Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

K.M. NOLAN, H.M. KELSEY, *and* D.C. MARRON, *Editors*

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By DAVID W. BEST, HARVEY M. KELSEY, DANNY K. HAGANS, *and*
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By DAVID W. BEST,[1] HARVEY M. KELSEY,[2] DANNY K. HAGANS,[3] and MARK ALPERT[4]

ABSTRACT

The Garrett Creek sediment budget is based on detailed measurements of fluvial hillslope erosion, streamside landsliding, and main-channel sediment storage in Garrett Creek. The study period, 1956 to 1980, which includes both an interval of widespread timber harvest and a sequence of major storms, represents a period of accelerated erosion in the watershed. Of the sediment contributed to the main channel during this time, fluvial slope erosion contributed 62 percent, and streamside landsliding contributed the rest. Of the total sediment input for the 25-year period, only 6 percent remained in storage in the lower main channel of Garrett Creek.

The sediment budget study concentrates on the measurement of fluvial hillslope erosion. Our fluvial erosion survey determined that almost all significant sources of fluvial erosion were created by road construction and logging. Because of this observation, we did a detailed study of stream crossings by roads. Two major causes of erosion accounted for 80 percent of all road-related fluvial slope erosion. Stream diversions caused by plugged culverts at crossings initiated 68 percent of road-related fluvial erosion, and the failure of road fills at established crossings initiated another 12 percent of such erosion. Because of the dominance of stream diversions as a cause of accelerated erosion, we have devised a diversion potential rating for road crossings. Steep-gradient roads that have inboard ditches and roads that cross drainage swales without dipping into them have the greatest diversion potential.

Most erosion in the Garrett Creek basin occurs during storm runoff of short duration but of sufficient magnitude to transport sediment. Land management is a major influence on geomorphic processes. Any attempt to assign long-term rates of denudation to erosive processes in this watershed must incorporate human influence as a permanent and significant independent variable.

INTRODUCTION

The objective of this study was to investigate the processes and the magnitude of hillslope erosion in Garrett Creek (drainage area of 10.8 km^2) and to place this erosion in the context of Garrett Creek's sediment budget. The study period 1956 to 1980 was selected because it includes (1) widespread timber harvest; (2) intense storms in 1955, 1964, 1972, and 1975 (Harden and others (1978); and (3) an excellent photographic record with aerial photographs for 1954, 1958, 1962, 1966, 1972, and 1978. The contribution of fluvial hillslope erosion was stressed in this study, although other sediment sources were measured as well. Contributions from fluvial hillslope erosion have been treated as an unknown in all previously proposed budgets for this region (Kelsey, 1980; Kelsey and others, 1981). From the studies of the magnitude and causes of fluvial hillslope erosion, it was concluded that logging roads are by far the major cause of such erosion. In the Garrett Creek basin, much of this erosion could have been prevented by better designed logging roads. The magnitude of road-related fluvial hillslope erosion approaches that of streamside landslide erosion, which is the only other significant sediment source in the Garrett Creek watershed.

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[1] Redwood National Park, Arcata, CA. 95521.

[2] Department of Geology, Humboldt State University, Arcata, CA 95521.

[3] Pacific Watershed Associates, Arcata, CA 95521.

[4] California Regional Water Quality Control Board, Santa Rosa, Calif.

CHARACTER OF THE GARRETT CREEK WATERSHED

Garrett Creek is a 10.8-km^2 elliptically shaped watershed on the east side of Redwood Creek, just upstream from Redwood National Park (fig. 1). Predominant rock types in the basin are unmetamorphosed and slightly metamorphosed sedimentary rocks of the Franciscan assemblage (Harden and others, 1981). Locally, tectonic blocks of greenstone are found. The fourth-order channel of Garrett Creek is moderately steep and has an average gradient of 0.18 m/m. Drainage density is 5,700 m/km^2. The predominant forest type is Douglas-fir. Oak woodlands and prairies are found on south-southwest slope exposures and on ridgetops. Minor amounts of redwood mixed with Douglas-fir are found on north-facing slopes. Basin hillslopes are generally convex in profile. Upper slope gradients range from 0.30 to 0.35 m/m, while gradients of footslopes average 0.65 to 0.70 m/m.

The headwater channels of Garrett Creek are in an incoherent sandstone-siltstone unit that is prone to mass movement. Channels of the middle portion are cut in coherent massive sandstone and interbedded sandstone, siltstone, and graywacke along approximately 760 m of channel length. A steep canyon is formed in this channel reach; sideslopes range from 70 percent to nearly vertical and average 80 to 100 percent. The channel has many waterfalls 3 to 5 m in height, and the canyon is inaccessible except along the channels. Conifers on the steepest canyon slopes near the channel have not been harvested. The lowermost portion of Garrett Creek flows through alternating coherent and incoherent rock units. Slope and channel gradients are less steep (averaging 50-55 and 13 percent, respectively) than the canyon reach upstream, and significant quantities of sediment are stored in channel bars. An active earthflow currently enters the lower creek along the left (southeast) bank.

LAND USE IN GARRETT CREEK

Prior to the initiation of timber harvest in the early 1950's, 46 percent of the basin supported old-growth coniferous forests, principally Douglas-fir with minor amounts of redwood in north-facing exposures. Roughly 30 percent of the basin is presently prairie grassland, and 25 percent is hardwood forests (fig. 1). Nearly all of the coniferous forests have been logged; the remaining uncut coniferous forests are found along the steep inner gorge of Garrett Creek and where such forests are interspersed with areas of uncut hardwood.

Most road construction in the basin accompanied periods of intense timber harvest. Between these periods, the roads for the most part were not used and were only sporadically maintained. Three major roads, and associated spur roads, give access to the watershed (fig. 1). Much of the fluvial hillslope erosion in the watershed between 1956 and 1980 relates to the histories of these major haul roads after their construction. Mainline Road is a permanent all-season road constructed prior to 1954 and originally paved for most its length. It enters the southern portion of the watershed at a midslope elevation of 300 m and climbs continuously for 4.8 km to the watershed divide at 902 m. Middle Garrett Road was constructed in several segments between 1954 and 1977. It is a high standard, unrocked road that traverses the middle to lower portions of the basin. Several spur roads provide access to the north and middle forks as well as to the recently logged northern slopes of the watershed. Nelson Road provides access to the lowermost, southern portions of the watershed. Construction first began prior to 1954, and the road was completed by 1965.

Early logging of the watershed involved annual cuts between 1948 and 1954, and averaged 50 acres per year. Logging downslope of Mainline Road was done by cable systems; logging upslope of Mainline Road was done by tractors. By 1954, 25 percent of the coniferous forest in the basin had been logged. Between 1955 and 1958, there was additional logging, and Middle Garrett Road was constructed to site A in figure 1. Between 1958 and 1962, there was little logging, and no additional road construction. The most intense logging occurred from 1962 to 1966 when approximately 27 percent of the coniferous forests was cut. By 1965, Nelson Road was completed, and Middle Garrett Road had been extended almost to the Middle Fork. By 1970, 78 percent of the forests had been logged, and Middle Garrett Road had been extended to site B in figure 1. Spur roads up both the north and middle forks also had been completed. During the next 7 years, there was again virtually no logging or road construction. In 1977, intense timber harvest recommenced with logging along all road systems and construction of the final segment of Middle Garrett Road. From 1978 to 1980, several additional logging plans were executed, including construction of a major spur road. Between 1978 and 1982, most of the previously cut areas were relogged; as a result, reconstruction of nearly all roads in the basin was required. The total length of the three major road systems is 12.7 km.

METHODS OF INVESTIGATION OF SEDIMENT SOURCES AND STORAGE

MEASURED SEDIMENT SOURCES

Major sediment sources in the drainage basin were identified, and sediment contributions from each were estimated. These sources consist of streamside land-

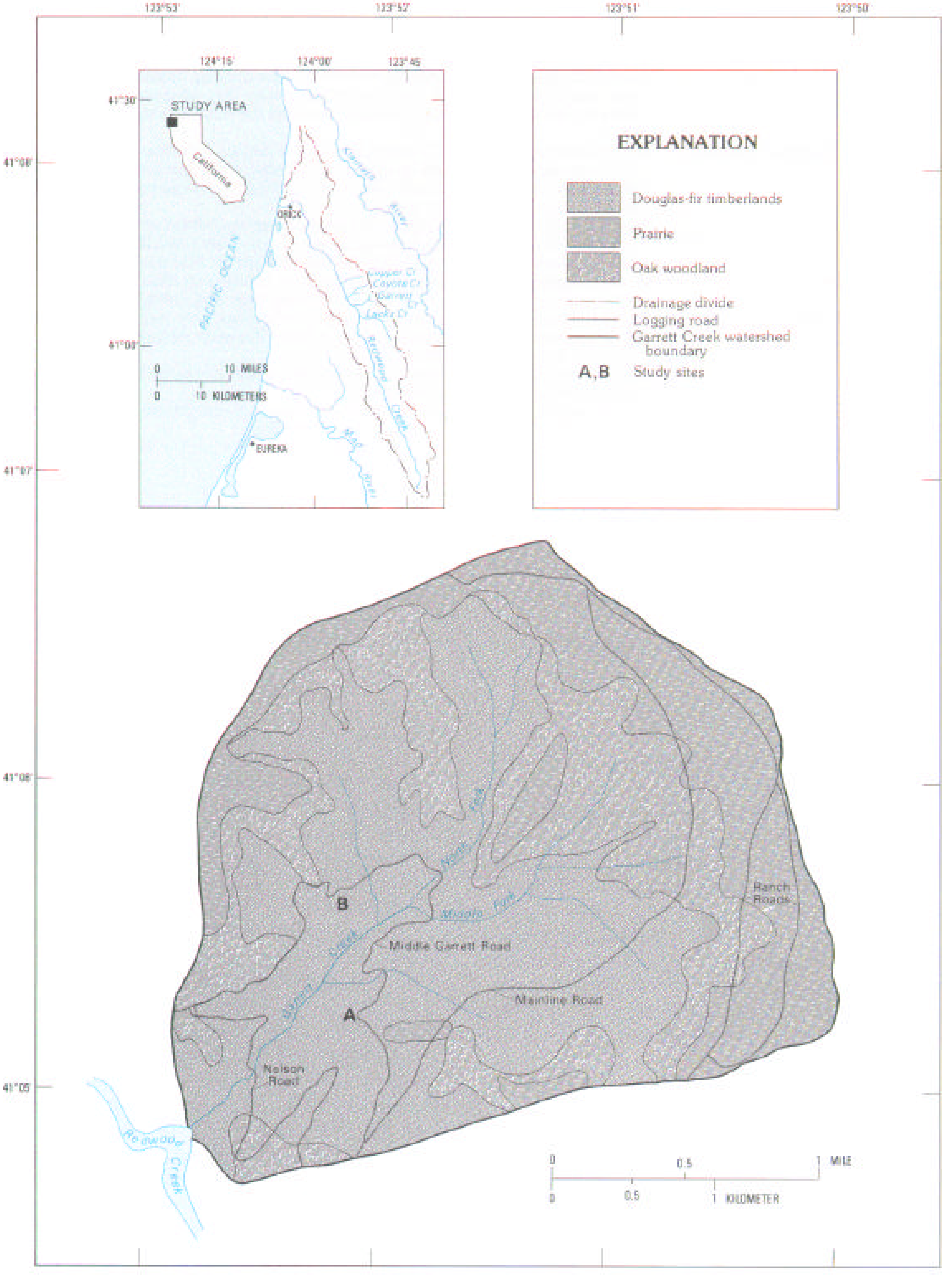


FIGURE 1.—Location map of the 10.8-km^2 Garrett Creek watershed showing the logging road network and the distribution of Douglas-fir timberlands and the prairie-oak woodlands. The inset map shows the relative locations of Copper Creek, Coyote Creek, Garrett Creek, and Lacks Creek within the Redwood Creek drainage basin.

TABLE I. --*Significant causes of road-related fluvial erosion in the Garrett Creek watershed*

Cause of erosion	Explanation of process
Stream diversions.............................	Erosion resulting from the diversion of a stream by a crossing. Includes erosion within a diversion channel (such as a road ditch), as well as erosion that subsequently occurs in a natural channel further downstream. Diversions are often the result of plugged or unmaintained culverts.
Failures of logging haul roads at crossings	Erosion resulting from road-fill failure at stream crossings, including culvert, bridge, and Humboldt crossings. (A Humboldt crossing is an installed crossing where logs, placed parallel to the direction of flow, are substituted for the installation of a culvert; as of about 1978, installation of Humboldt crossings ceased.)
Crossing not to grade	Erosion of the channel in the vicinity of crossing when the culvert or water conduit is not placed at channel grade. Other causes include poorly constructed fills, lack of energy dissipation measures at culvert outlets, and conduits that deflect flow into stream banks.
Road-intercepted runoff.......................	Erosion resulting from the interception, diversion, and concentration of surface runoff by roads; an example is erosion caused by water emanating from road cutbanks.
Misplaced culvert or crossing	Erosion resulting from misplacement of culvert or crossing; such misplacement usually forms a gully originating at the downspout of the culvert. The gully continues downslope, generally for 15 to 50 m, until it rejoins the proper channel.
Failure of a fill crossing..............................	Erosion resulting from the placement of fill where a culvert was needed, or failure to identify a stream channel during road construction.
Inboard ditch erosion................................	Erosion resulting from concentration of surface runoff in road ditches; this concentration causes small gullies less than 0.4 m^2 in cross-sectional area.

slides, road-fill and cutbank failures, road-related fluvial erosion, skid-trail-related fluvial erosion, debris torrents, erosion of natural channels in prairie and hardwood areas, and sediment stored in channels. Previous studies in the watershed furnished the streamside landslide (Kelsey and others, 1981) and sediment storage data (chap. K, this volume).

STREAMSIDE LANDSLIDES

The volumes of the 23 largest landslides in the basin were measured; all of these landslides occurred along the lower 1.8 km of the channel below the confluence of the north and middle forks of Garrett Creek. Landslide volumes were determined by first measuring the surface area of the slide with a tape and rangefinder. Average depths were then estimated from the height of slide scarps and by mentally reconstructing the prelandslide ground surface. Data presented by Kelsey and others (1981) indicate that approximately 85 percent of the volume of sediment contributed by streamside landslides can be measured by using the above techniques.

SEDIMENT STORAGE IN CHANNELS

Sediment stored in fill terraces and in association with large organic debris was measured along the lower 3,300 m of the Garrett Creek channel (the lower three-quarters of the channel from the headwaters to the mouth). The volume of material stored in terraces was determined by measuring terrace surface area and average height above the present thalweg. The amount of sediment stored upstream from a debris jam was determined by treating the trapped sediment as a wedge. The surface area of the deposits associated with the debris was measured, and the depth of sediment in storage was taken as one-half the height of the debris jam. Buried tree stumps, root wads, boulders, and other objects that are now partially exhumed were used to determine depth of recent aggradation.

FLUVIAL HILLSLOPE EROSION

This study concentrates on the measurement of fluvial hillslope erosion. Total fluvial hillslope erosion was estimated from measurements made in the field and on aerial photographs. The largest fluvial erosion features were identified through aerial photographs and field reconnaissance and then measured in the field by using tape-and-compass techniques. These fluvial erosion features included three large debris torrents. Although these debris torrents are mass-movement features, the sediment mobilized by them was fluvially transported and then reworked by gully erosion during later storm events. The volumes of more moderate-sized features were calculated from aerial photographs or from tape-and-compass measurements recorded during field mapping. Each feature was classified according to one of seven erosion causes (table 1). The survey indicated that all the significant sources of fluvially eroded sediment were caused by road construction and logging. Fluvial erosion on undisturbed grassland or hardwood forest areas was minor compared to logging-related fluvial erosion. Because of the above observations, stream crossings along the entire length of Mainline Road, Middle Garrett Road, Nelson Road, and all spur roads were classified according to their type, size, previous failure history, and resulting erosion.

TABLE 2.— *Inventory of the three main road systems for road crossings, crossing diversions, and the amount of sediment eroded due to diversions in the Garrett Creek watershed*

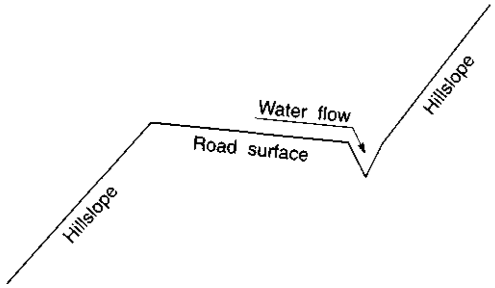
Road system	Number of road crossings	Number of crossings that diverted	Percent that diverted	Mass of eroded sediment (megagrams)
Mainline Road	27	13	48	63,472
Mainline spurs...........	24	1	4	82
Middle Garrett Road ...	20	1	5	60
Middle Garrett spurs ...	28	0	0	0
Nelson Road	10	0	0	0
Nelson spurs	2	0	0	0

[1] Crossings included culverts, bridges, Humboldt crossings, and fill. A Humboldt crossing is an installed crossing where logs, placed parallel to the direction of flow, are substituted for the installation of a culvert; as of about 1978, installation of Humboldt crossings ceased.

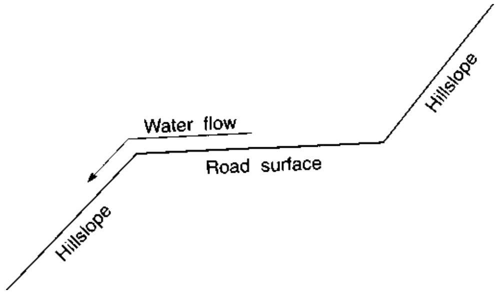
SOURCES OF FLUVIAL HILLSLOPE EROSION

MAJOR CAUSES AND SITES OF FLUVIAL EROSION

Measurable fluvial erosion that clearly occurred between 1956 and 1980 was studied most intensively. Most instances of erosion during this time involved crossings; that is, sites where a road crosses an established drainage channel on the hillslope. A fill crossing is a crossing in which drainage through the fill was not accommodated by a culvert, bridge, or other installation. An installed crossing does contain such an installation. Table 1 summarizes significant causes of fluvial erosion in the Garrett Creek watershed.



A. Insloped road and ditch



B. Outsloped road

FIGURE 2.—Logging road profiles showing (A) Insloped road with inboard ditch and *(E)* Outsloped road with no drainage ditch. Arrows show direction of flow of any water that would pond on the road surface if an adjacent culverted crossing became clogged. In *A,* the water is diverted down the inboard ditch; in *B,* the water traverses the road and flows back into the stream channel.

STREAM DIVERSIONS

Stream diversions at road crossings are the most important causes of fluvial erosion in the watershed. Such diversions typically occur when a culvert plugs and flow is diverted down the inboard ditch instead of breaching the road fill. Diversions are more prone to occur on insloped roads with inboard ditches than on outsloped roads (fig. 2). There were 15 separate stream diversions within the watershed, and all except 1 were on the Mainline Road system (table 2). These diversions eroded about 64,000 Mg of sediment (assumed density of sediment=1.6 g/cm^3).

The occurrence of stream diversions is highly variable throughout the basin and depends on how a road crosses the stream. A stream within a well-incised drainage, where the road descends to the crossing from either side, cannot be diverted, even when flow exceeds culvert capacity. In such cases, flow crosses the road surface and results in erosion of a part of the crossing. Such erosion is only a minor portion of total fluvial erosion measured in the Garrett Creek watershed.

The most important factor in determining the probability of stream diversion is the gradient of the road at the point of crossing. If the road is steep, as Mainline Road is, it has at least one approach that lies below the crossing. The potential for diversions at such crossings is high, especially when an inboard ditch is present and the road surface slopes toward the inboard ditch (fig. 2). Whenever stream discharge exceeds culvert capacity, a pond forms behind the road. When the pond height reaches the road surface, flow must either cross the road (as in the case of an outsloped road) or divert down the inboard edge. Outsloping of the road surfaces tends to encourage flow to cross the road surface, whereas an inboard ditch tends to become a spillway for any ponded water. Once a diversion occurs, the increased flow contributed to an adjacent road crossing may be enough to exceed the discharge capacity of that crossing, regardless of the level of maintenance or condition of the crossing. Even when the culvert at the adjacent crossing can accommodate the combined flow, the increased flow may still result in channel scour and bank erosion below the culvert. A diversion on a continually descending, slightly insloped road with an inboard ditch may set off a series of diversions. Such chain-reaction diversions may result in the combined flow being diverted onto a hillslope, where far more erosion results than if the flow entered a stream channel.

Stream diversions at major crossings can concentrate large volumes of sediment-laden water in a single small channel with erosionally catastrophic results. Three large debris torrents (channel-confined debris flows) in the Garrett Creek watershed were caused by such diversions on the Mainline Road. The debris torrents contributed 44,000 Mg of sediment to Garrett Creek, and an additional 9,400 to 26,700 Mg remain on the slopes in a debris fan near Nelson Road. These debris torrents account for 67 percent of all erosion caused by diversions at crossings. The second largest debris torrent resulted from a chain reaction of stream diversions along 300 m of road. The combined flow at two crossings was diverted down the inboard ditch and onto the slope. A similar chain reaction occurred farther upslope on the same road, where flow from six crossings was diverted down the inboard ditch and concentrated into one channel; substantial channel bank erosion and scour resulted.

Diversion potential is a measure of the probability that a diversion will occur if flow at a crossing exceeds the capacity of the culvert. A diversion potential rating based on road characteristics and slope morphology has been developed. The size of the installed culvert, erodibility of the channel bed, and drainage area above the crossing were not considered. Each crossing was examined in the field and assigned one of three ratings. For crossings that have low diversion potential, the road dips into and out of the drainage swale as the road crosses the stream. Road crossings that have a moderate diversion potential dip only slightly into drainage depressions; should a diversion occur, the length of the diverted channel would likely be less than 30 m. For crossings that have a high diversion potential, the road surface slopes steeply (greater than 5 percent) away from stream crossing, and there is no well-defined berm that separates the pond area behind the crossing from the inboard ditch continuing downslope. Often the road surface is slightly insloped, and there is an inboard ditch.

Table 3 compares diversion potential with frequency of stream diversions for the major roads. Diversions occurred in 50 percent of the high-diversion-potential crossings, 38 percent of the moderate-diversion-potential crossings, and in none of the low-diversion-potential crossings. Of total mass of sediment eroded, 94 percent came from high-diversion-potential crossings. Differences in stream incision or stream order at the major crossings were not as significant a factor in causing diversion as road gradient at the crossings. Mainline Road, having an average gradient of 11 percent and a high number of crossings, accounted for nearly all the high-diversion-potential crossings. Even though most of the crossing diversions on the Mainline Road have been rebuilt, diversion potential remains just as high because road gradient, road inslope, and road ditch remain the same.

TABLE 3. — *Comparison of the diversion potential with observed frequency of stream diversions at stream crossings along the major road systems*

Mainline Road within Douglas-fir terrain				
Diversion potential	Low	Moderate	High	
Number of crossings	1	4	6	
Crossings that divert	0	1	5	
Percent that divert	0	25	83	
Mass of sediment eroded (Mg) ...	0	2,357	57,912	
Mainline Road within hardwood terrain				
Diversion	Low	Moderate	High	Unknown
Number of crossings.................	3	5	4	4
Crossings that divert	0	4	3	0
Percent that divert	0	80	75	0
Mass of sediment eroded (Mg) ...	0	1,439	1,764	0
Middle Garrett Road				
Diversion potential	Low	Moderate	High	
Number of crossings	10	5	[1]5	
Crossings that divert.	0	1	0	
Percent that divert	0	20	0	
Mass of sediment eroded (Mg). . .	0	60	0	
Nelson Road				
Diversion potential	Low	Moderate	High	
Number of crossings	7	2	1	
Crossings that divert.	0	0	0	
Percent that divert	0	0	0	
Mass of sediment eroded (Mg). . .	0	0	0	

[1] Four of five crossings that had high diversion potentials were constructed on small ephemeral streams in 1977, and none have experienced a major storm.

The two roads having lower diversion potential are significantly different from Mainline Road. Both are outsloped and lack an inboard ditch. The roads climb steeply in several locations but tend to be horizontal at major stream crossings.

FAILURE OF HAUL-ROAD CROSSINGS

Failure of haul-road crossings is a significant source of fluvial erosion, and road crossing size is the variable most responsible for determining the magnitude of this erosion source. Three factors are important in determining the size of haul-road crossings: stream incision and gradient, road width, and road type. A more incised stream channel requires more fill to reach a level surface suitable for a road. In addition, a 12-m road requires considerably more than twice the fill of a 6-m road; the additional width usually must be added to the outside edge of the road where the depth of fill is greater. Finally, major haul roads usually have minimal dips at the crossing and require a greater depth of fill. Also, in minimizing turns in the road as the crossing is approached, there is a tendency to "bridge" the steep inner gorge of channels rather than to contour the road to the hillslope.

TABLE 4.—*Erosion data for fills at installed crossings on the three main road systems in the Garrett Creek watershed*

Road system	Hillslope position	Average volume of fill in road crossings (m^3)	Average volume of erosion (fill and native material) from crossings that failed (m^3)	Percent of road crossings that failed
Mainline Road	. Upper middle	178	186	51
Middle Garrett Road ..	. Middle lower	158	144	42
Nelson Road	. Lower	104	74	50

TABLE 5.—*Histories of road crossings in the Garrett Creek watershed*

[Numbers refer to crossing history and do not imply present state or condition of the road crossing. Most crossings have subsequently been rebuilt]

Crossing history	Number	Percent of total
Installed crossings that failed	[1]43	29
Fill crossings that failed	5	4
Installed crossings that remained intact	33	30
Fill crossings that remained intact	25	22
Unknown	5	4
Total	111	

[1] The 43 crossings (of 111) that failed represent at least 52 failures; thus, some crossings failed more than once.

Although the Mainline Road crosses the middle and upper portions of the basin, where streams are smaller and less incised, the large width of this road results in larger fills overall than are needed along either Middle Garrett Road or Nelson Road. Table 4 shows that fills in the Mainline Road crossings, despite their positions higher on the hillslope, failed more often than those on the lower roads. These data suggest that culvert size and proper installation are more important than hillslope position and upslope drainage area in determining the magnitude of crossing failures. Improved road construction practices in the early 1980's have demonstrably reduced crossing failures.

The road-crossing history for Garrett Creek (table 5) shows that 48 of 111 crossings failed during the study period. Only 5 of these 48 crossings were fills that had no drainage conduit; the remaining 43 sites had a culvert or Humboldt fill that clogged and caused failure. Despite the prevalence of crossing failures, sediment contributions to Garrett Creek from these failures account for only 12 percent of road-related fluvial erosion.

OTHER SOURCES OF FLUVIAL EROSION

Most remaining fluvial erosion was either road related or caused by skid-trail construction during logging. Sources and quantities of road-related fluvial erosion are summarized in table 6. After diversions and the failures of installed crossings, erosion resulting from culverts not placed at grade was most important, amounting to 12 percent of total road-related fluvial erosion. Approximately 85 percent of this erosion occurred at crossings on Mainline Road. Most of these culverts were originally Humboldt crossings. When these crossings failed, they were replaced with culverts, but the remaining fill was generally not excavated, and the logs used in the Humboldt crossings were left in place. The culverts were placed above the logs and commonly created a vertical drop of a meter or more at the outlet. As a result, considerable bank erosion and channel scour occurred below many of the crossings.

TABLE 6. —*Summary of causes of road-related fluvial erosion in the Garrett Creek watershed*

[Data include logging haul roads but not skid trails]

Cause of erosion	Mass of sediment (Mg)	Number of individual features	Average size (Mg)
Stream diversions	63,614	15	4,240
Failures of installed crossings	11,192	43/52	196
Crossing not to grade.	11,524	12	960
Misplaced culvert	2,951	5	590
Road-intercepted runoff.	2,002	10	200
Failures of fill crossing.	498	5	100
Erosion of inboard ditches.	2,086	23	91
Total...	96,107	123	

Erosion resulting from misplaced culverts contributed 5 percent of sediment (table 6). Only five crossings in the basin, all on the Mainline Road System, had misplaced culverts. The misplaced culverts were chiefly reconstructions of failed Humboldt crossings. Misplaced culverts were all placed within 20 m of the true channel, and they all resulted in short (less than 30 m) gullies that had relatively large cross-sectional areas.

Skid-trail-related fluvial erosion came from two sources: stream diversions at trail crossings and rill development on skid trails. There were four skid diversions contributing 47 percent of skid-trail-related fluvial erosion. Plot studies of rill erosion in the Redwood Creek basin on terrain similar to that of the Garrett Creek watershed provide the erosion rate that we used for Garrett Creek skid trails. Total skid-trail-related fluvial erosion was 29,182 Mg (table 7).

FLUVIAL HILLSLOPE EROSION: COMPARISON WITH ADJACENT BASIN

Both Garrett Creek and an adjacent Redwood Creek tributary to the northwest, Copper Creek (fig. 1), have been the sites of detailed surveys of fluvial erosion. The Copper Creek (drainage area=7.3 km^2) study (Weaver and others, 1981) documents an 8-year episode of extremely rapid, storm-caused fluvial slope erosion following intensive logging and road construction in a 2.5-km^2 portion of the watershed.

In both watersheds, stream diversions at installed crossings and skid-trail crossings were the single largest cause of fluvial hillslope erosion (75 percent and 43 percent, respectively, of the total measured fluvial slope erosion in the Copper and Garrett study areas). A higher volume of eroded material from the slopes of Copper Creek is the result of multiple diversions. In Copper Creek, Weaver and others (Chap. I, this volume) concluded that most fluvial slope erosion from diversions occurred during major storms in 1972 and 1975.

Although sites and causes of fluvial slope erosion in the two watersheds are similar, the volume of erosion at Copper Creek was much higher. Fluvial slope erosion for Copper Creek from 1971 to 1979 was 177,300 Mg (chap. I, this volume). For comparison, road-related and skid-trail-related fluvial erosion in Garrett Creek for 1956 to 1980 was 123,050 Mg. The greater erosion at Copper Creek is due to a different land use history. Logging in Copper Creek took place rapidly over a few years, and then the entire dead-end road network was abandoned in 1971. Garrett Creek has been more or less continually harvested and contains through-going roads, so that most crossing failures and diversions were corrected fairly soon after they occurred. The sporadic but nonetheless more frequent maintenance at Garrett Creek prevented the repeated diversions and rediversions of gullied streamflow that contributed the extremely high volumes of eroded material to Copper Creek.

SEDIMENT BUDGET FOR GARRETT CREEK

Our sediment budget for Garrett Creek is based on measurements of fluvial hillslope erosion, streamside landslides, and stored sediment in the main channel of Garrett Creek. The budget data (table 7) are presented in terms of total volumes for the 1956-80 period rather than in terms of rates of sediment input and output. The latter method may be preferable because it assigns rates to processes. However, it is not known how the rates that were measured during the 1956-80 period of intensive land use compare to long-term rates.

The sediment budget in table 7 shows five major sources of sediment input. For the first four sources (77 percent of input), the entire population of erosion sites was measured in the field and did not involve extrapolation from the erosion rate of a sample. To this extent, data shown in the first four rows of table 7 differ from other sediment budget data for the Pacific Coast Ranges (Dietrich and Dunne, 1978; Kelsey, 1980; Kelsey and others, 1981; Lehre, 1982), where most of the sediment contribution has been determined from sample rates or from previous field studies.

The fluvial contribution from prairie and hardwood areas (table 7) in the basin not otherwise influenced by road building is difficult to quantify because these erosion sources involve enlargement of previously existing gullies and the increase in volume can only be estimated. A uniform sediment yield rate of 509 (Mg/km^2)/yr has been applied for this area. This rate is based on a measured rate of erosion for a geographically similar 22-hectare sample plot in Lacks Creek, an adjacent basin to the southeast (fig. 1). The Lacks Creek plot was undisturbed except for a minor ranch road. The sample erosion rate is conservative and includes enlargement of natural channels, as well as gully and rill erosion within relatively stable hardwood terrain.

TABLE 7. —*Simplified sediment budget for the 10.8-km Garrett Creek watershed, 1956—80*

Budget component	Mass of sediment (Mg)	Percent of total input
Input		
Road-related gully erosion[1]	50,442	16
Road-related debris torrents[1]	43,426	14
Skid-trail-related fluvial erosion.	29,182	9
Streamside landslides	121,412	38
Fluvial erosion from prairie-hardwood areas (estimated)	73,776	23
Storage		
Additions to alluvial storage	18,800	100
Output		
Inferred sediment yield for 25-year budget period.........................	299,438	100

[1] Road-related erosion sources are itemized by cause of erosion in table 6.

Bank erosion and channel downcutting in forested areas, which are neither obvious from field surveys nor visible on aerial photographs, have been neglected in all measurements done to date. Such erosion may be significant and is highly variable throughout the basin. Rainsplash and sheet erosion was considered to be insignificant in all budget calculations. Reid and others (1981) have measured rainsplash and sheet erosion rates from logging roads. If their rates are applied to roads in Garrett Creek, the sediment yield for the study period increases by a maximum of 0.5 percent. Other surface area plot studies by U.S. National Park Service scientists in the Redwood Creek basin have similarly concluded that sheet erosion is insignificant compared to channel processes (K.J. Kveton and R.A. Sonnevil, Redwood National Park, written commun., 1982).

The sediment budget for Garrett Creek (table 7) shows that roughly 318,000 Mg of sediment has entered the main channel of Garrett Creek between 1956 and 1980. Approximately 31 percent of the total input resulted from the seven forms of road-related fluvial erosion listed in table 6. Three road-related debris torrents alone account for 14 percent of total sediment input (table 7). Most of the fluvial erosion, 63 percent, came from the Douglas-fir portion of the basin (drainage area=5.0 km^2; 46 percent of total drainage area of Garrett Creek). The road-related fluvial erosion resulted in large measure from poor road and skid-trail construction and design and

TABLE 8. —*Comparison of watershed characteristics and sediment yields for Coyote Creek, Garrett Creek, and Lacks Creek*

Drainage basin	Drainage area (km^2)	Drainage length (km)	Average gradient	Estimated sediment yield [(Mg/km^2)/yr]
Coyote Creek	20.4	6.5	0.13	12,500
Garrett Creek..................	10.8	4.5	.18	1,110
Lacks Creek	44.0	13.6	.06	11,600

[1] Based on U.S. Geological Survey gaging station records for water year 1980.

could have been prevented. Fluvial hillslope erosion from the remaining unlogged prairie and oak woodlands portion of the basin (drainage area=5.8 km^2; 54 percent of total drainage area of Garrett Creek) constitutes 37 percent of fluvial slope erosion. Comparative fluvial sediment yields from the Douglas-fir and prairie-oak woodland areas are 1,002 and 509 (Mg/km^2)/yr, respectively. Prairie-oak woodland areas generally have considerably higher rates of erosion than forested Douglas-fir areas in northern California (Kelsey, 1980). Erosion from logging roads in Garrett Creek has reversed this situation for the period 1954-80.

Of the total sediment input from the basin, only 6 percent, or about 19,000 Mg, remained in storage—the remaining sediment has been flushed downstream to Redwood Creek. The actual amount of remaining sediment is probably less than 6 percent because some of the stored sediment was present prior to the beginning of the budget period.

The lack of a gaging station prevents the direct calculation of sediment yield from the Garrett Creek basin for 1956-80. Based on calculations from the sediment budget in table 7 (input to channel minus storage), the inferred sediment output is about 299,000 Mg or 1,100 (Mg/km^2)/yr. This inferred sediment yield seems reasonable when compared to sediment yields estimated from gaging station data for the adjacent similar watersheds of Coyote Creek and Lacks Creek (table 8), though sediment yields for the three basins are not strictly comparable because of the different measurement periods. The sediment yield for Coyote Creek, Garrett Creek, and Lacks Creek ranges from 1,110 to 2,500 (Mg/km^2)/yr. This range in yield is comparable to long-term estimates (1954-80) for Redwood Creek at Orick (drainage area=720 km^2) of 2,100 (Mg/km^2)/yr (James Knott, U.S. Geological Survey, written commun., 1981).

CONCLUSIONS

The dominant erosion processes that deliver sediment to perennial or intermittent channels in Garrett Creek are related to major storms of brief duration. The significant erosion of the last 25 years occurred during storms that lasted hours or a few days. Even prior to intensive logging of steep forest lands, most geomorphic change in northern California occurred within hours or a few days per year (Kelsey, 1980). The Garrett Creek study shows that the construction of logging roads greatly increases the rate of hillslope erosion. For this reason, land management must be considered in the long term as another independent variable, together with climate, tectonic processes, and geology, in determining erosion rates. Long-term models of sediment transport, as well as short-term predictions of erosion, require probabilistic analysis of all these independent variables.

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