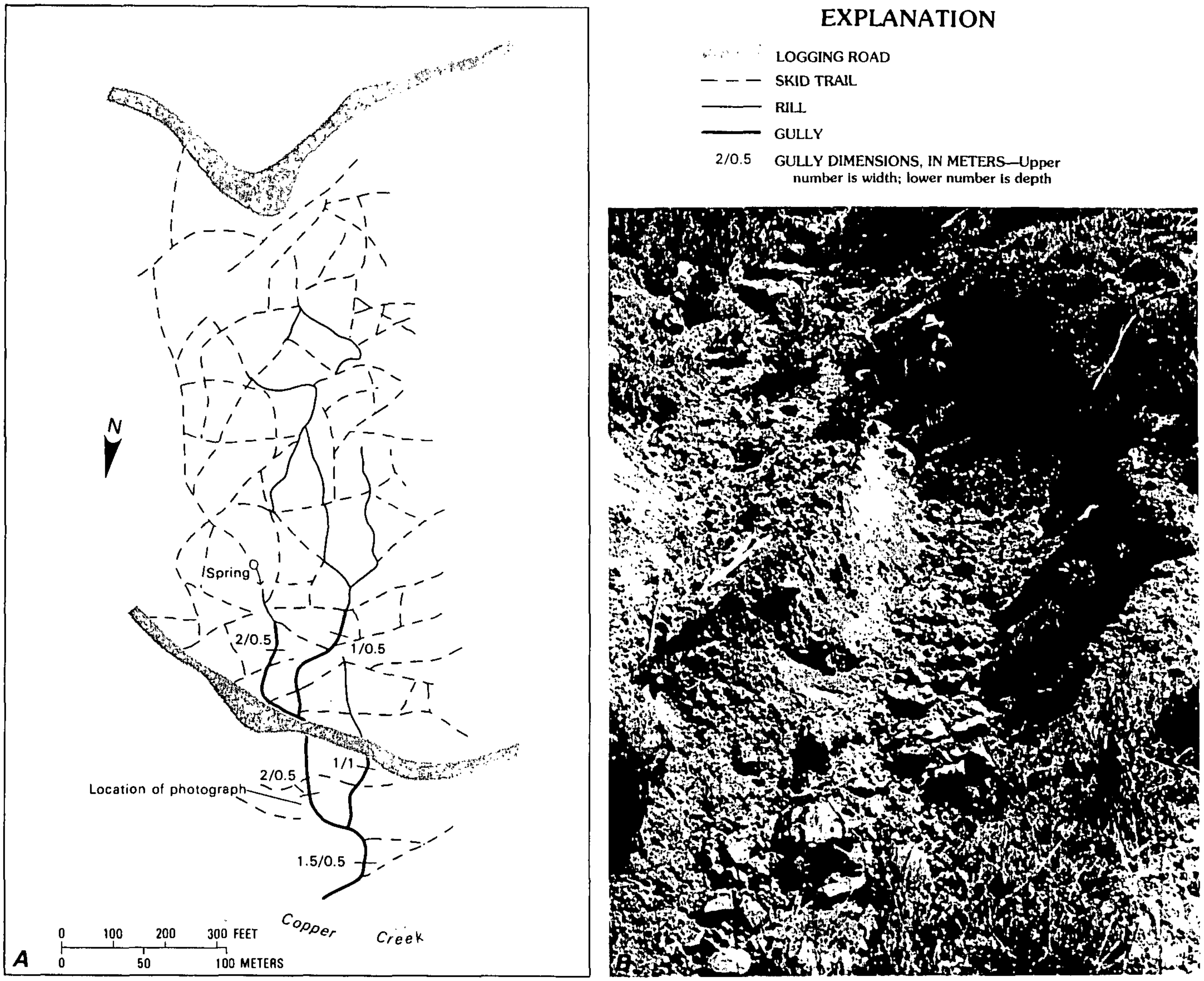


FIGURE 9.—Gullies created by increased surface runoff over the skid-trail network in a tractor-yarded area. *A*, Planimetric map showing gully system caused by concentrated runoff flowing on skid trails. Note the comparatively small gully dimensions shown on the map. Total gully erosion from the network was 350 m^3. *B*, Photograph of typical gully caused by increased surface runoff.

TABLE 4.—*Sources and amounts of sediment produced from the South Copper Creek study site*

[Figures may not add to 100 percent due to rounding]

Sediment source	Percent of total volume of material eroded from: Upper slopes	Upper middle slopes	Lower middle slopes	Lower slopes	Total sediment production[1]: Percent contributed to total volume	Volume (m^3)
Fluvial processes:						
New gully systems developed since logging[2]	1	10	54	36	70	87,100
Gullied or enlarged natural stream channels	0	4	41	55	13	16,200
Mass-movement processes:						
Landslides associated with logging roads	0	0	0	100	8	9,900
Slumps on logging roads	2	3	64	32	4	5,000
Combined failure and gullying of logging road fill	0	9	13	78	3	3,700
Failure of logging road fill	19	12	25	44	2	2,500
Total	1	8	46	45	100	124,400

[1] Does not include 12,030 m^3 of streamside landsliding along the main channel of Copper Creek; also excludes sheet and rill erosion, and isolated bank failures along tributary streams.

[2] Includes all gullies or segments of gullies having cross sections larger than 0.1 m^2.

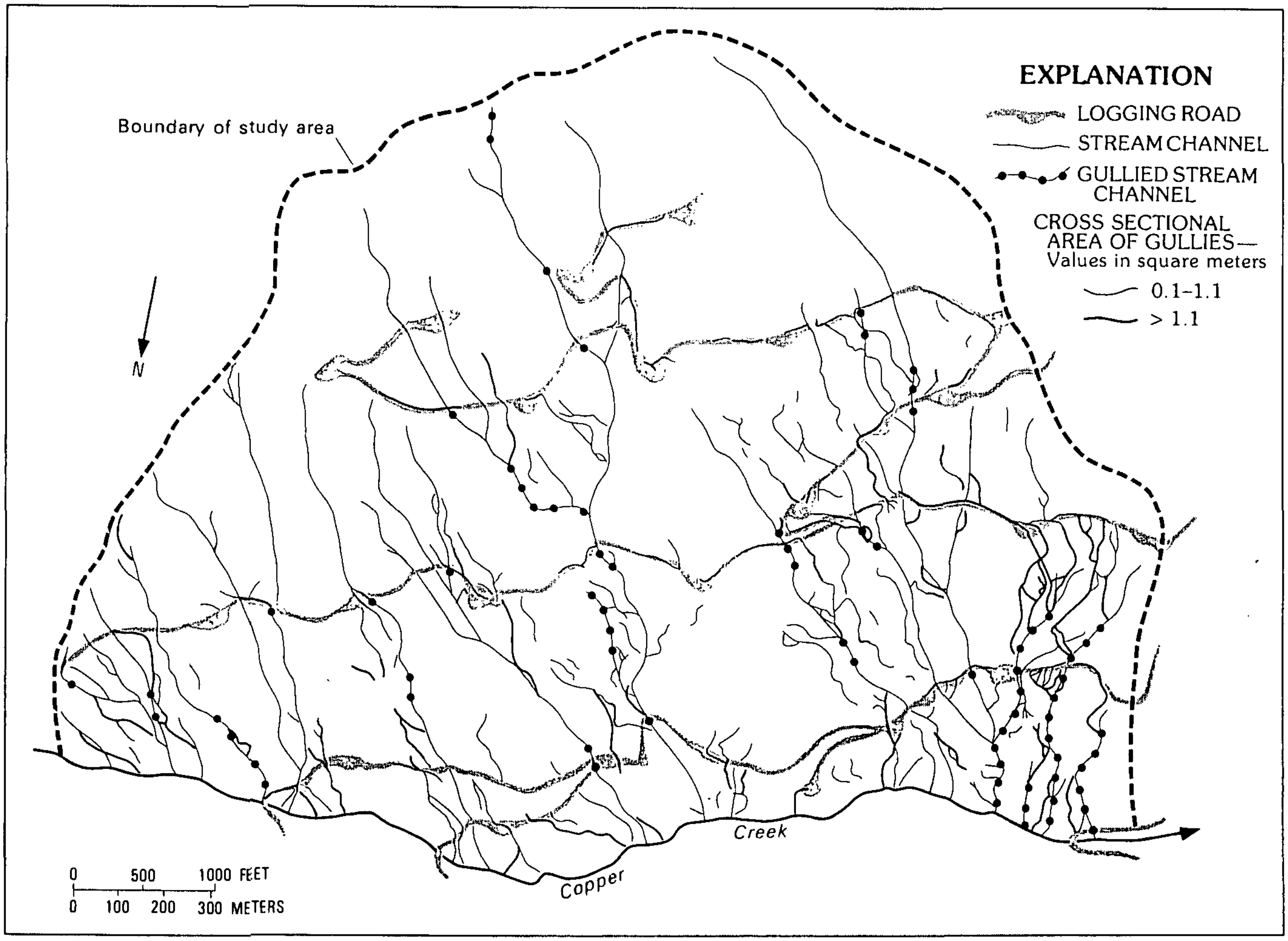


FIGURE 10.—Gully systems on the 246-hectare South Copper Creek study site. Rills less than 0.1 m^2 in cross-sectional area are not shown. Gullies were mapped and measured in 1979.

TABLE 5.—*Mean cross-sectional area, total length, and total volume of gullies attributed to primary causes, South Copper Creek study site*

Primary cause of gullying	Mean cross-sectional area (m^2)	Total gully length (km)	Percent contributed to total volume of eroded material	Volume of eroded material (m^3)
Plugged culverts on logging roads..	9	3.4	38	33,400
Hillslope stream diversions at skid-trail crossings.	4	7.6	36	31,300
Lack of culverts on logging roads...	4	3.3	15	13,200
Misplaced culverts on logging road .	5	.8	5	4,000
Increased surface runoff...........	1	3.9	4	3,700
Interception and concentration of road surface runoff.	1	1.3	2	1,500
Total......................	4	20.3	100	87,100

(2) Diversion of streams at tractor-constructed skid-trail stream crossings on logged hillslopes (36 percent); and

(3) Lack of culverts on logging roads at stream crossings and consequent diversion of streams into roadside ditches and eventually across overland areas or into nearby stream channels (15 percent).

Three other identified causes accounted for the remaining 11 percent of the total measured gully volume. At least 94 percent of the total volume of gully erosion on the South Copper Creek study site was caused by stream diversions (table 5).

During road construction, culverts were generally placed only at crossings of the largest streams. In South Copper Creek, the plugging of many of these culverts after the road was abandoned in 1972 caused the diversion of several second-order streams and the development of large hillslope gullies (fig. 11). Although gullies that developed in response to plugged culverts accounted for the greatest volume of sediment production from a single cause (38 percent), they constituted a comparatively short total length of new channel (17 percent of the total measured length; table 5). Thus, the largest stream discharges developed gully systems with the greatest cross-sectional areas. These gullies were more than twice as large, in cross-sectional area, as those attributed to the next leading cause, hillslope stream diversion at skid-trail crossings (table 5). However, the streamflow diverted at plugged culverts quickly rejoined natural, preexisting channels.

In contrast to road crossings, skid-trail crossings on hillslopes were commonly constructed on small, intermittent or ephemeral streams. Fill was generally bulldozed into the channel without the installation of a culvert. The consequent diversions of these streams created extensive gully systems on the dense network of logging skid trails between the major drainage channels. Although gully cross sections were moderate in size (average cross-sectional area of 4 m^2), the gullies derived from stream diversions at skid-trail crossings accounted for over one-third (37 percent) of the total cumulative length and 36 percent of the total volume of eroded material (table 5).

It is noteworthy that gullies that developed on bare-soil areas and whose source of discharge could be attributed only to increased surface runoff from direct rainfall or intercepted subsurface flow accounted for 19 percent of the total length of measured gullies but for only 4 percent of the total volume. Such gullies, although abundant on the study site, eroded comparatively little soil.

VARIABILITY OF GULLY YIELDS AMONG THE NINE STUDY SITES

Besides the gully erosion on the South Copper Creek study site, 242,400 m^3 of material was eroded by gullies within the other eight study sites, which have a total area of 1,968 ha (table 6).

At the time of the inventory, a wide variation in gully yields was discerned between different study sites. Gully yields in table 6 can be divided into three groups (1) Lower Slide, North Copper, Maneze, and South Copper Creek sites have high yields, exceeding 170 m^3/ha, (2) both of the Bridge Creek sites plus the Dolason and Upper Slide Creek sites have more moderate gully yields, ranging from 52 to 77 m^3/ha, and (3) the Bond Creek study site, which yielded only 3 m^3/ha.

Much of the variability among sites is apparently due to differences in physical site variables and, to a lesser degree, to the timing of logging relative to major storm events. Inasmuch as all the study sites were clearcut and tractor-yarded by the same techniques and to nearly the same degree of ground disturbance, differences in land use practices cannot readily explain the wide range of gully yields. Likewise, each area had nearly the same rainfall rates and volumes during storms in 1964, 1972, and 1975.

TABLE 6.—*Data on gullies at nine study sites in the lower Redwood Creek catchment*

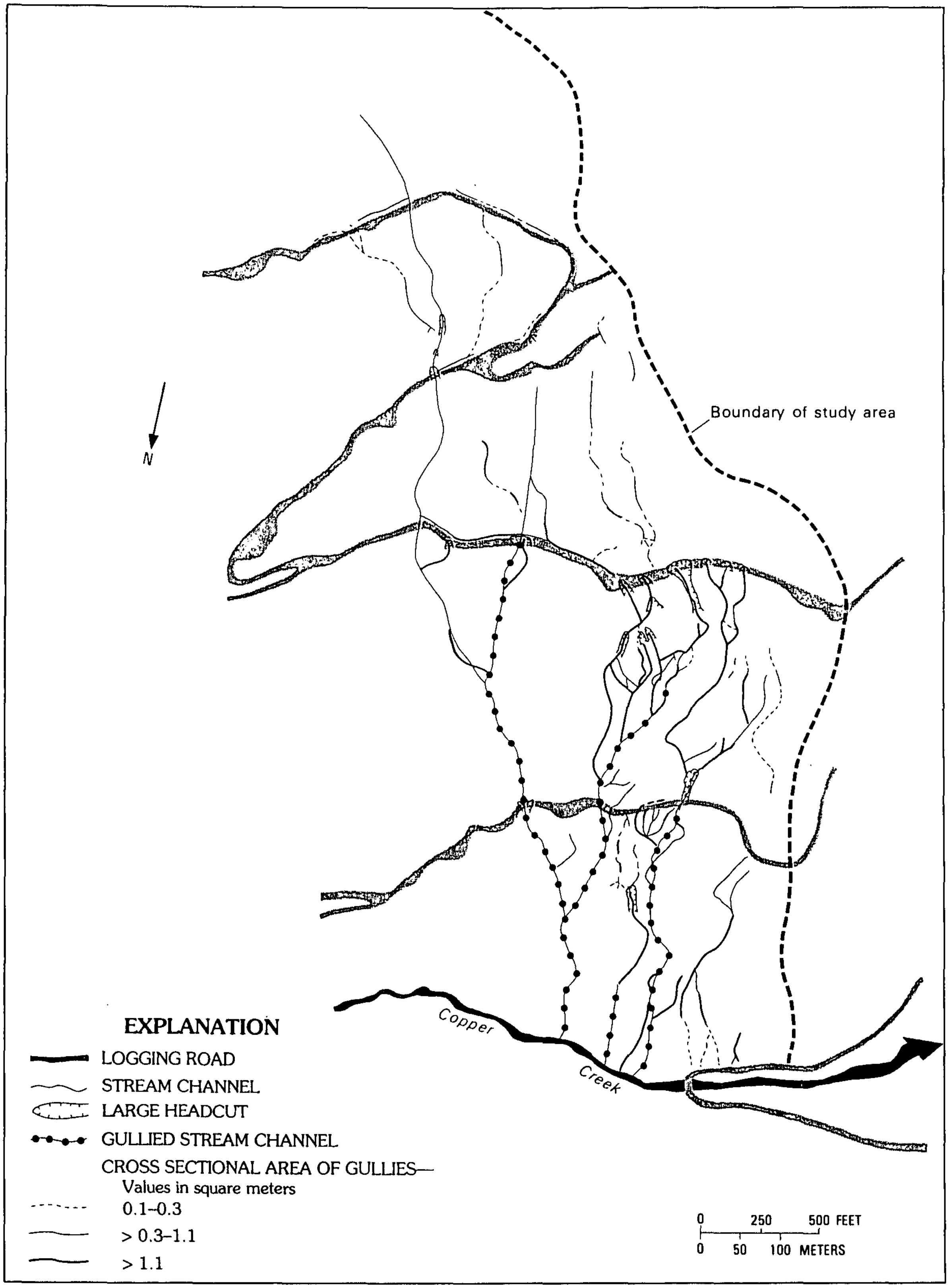
Site name and number (from fig. 1)	Area (ha)	Gully length (km)	Number of cross sections measured	Total gully volume (m^3)	Gully yield (m^3/ha)	Gully density (m/ha)	[1]Mean gully cross-sectional area (m^2)
High yield sites							
South Copper (79–2)	246	20.3	3,168	87,100	354	83	4.3
North Copper (81–1)	410	12.7	377	108,500	265	31	8.5
Maneze (80–2)	172	8.5	380	36,000	209	49	4.2
Lower Slide (81–3)	198	5.0	149	34,400	174	25	6.9
Moderate yield sites							
Bridge (80–6)	304	14.8	826	23,300	77	49	1.6
Upper Slide (81–3)	239	6.4	474	17,300	72	27	2.7
Dolason (80–5)	144	2.6	132	7,900	55	18	3.0
Bridge (80–3)	275	4.7	238	14,300	52	17	3.0
Low yield site							
Bond (82–4)	226	0.8	37	700	3	4	0.9
Total	2,214	75.8	5,781	329,500	149	34	4.3

[1] Mean gully cross-sectional area=total gully volume divided by total gully length.

Study sites within the high yield group are all underlain by sheared mudstones and sandstones of the Incoherent unit of Coyote Creek (table 3). The dominant soil mantling the high yield sites is the Coppercreek series. This soil is deep and, compared to soils on the sites displaying lower gully yields, is characterized by relatively low clay content and very low gravel-sized rock-fragment content in the A and B horizons. The subsoil lacks both sufficient clay to develop cohesive, resistant structural aggregates and sufficient rock fragments to produce a stabilizing armor once soil erosion has begun.

Less intense gullying on the four sites in the middle-yield category (table 6) is explained by several different factors. Cutover land in the Dolason study site is underlain by the same erodible Coppercreek soil that dominates the four high yield sites. However, two factors have acted to moderate gully erosion. First, slightly over half of the forested land at Dolason was cut, and 40 percent of the logging roads were built in 1977, more than 2 years after the last major storm in the Redwood Creek basin. Basinwide peak runoff since 1977 has not exceeded the 2-year return period event. Second, 56 percent of the Dolason study site consisted of prairie grassland traversed by a single logging road. Disruption of the drainage network was much less severe than on either Upper Slide or North Copper Creek grassland areas.

Bedrock and soil characteristics on the Upper Slide Creek site (tables 2, 3) probably account for its moderate gully yields. The steep slopes on massive sandstones of the Coherent unit of Lacks Creek have developed comparatively shallow soils. Although the shallow soil is low in clay content, its high content of rock fragments reduces the probability that large gullies will form.


Boundary of study area
N
Copper Creek
EXPLANATION
LOGGING ROAD
STREAM CHANNEL
LARGE HEADCUT
GULLIED STREAM CHANNEL
CROSS SECTIONAL AREA OF GULLIES—
Values in square meters
0.1–0.3
> 0.3–1.1
> 1.1
0 250 500 FEET
0 50 100 METERS

Developing gullies quickly reach bedrock or are armored by a lag of coarse rock fragments.

The gully yield from the Bridge Creek study sites was also within the moderate range (table 6). Both sites are remarkably similar in area, underlying bedrock, average slopes, and timber harvest history (table 3). The predominate soils on both sites are a complex of the deep, highly erodible Devilscreek and Coppercreek series, with Lack soils on the broad, rocky ridges. Although all the large gullies were located on the more erodible soils, the yield from each site was moderated by one or more factors. First, drainage areas are small, so many of the stream diversions resulted in relatively small gullies. Second, minimal erosion on the Lack soil areas effectively diluted average yields from each site. Third, unlike the highyield sites, most logging roads on these two sites were kept open, active, and maintained, and so stream diversions were quickly repaired or stabilized. Finally, approximately one-half the area of each site was clearcut after 1972 and therefore experienced only one significant gully-producing storm (1975).

The moderate, comparable gully yield from both Bridge Creek sites also arises from two contrasting characteristics of their logging road systems. The 80–6 Bridge Creek unit contained over 11 km of logging roads, which contoured the hillside at five separate elevations. As a result of the lack of maintenance on several roads after final clearcutting, many diversions of small streams contributed to the high density (49 m/ha) of small gullies on the site (table 6).

By contrast, only 4.8 km of road were constructed on the 80–3 Bridge Creek site, including a 1.6-km section that climbed obliquely up and across the unit. The probability of stream diversions along roads that cross contours is far greater than on roads that follow hillslope contours or dip into the stream crossing at both approaches (chap. M, this volume). Multiple diversions of second-order streams along the continuously ascending logging road on the 80–3 Bridge Creek unit produced fewer gullies than on the 80–6 Bridge Creek site (table 6), but the average cross-sectional area (gully volume/gully length) was almost twice as large. For example, 77 percent of the measured gully cross-sectional areas on site 80–3 exceeded 4.5 m^2, whereas only 49 percent of those on the 80–5 site were in this category of large gullies. Because gully frequency compensated for gully size, the yield from both Bridge Creek study sites was comparable.

Finally, two factors explain the anomalously low gully yield on the Bond Creek site. First, approximately one-half of the unit had not been disturbed by timber harvest until 1976. By the time of the erosion inventory in 1981 to 1982, the clearcut area had not experienced a major runoff event. Second, the low gullying rate can also be explained by the site's stable soil characteristics. Most of the Bond Creek study site is underlain by Trailhead and Fortyfour soils (table 3). Both series are marked by relatively high concentrations of clay and iron in their B horizons. This content appears to significantly retard surface erosion by reducing the rate at which flowing water is able to cut down below the more erodible A horizon material. High clay and iron content, and a blocky soil structure, greatly increase aggregate stability (Singer and others, 1978) and therefore decrease the potential for formation of rills and gullies.

In summary, stream diversions—the main cause of gullying—were observed at all sites. The frequency of diversions was positively related to the density of logging roads and to the number of major storms (of 10- to 20-year recurrence interval) at each site since road construction and harvesting. For example, the parts of the Dolason and Bond Creek study sites that were logged since 1975 had relatively few diversions, and the small streams that were diverted had caused very little erosion in the following 5- to 7-year period after logging.

Road systems that had been abandoned and not maintained through one or more major storms were associated with substantially more gully erosion than regularly used logging roads. For example, the entire road system in the South Copper Creek study site had been completely abandoned, for the second time, by 1972. Consequently, gully densities and gully yields from that site were unmatched in the lower Redwood Creek basin.

Regardless of the association between road density and frequency of stream diversions, these factors are not consistently correlated with gully yield. The volumes of gullies caused by diversions of similar-size streams are clearly related to properties of the underlying soil. For example, the high content of clay and iron and the blocky structure of the Trailhead soil in Bond Creek made it very resistant to erosion. Likewise, although the A horizon of the Lack soils of Upper Slide Creek is more easily eroded, the abundance of coarse rock fragments in the shallow B horizon armored newly formed gullies and prevented the formation of large channels. Finally, the deep Devilscreek and Coppercreek soils lacked both sufficient clay and rock fragment content to prevent or minimize erosion when subjected to concentrated surface

◀ FIGURE 11.—Measured gully network on a portion of the western side of the South Copper Creek study site. (The same area is shown in the 1972 aerial photograph of fig. 4.) This was the most intensely gullied of the nine study sites. The abundance of large gullies and enlarged stream channels on the middle and lower slopes was a result of stream diversions at crossings of streams by roads and skid trails. Total measured gully erosion for the mapped area was 40,600 m^3. Gullies larger than 1.1 m^2 in cross-sectional area accounted for 97 percent of this volume.

TABLE 7.—*Comparison of gully erosion caused by stream diversions on four study sites*

Study site and number (from fig. 1)	Area (ha)	Gully volume (m^3)	Gully erosion attributed to stream diversions		Percent of total volume of eroded material according to cause of stream diversion		
			(m^3)	(percent of total)	Plugged culvert[1]	Hillslope diversion[2]	Lack of culvert[3]
South Copper (79–2)	246	87,100	81,900	[4]94	41	38	21
Upper Slide (81–3)	239	17,300	11,300	65	4	10	86
Bridge (80–3)	275	14,300	12,200	85	77	11	12
Bond (82–4)	226	700	600	86	83	1	16
Total	986	119,400	106,900	89	41	32	27

[1] Streamflow diverted by plugged culvert on logging road.
[2] Flow diverted out of channel at tractor-constructed skid-trail crossing.
[3] Culvert not installed at logging-road stream crossing; flow diverted out of channel. Includes misplaced culvert category of table 5.
[4] Causes 1–4, table 5.

runoff or diverted streamflows. Sites mantled by these soils were especially prone to gullying.

VARIABILITY OF GULLY YIELDS AND GULLY DIMENSIONS WITHIN STUDY SITES

In the four sites that were studied in sufficient detail to permit comparisons between the cause of erosion and eventual gully yield, 89 percent of the gully erosion was attributed to stream diversions (table 7). Three major causes of stream diversions were identified: plugged culverts (41 percent), unculverted skid-trail crossings (32 percent), and unculverted logging-road crossings (27 percent) (table 7).

The size of the drainage area of a diverted stream strongly influenced gully dimensions and yield. For example, stream diversions were about equally common on the upper and lower slopes of the South Copper Creek study site. However, 93 percent of the gully erosion from diversions occurred in the lower half of the hillslope where stream discharges were comparatively greater (that is, larger drainage area). The relatively high frequency of large gullies in the lower hillslope areas of South Copper Creek is apparent in figure 10.

Both the volume of eroded material (table 7) and the total length of gullies attributed to stream diversions varied widely from one site to another. In the Upper Slide Creek study site, 86 percent of the total measured gully volume and 45 percent of the total gully length was attributed to a lack of culverts at some road crossings. By contrast, 77 percent of the measured gully volume and 84 percent of the total gully length on the 80–3 Bridge Creek study site was attributed to plugged culverts and the consequent diversion of streams along inside road ditches, from which the gullies eventually cut across the road prism and down unprotected, bare hillslopes. Gully erosion at the Bond Creek site was more than an order of magnitude lower when compared to the other study sites, yet the proportion of total erosion attributable to the three mechanisms of stream diversion remained high. In South Copper Creek, streams

TABLE 8.—*Total gully length and volume as distributed among four cross-sectional size categories on nine study sites in the lower Redwood Creek basin*

[Figures may not add to 100 percent due to rounding]

Study site and number (from fig. 1)	Percent of total volume of eroded material according to gully cross-sectional size categories			
	<0.1 m^2	0.1 to 1.1 m^2	>1.1 to <4.5 m^2	≥4.5 m^2
South Copper (79–2)	1	4	14	81
North Copper (81–1)	1	2	8	89
Maneze (80–2)	1	7	12	80
Lower Slide (81–2)	1	4	6	89
Bridge (80–6)	5	14	32	49
Upper Slide (81–3)	3	9	19	69
Dolason (80–5)	3	6	23	68
Bridge (80–3)	2	9	12	77
Bond (82–4)	18	12	2	68
Total gully volume (m^3)	4,280	16,510	41,828	266,992
Percent of total	1	5	13	81
Total gully length (km)	18.2	26.4	17.4	13.7
Percent of total	24	35	23	18

diverted at tractor-constructed skid-trail crossings accounted for 36 percent of the measured gully volume, whereas such diversions had accounted for no more than 11 percent of the measured gully volume on each of the other sites.

At all nine study sites, gullies formed on cutover lands had a wide range of lengths and cross-sectional areas (table 8). Small gullies, although widespread on all sites, produced comparatively little sediment. Gullies that averaged less than 1.1 m^2 in cross-sectional area accounted for nearly 60 percent of total gully length but only 6 percent of the measured volume of material eroded (table 8). The largest gullies, those 4.5 m^2 or larger in cross-sectional size, were the major contributors to fluvial sediment production. Approximately 50 percent or more of the gully yield on every site was produced by the formation of these large gullies (table 8).

Analysis of data from the detailed South Copper Creek inventory suggests that streams diverted by the plugging of logging-road culverts produce the largest gullies in downslope areas. Plugged culverts commonly result from the installation of undersized structures or from lack of maintenance following road construction.

Although diversions by plugged culverts account for only 17 percent of the total length of gullies formed in South Copper Creek, gullies formed by this process had an average cross-sectional area of 9 m^2 and produced roughly 38 percent of the total volume of material eroded by gullies (table 5). By comparison, gullies that were formed by stream diversions at skid-trail crossing on hillslopes averaged 4 m^2 in cross-sectional area. Although such hillslope stream diversions produced gullies that were less than half the average cross-sectional area of those caused by plugged culverts, their total length (7.6 km) was twice as great. Thus, the total volume of eroded material produced by these two mechanisms of stream diversion was about equal.

In the third category of causes shown in table 5, small unculverted streams crossed by a logging road were commonly diverted down an inside ditch and discharged through a ditch relief culvert, or at the next culverted stream crossing, before reentering a natural stream channel. Gullies formed by these intentional diversions were similar in average cross-sectional area to those produced by skid-trail stream diversions but had a much shorter total length. Gullies attributed to the last three causes in table 5 were either very short or very small, or both, and accounted for only a small percentage of the total sediment production.

DISCUSSION AND CONCLUSIONS

MAGNITUDE AND CAUSES OF GULLY EROSION

Stream diversions produced most of the largest gullies and the bulk of fluvial erosion from the roaded and tractor-logged hillslopes. Extensive gullying commonly occurred when culvert inlets became plugged with sediment and debris, diverting streamflow from the natural channel. Undersized culverts, the absence of debris trash racks (wooden structures that keep organic debris from plugging culvert inlets), and lack of maintenance on abandoned roads were typically responsible for such diversions. Streams that were culverted at road crossings were larger, well-incised, intermittent or perennial watercourses that carried flow during the summer logging season. Thus, diversions caused by plugged culverts frequently involved comparatively large streams and produced large gullies (table 5). However, the lengths of these gullies were limited because the natural channels were well incised into the hillslope, and diverted flow often returned quickly across the steep sideslopes to the original or an adjacent watercourse.

Skid-trail crossings of stream channels were generally constructed on watercourses that were either poorly incised or nearly dry during the summer period, when most harvest operations occurred. Diversion of these ephemeral and small intermittent streams during the subsequent winter created moderate-sized gullies that commonly traversed long segments of hillslope, following skid-trail paths without encountering either natural stream channels or logging-road obstructions that might route the water into a nearby stream. Hillslope stream diversions caused by skid-trail crossings can produce extensive gullying as occurred at the South Copper Creek study site (table 7).

In addition to the influence of land use variables, physical soil characteristics have a strong influence on gully yields. Gullies developed on cohesive, clay-rich soils in Bond Creek (tables 2, 3) averaged less than 1.0 m^2 in cross-sectional area (table 6). Those formed on the shallow rocky soils of Upper Slide Creek averaged an intermediate 2.7 m^2 in area. Finally, the sites of high gully yield were exclusively located on soils that contained comparatively low concentrations of clay and rock fragments. Mean gully dimensions on these areas ranged from 4.2 m^2 on the Maneze Creek site to 8.5 m^2 on the North Copper Creek site (table 6).

The magnitude of gully erosion in the study sites did not vary consistently with average hillslope gradient, with the abundance of steep hillslopes, with slope length, or with hillslope position (tables 3, 6). However, while these variables were less important than land use factors and soil characteristics, they apparently still had some influence on gully yields. For example, slopes less than 20 percent in gradient were rarely gullied. All study sites having over 40 percent of their area in gentle upland slopes ($\leq$30 percent gradient) showed low to moderate gully yields.

Similarly, all the high yield sites included both lower and middle hillslope positions, and at least 66 percent of each site was moderate to steep, having a slope gradient greater than 30 percent (tables 3, 6). However, the inverse situations were not as consistently correlated with gully yields. That is, not all sites in the low or moderate yield category (3 to 77 m^3/ha, table 6) were dominated by gentle slopes, and several of the steepest sites did not show high rates of gully erosion (tables 3, 6). In the latter situations, differences in soil characteristics and the timing of land use in relation to storm events were of overriding importance.

SEDIMENT SOURCES AND TRANSPORT IN THE LOWER REDWOOD CREEK BASIN

Although not a principal objective of this investigation, gully yields for the lower Redwood Creek drainage basin (fig. 1) were estimated from data obtained in the nine study sites. Logged areas in the lower basin were first divided into units of similar land use practice (table 9). On study sites, virtually all gully erosion emanated from tractor-yarded hillslopes and prairie areas traversed by logging roads. Areas subjected to this type of logging or road building occupy 55 percent of the lower basin and constitute the source region used for calculating postharvest gully erosion. Overall road density in the nine study sites is virtually equivalent to that for the 10,770 ha of tractor-logged forest lands and roaded prairie areas of the lower Redwood Creek basin (table 9).

Early logging methods (which utilized steam donkeys and cable-yarding, together with ridgetop railroad systems for log hauling) caused much less ground disturbance and drainage-pattern disruption than recent tractor-yarding techniques (Janda and others, 1975). Gully formation in areas logged by early methods was assumed to be negligible. Although more modern cable-yarding practices require extensive road networks, such logging became common in the lower basin only after the last major flood in 1975. Field observations and data from the study sites suggest that gullying on these recently cable-yarded hillslopes has also been negligible.

However, on roaded grasslands and tractor-yarded hillslopes logged prior to 1975, soil properties and related site conditions (an undifferentiated combination of factors including bedrock lithology, structure, hillslope gradient, slope morphology, and drainage density) were found to be closely related to expected gully yields. For this reason, the lower basin source area was divided into three major terrain categories, based principally on major soil types and their corresponding geologic and geomorphic associations (table 10). Expected gully yields were then assigned to each category according to measurements from the nine study sites (table 6).

Gully yields from cutover study sites varied greatly (table 6), even though these areas experienced similar land use practices and histories. High yield terrain, where gully erosion was estimated to average 260 m^3/ha, occupies only 31 percent of the selected land base in the lower basin but yielded approximately 70 percent of eroded volume (table 10). In contrast, 16 percent of the land base, which made up the low yield category, was estimated to account for less than 1 percent of the total gully erosion in the lower basin. Clearly, a small percentage of the disturbed land in a watershed can contribute a large proportion of the total sediment production by gullies.

In addition, basins that contain large areas of highyield terrain (lands that are especially subject to fluvial gully erosion) may undergo far more erosion from gullying than from landsliding. For example, Kelsey (1980) has estimated that, for the period 1941 to 1975, over 90 percent of the hillslope fluvial erosion in the upper 575 km^2 of the Van Duzen River drainage basin (located 70 km south of the lower Redwood Creek basin) was derived from 38 percent of the watershed area. Because

TABLE 9.—*Land use status and land base data used to compute gully yields from areas in the lower Redwood Creek basin*

[Land use status is from chapter C, this volume]

	Nine sites of this study	Lower Redwood Creek basin
Land data (ha)		
Total area	2,214	19,650
Grassland	489	800
Uncut	0	5,900
Logged area	1,725	12,950
Percent of cutover land area		
Logging method:		
Steam donkey; no roads; pre-1948	0	4
Unknown methods; probably pre-1948	0	9
Cable-yarding; road construction; post-1948	5	10
Tractor-yarding; road construction; post-1948	95	77
Land base data		
Total land base used to compute gully yields (ha) (tractor-yarded area plus roaded grasslands)	2,214	10,770
Logging road density in land base (km/ha)	.027	.026

TABLE 10.—*Estimated gully erosion in the lower Redwood Creek basin (1948–80), according to major terrain categories*

Terrain category	Principal soils	Expected gully yield[1] (m^3/ha)	Distribution of major terrain types in the lower Redwood Creek basin[2] (Percent of basin area)	Distribution of major terrain types in the lower Redwood Creek basin[2] (ha)	Volume of material eroded by gullies in lower basin (m^3)
High yield	Coppercreek, Atwell.	260	31	3,340	868,400
Moderate yield	Devilscreek, Lack, Slidecreek.	65	32	3,450	224,250
Low yield	Trailhead, Fortyfour.	5	16	1,720	8,600
Undifferentiated	Unsampled	5–65	21	2,260	[3]56,500
Total			100	10,770	1,157,750

[1] Averaged values (rounded to the nearest 5 m^3/ha) based on gully yields from study sites where gully yield equals total gully volume divided by total site area within each terrain category (from table 6).

[2] Restricted to tractor-yarded areas logged since 1948 and roaded prairies (from table 9).

[3] We estimate that two-thirds of the undifferentiated soils will be classified in the low yield category and that the remainder will fall in the moderate yield range.

of widespread disruption of the natural grass cover by earthflow movement and road construction, gully yields accounted for about 75 percent of the total sediment production. Similarly, a preliminary sediment budget for the upper 175 km^2 of the Redwood Creek basin (Kelsey and others, 1981) indicates that fluvial erosion from hillslope areas may have accounted for nearly 70 percent of the sediment input to that reach of the Redwood Creek channel from 1956 to 1980.

In contrast to these high yield areas, gully erosion in the 197-km^2 lower Redwood Creek basin is estimated to have contributed about 25 percent less sediment than streamside landslides over approximately the same time period (1948–80) (table 11). This yield contrasts with the relative importance of fluvial sediment production measured in the Garrett Creek basin, a 10.8-km^2 tributary to Redwood Creek 11 km upstream of the Copper Creek

TABLE 11.—*Sediment sources, storage, and transport in the lower Redwood Creek basin (1954–80)*

Sediment source	Sediment quantity[1] (10^6 m^3)	Sediment quantity[1] (10^6 Mg)	Sediment yield (Mg/km^2)
Gully erosion[2] (1948–80)	1.16	1.74	
Other fluvial erosion[3] (1948–80)	.35	.53	23,500
Landslides along Redwood Creek and major tributaries[4] (1959–80)	1.57	2.36	
Sediment stored in major tributary channels[5] (as of 1981)	.35	.67	
Sediment stored in lower Redwood Creek channel[6] (1947–80)	3.10	5.95	
Sediment discharge of Redwood Creek at Orick, Calif.[7] (1954–80)	21.31	40.92	66,400
Sediment discharge of Redwood Creek at old south park boundary[7] (1954–80)	16.72	32.10	67,000

[1] Soil density of 1.50 g/cm^3 used for landslide and gully erosion; 1.92 g/cm^3 used for channel-stored sediments and transported sediment.
[2] Gully volumes from table 10 (this study).
[3] Hagans and Weaver, 1987; includes sheet erosion, rill erosion, and washed out (eroded) stream crossings.
[4] Kelsey and others (chap. J, this volume).
[5] Pitlick (chap. K, this volume).
[6] Madej (chap. O, this volume)
[7] J.R. Crippen, U.S. Geological Survey, written commun.; gaging stations at Orick and old south park boundary are shown on figure 1; data exclude yield from Prairie Creek.

study site. In Garrett Creek, fluvial sources delivered 62 percent of the total measured volume of eroded material (chap. M, this volume). Much of the Garrett Creek basin is underlain by the same incoherent geologic bedrock as high yield terrain in the lower Redwood Creek basin. For this reason, actual fluvial erosion during the measurement periods was 61 percent greater in Garrett Creek (18,500 Mg/km^2) than in the much larger lower Redwood Creek basin (11,500 Mg/km^2).

Over the last three decades, sediment yield from the upper Redwood Creek basin has been much higher than from downstream areas (table 11). Measured sediment production in the lower basin, including both landsliding and fluvial erosion, was only 11 percent of the measured sediment discharge at Orick. Significantly, 43 percent more sediment was stored in lower basin stream channels during this period than was produced by local erosion. U.S. Geological Survey gaging records show unit sediment yields for upstream areas (old south park boundary, table 11) to be approximately equal to that for the basin as a whole. Thus, measured hillslope erosion in the lower Redwood Creek basin directly contributes to channel aggradation and increases in the volume of channel-stored sediment. Gully erosion in the lower basin, while a significant source of sediment in that region, contributes much less to total yield than the volume of sediment derived from upstream areas and moved through, or stored in, the lower Redwood Creek channel.

IMPLICATIONS FOR DETERMINING GULLY EROSION IN LARGE BASINS

Detailed measurements of gully systems on the South Copper Creek study site indicate that only a very limited, select number of gullies need be measured to reliably estimate the total quantity of sediment produced by gullies on logged and roaded lands. For example, 95 percent of the gully erosion in this one study site can be accounted for by measuring only those gullies over 1.1 m^2 in cross-sectional area (table 8). In addition, only 51 percent of the cumulative length of gullies on the site require measurement. Similarly, by limiting an investigation to only those gullies having cross-sectional areas larger than 4.5 m^2, 81 percent of the total gully volume would be obtained by measuring less than 25 percent of the cumulative network length. The continuous function relating gully length, gully cross-sectional area, and cumulative volume of soil erosion is shown in figure 12.

Documentation of gully erosion on the study sites reveals almost precisely the same relationship as shown in figure 12 between gully size and contribution to sediment production. That is, gullies over 1.1 m^2 in cross-sectional area accounted for 94 percent of the total measured fluvial erosion, whereas those larger than 4.5 m^2 contributed 81 percent (table 8). By measuring these larger features, only 18 percent of the gullies, by length, would need to be measured (table 8).

Gully-derived sediment production from steepland coastal terrain similar to that of the lower Redwood Creek basin can be closely determined by limiting sediment source inventories to gullies formed by stream diversions at road and skid-trail crossings. In forested or grassland basins that have been subjected to road building or timber harvesting, gullies produced by diversions will include, almost without exception, all the largest fluvial erosion features to be found in a basin. An accurate estimate of sediment production can then be made by measuring only the largest gullies. These account for a large percentage of the total volume of fluvial erosion but only a small portion of the cumulative length of the gully network (fig. 12).

One factor that may help limit the areal scope of inventories could include the identification and elimination of areas that are likely to have low gully yields. These include sites dominated by gentle slopes, upper hillslope positions, cohesive or rocky soils, and few or no roads or streams. A second factor is the prediction of areas of potentially high yield. These include regions of moderate to steep slopes, lower hillslope positions, high

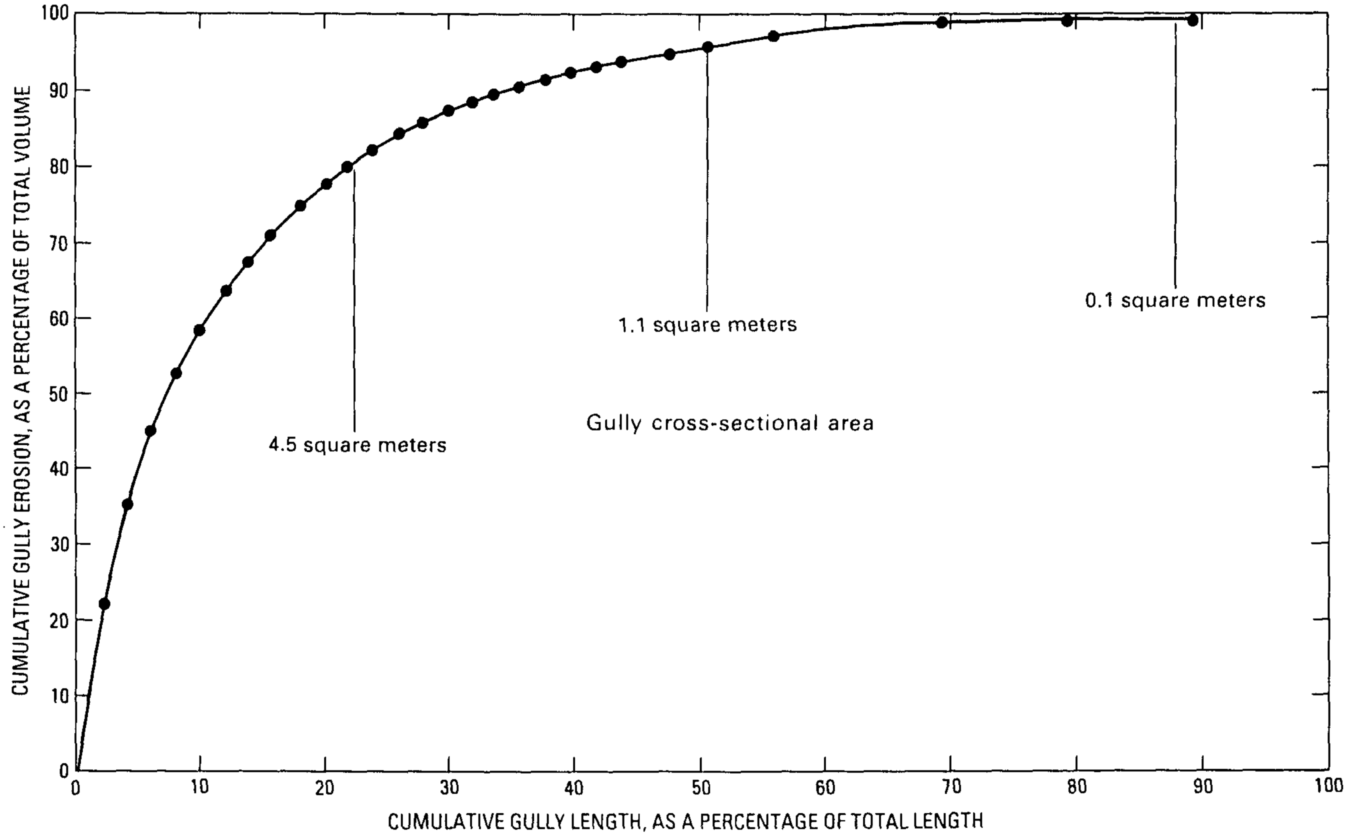


FIGURE 12.—Relations among cumulative gully length, gully cross-sectional area, and cumulative volume of gully erosion on the South Copper Creek study area. Gullies are plotted in order of descending cross-sectional area. (Largest cross sections are plotted first, followed by successively smaller sizes, and ending with the smallest gullies.) The relationship indicates that the largest gullies (for example, those over 4.5 m^2 in cross-sectional area) accounted for the bulk of total erosion, yet constituted a relatively small proportion of the total gully network. Small gullies were abundant but produced comparatively little sediment.

road and stream densities, old or abandoned (unmaintained) road systems, and erodible soils that are noncohesive and low in clay and in rock fragment content.

CONTROL AND PREVENTION OF GULLY EROSION ON LOGGED LANDS

Most of the increased gully-derived sediment production in the lower Redwood Creek basin could have been prevented by careful land management and erosion control practices. For example, such techniques as (1) excavating or dishing-out skid-trail stream crossings, (2) installing properly sized culverts wherever logging roads crossed channels of perennial, intermittent, or ephemeral streams, and (3) maintaining roads and drainage structures (especially during and immediately following storms) could have prevented approximately 85 percent, or more, of the documented gully erosion. To minimize long-term postharvest erosion from logged areas, roads can be either continually maintained or "put to bed" through the practices of water-barring, culvert removal, and stream-crossing excavations. These measures will virtually eliminate postharvest stream diversions and the resulting increase in gully-derived sediment production.

Logging activities constitute only one of the factors contributing to greatly increased rates of gully erosion. Factors such as climate, topography, soil type, and geology affect the susceptibility of logged land to postharvest erosion. Information gathered from study sites within the lower Redwood Creek basin suggests that the amount of postharvest fluvial erosion closely reflects specific logging practices, as well as physical site conditions.

On sites of equal erodibility, the severity of the erosional problems reflects not so much the actual logging methods as the practices employed to reduce stream diversions during and following the harvest operations. Postharvest erosion control, while potentially beneficial, is more costly and less effective than careful planning and prevention, since many of the sources of increased post-harvest sediment production may become inaccessible, uncontrollably large, or inactive over time.

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