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Magnitude, cause and basin response to fluvial erosion, Redwood Creek basin, northern California

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ABSTRACT Detailed erosion inventories and geomorphic mapping document the magnitude and causes of fluvial sediment production from hillslopes in the 197 km^2 lower Redwood Creek basin. Sediment production from various fluvial erosion processes (gully erosion, 37%; washed out stream crossings, 7%; and surface erosion from bare soil areas, 4%) is nearly equal in volume to material derived from mass movement processes (52%). The leading cause of gully erosion is the diversion of streamflow at logging road and skid trail stream crossings. A simple predictive methodology, based principally on road gradient, successfully identifies stream crossings with a high potential for stream diversion (DP). Undersized culverts, infrequent culvert maintenance and the occurrence of high DP stream crossings have combined with infrequent, severe winter storms to trigger widespread gully erosion. Long term effects of fluvial erosion include increased hillslope drainage density, enlarged stream channels and downstream effects including bank erosion and decreased pool frequency.

INTRODUCTION

A significant problem associated with commercial timber harvesting and road building in mountainous terrain is the increased rate of soil erosion and sediment yield frequently associated with these landuse practices (Anderson, 1979; Kelsey, 1980; Swanson, 1981). The Redwood Creek drainage basin (located in coastal Humboldt County about 480 km north of San Francisco, California) displays exceptionally high rates of erosion brought about by a combination of physiographic, geologic and climatic factors, together with complex landuse patterns (Kelsey et al., 1981; Janda et al., 1975).

In particular, fluvial erosion on harvested forest land in the Redwood Creek basin has been significantly increased over undisturbed conditions, probably to a greater degree than erosion from mass movement processes (Janda et al., 1975). Nolan et al. (1976) noted an increase in the basin-wide abundance of gullies from 1947 to 1974, coincident with widespread timber harvest. In addition, preliminary data from sediment budget studies suggest fluvial erosion from hillslopes contributed 68% of the sediment input to the main channel of Redwood Creek above U.S. Highway 299 between 1956 and 1980 (Kelsey et al., 1981; Fig. 1, this paper). Locally intense gully erosion has also been recorded in several tributary basins (Weaver et al., 1981; Best et al., in press).

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 (Weaver et al., in press). For the investigation, gullies were defined as newly formed channels greater than 0.1 m^2 in cross-sectional area. In addition, fluvial erosion originating from logging road and skid trail stream crossings, as well as from surface erosional processes (rain splash and rill erosion) on bare soil areas were estimated.

Specific objectives of this paper are:

(a) to describe the magnitude and causes of gully erosion on a variety of sites in the 197 km^2 lower Redwood Creek basin;

(b) to extrapolate the volume of gully and other fluvial erosion to the lower Redwood Creek basin, and to compare this to the volume of material introduced by landslide processes;

(c) to describe a method for evaluating the potential for stream diversions at logging road stream crossings (the major cause of gullying); and

(d) to discuss the long term effects of landuse-caused fluvial erosion on the Redwood Creek basin.

STUDY AREA

The study area encompasses roughly the lower one-third (197 km^2) of the 720 km^2 Redwood Creek basin (Fig. 1). The Redwood Creek basin is underlain by rocks of the Franciscan Assemblage (Harden et al., 1981), a Mesozoic to early Cenozoic accumulation of weakly indurated and pervasively sheared continental margin deposits. The Grogan Fault, expressed as a well-defined NNW-trending lineament, bisects the basin and juxtaposes unmetamorphosed clastic sedimentary rocks to the east against metamorphosed schistose rocks to the west. Soils developed on these rock types are highly varied and have been extensively studied by Marron (1982) and Popenoe (unpublished NPS reports). In general, soils are moderately coarse in texture and have high infiltration capacities but possess little cohesion and very low shear strength.

The drainage basin is characterized by high relief (1500 meters), moderately steep hillslopes ($\overline{x} = 14^o$) and narrow valley bottoms (Janda et al., 1975). Most hillslopes exhibit a distinct convexity with the steepest hillslope segments adjacent to stream channels and more moderate gradients at middle and upper slope positions. Annual precipitation between 1938 and 1980 averaged 2000 mm, of which 90% occurred between October and May.

For most study results presented in this summary paper, the period of record extends from c. 1947 to 1980. This time frame was selected for three principle reasons: (a) it includes a period of widespread timber harvesting; roughly 81% of the coniferous forest was logged, resulting in the construction of approximately 2000 km of roads and over 9000 km of skid trails (Best, 1984), (b) a series of five storms occurred with recurrence intervals of 10 to 50 years (Coghlan, 1984; Harden et al., 1978), and (c) extensive data on watershed changes and erosion rates were available from sequential aerial photographs, field mapping and stream gauging records.

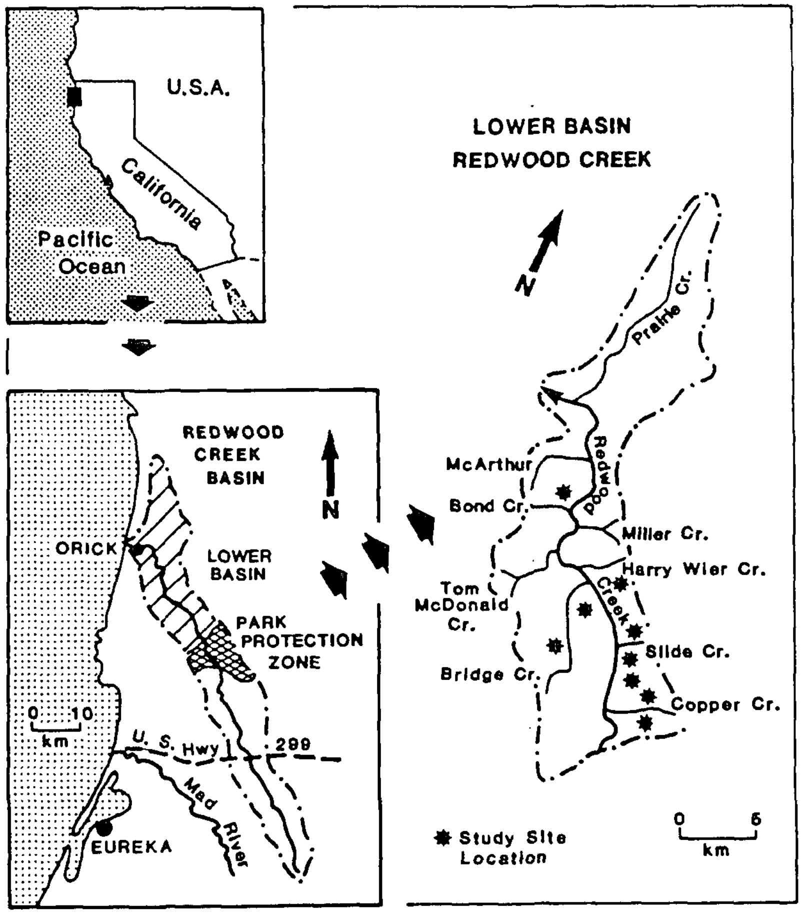

FIG.1 Location map of the Redwood Creek basin showing study sites.

GULLY EROSION IN THE LOWER BASIN

Nine study sites in the lower Redwood Creek basin, totaling 22 km^2, were geomorphically mapped at a scale of 1:1200 (Fig. 1). The study sites displayed the variety of geologic bedrock types, soil materials, hillslope positions, slope gradients, drainage densities, logging and roading histories and flood producing storm histories present in the basin (Weaver et al., in press). Several of the sites were specifically chosen because of their apparent low rate of fluvial hillslope erosion.

On eight of the study sites, totaling 1968 ha, gully widths and depths were estimated at least every 21 m. Volumes were then computed by multiplying the cross-sectional area by the corresponding length of gully reach. On the 246 ha South Copper Creek study site, all gullies were 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. More frequent and accurate field measurements on the South Copper Creek unit were eventually used to compare with and evaluate results from less intensive sampling on the other eight study sites.

The nine sites yielded 329 500 m^3 of gully erosion (Table 1). At the time of the inventory, there was a wide variation in gully yields between the nine different study sites. Gully yields from Table 1 can be divided into three groups. Lower Slide, North Copper, Maneze, and South Copper Creek sites generated high yields exceeding 170 m^3/ha. Both of the Bridge Creek units plus the Dolason and Upper Slide Creek sites displayed relatively more moderate gully yields ranging from 52 to 77 m^3/ha. Finally, the Bond Creek study site yielded only 3 m^3/ha.

Much of the variability between sites apparently stems from differences in physical site variables and, to a lesser degree, on the timing of logging relative to major storm events. Study sites within the high yield group are all underlain by sheared mudstones and sandstones of the Incoherent Unit of Coyote Creek, a member of the Franciscan Assemblage (Harden et al., 1981). The dominant soil mantling the high yield sites is the Coppercreek series of inceptisols with fine loamy, mixed and isomesic characteristics. This soil is deep (100-150 cm) and, compared to soils on the sites displaying lower gully yields, contains relatively low clay content and very low gravel-size and larger 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 (Weaver et al., in press).

LOWER BASIN FLUVIAL EROSION

Gully yield for the entire lower Redwood Creek basin (197 km^2) was estimated from data obtained on the nine study sites. The methodology used is explained in Weaver et al. (in press). In general, we divided the lower basin into three major terrain categories, based principally on major soil types, their corresponding geologic, geomorphic and topographic characteristics, landuse

TABLE 1 Gully erosion on nine sites in the lower Redwood Creek basin

Site name	Area (ha)	Gully length (km)	Number of cross sections	Total gully volume (m^3)	Gully yield (m^3/ha)	Gully density (m/ha)
South Copper	246	20.3	3168	87 100	354	83
North Copper	410	12.7	377	108 500	265	31
Maneze	172	8.5	380	36 000	209	49
Lower Slide	198	5.0	149	34 400	174	25
North Bridge	304	14.8	826	23 300	77	49
Upper Slide	239	6.4	474	17 300	72	27
Dolason	144	2.6	132	7 900	55	18
South Bridge	275	4.7	238	14 300	52	17
Bond	226	0.8	37	700	3	4
TOTAL	2214	75.8	5781	329 500	149	34

history and fluvial erosion rates obtained from the study sites.

High yield terrain from Table 1, where gully erosion was estimated to average 260 m^3/ha, occupies 31% of the selected land base in the lower basin but yielded approximately 75% of the eroded volume. In contrast, 30% of the land base (that area included in the low yield category), was estimated to account for less than 2% of the total gully erosion in the lower basin. Clearly a small portion of the disturbed land in a watershed can contribute a large proportion of the total sediment production from gullies. The estimated total gully erosion in the lower basin amounts to a volume of over 1.1×10^6 m^3 (Table 2).

Data from the field study also suggested the volume of gully erosion far exceeded the volume of sediment derived from other sources of fluvial erosion (i.e. sediment yield from erosion of logging road and skid trail stream crossings, rill erosion, and rain splash on bare soil areas). To test these field observations, erosion at 418 representative logging road and skid trail stream crossings on 947 hectares of tractor yarded terrain were measured. Erosion at the sampled stream crossings totalled 19 900 m^3.

Applying this sample stream crossing density (0.44 crossings/ha) and erosion rate (48 m^3/crossing) to the total land area which had been tractor logged (10 770 ha), it is estimated that erosion of the 4740 road and skid trail stream crossings totalled 225 600 m^3 (Table 2). This volume of erosion, while significant, amounts to only 15% of the total volume of fluvial erosion in the lower basin.

In Redwood Creek, sediment production from surface erosion (i.e. rain splash and rill erosion) was the least important constituent of total lower basin sediment yield. The volume of sediment yield generated by surface erosion processes was determined by measuring the total bare soil area present following logging operations in the lower basin, determining which areas could deliver sediment to stream channels (3600 ha), applying an erosion rate, and estimating recovery times and revegetation rates (ranging up to 10 years).

Erosion rates applied to the total bare soil area were determined by analyzing NPS sediment trough data and by applying results from USGS erosion pin studies (Marron et al., in press). Sediment trough data indicated between 0.05 and 0.1 cm of ground surface lowering occurs during the first winter following ground disturbance. In succeeding years, erosion rates are dramatically reduced because of revegetation and an armoring effect as fines are

TABLE 2 Measured sediment sources in the lower Redwood Creek basin (c. 1954-1980)

Sediment source	Volume (m^3)	Total yield (%)
Fluvial Erosion		
Gullies	1 157 400	37
Eroded Stream Crossings	225 600	7
Surface Erosion	124 400	4
Mass Soil Movements		
Streamside Landslides	1 600 000	52
Totals	3 107 400	100

winnowed away and a coarse surface lag develops. USGS erosion pin data yielded comparable mean elevation changes of -0.06 cm on tractor-logged sandstone slopes to -0.42 cm on tractor-logged schist slopes (Marron et al., in press).

Applying these erosion rates to bare soil areas within the three terrain types identified by the gully study, the total volume of sediment delivered to stream channels by surface erosion processes between 1954 and 1980 was estimated to be 124 400 m^3 or roughly 8% of the total fluvial erosion in the lower basin (Table 2). These results indicate surface erosion processes acting on bare soil areas, while directly linked to landuse practices, are a minor contributor to downstream erosion and sedimentation impacts in the Redwood Creek basin.

We estimate total fluvial hillslope erosion in the lower Redwood Creek drainage basin to be over 1.5 x 10^6 m^3 since the advent of widespread logging and road building. For comparison purposes, Kelsey et al. (in press) measured landslide inputs in the lower basin adjacent to Redwood Creek and from its major tributaries. They concluded 1.6 x 10^6 m^3 of sediment, originating from a variety of landslide mechanisms, contributed to the lower basin stream channels between 1954 and 1980 (Table 2). In Redwood Creek, sediment production by fluvial erosion processes (primarily gullying) is nearly equal in volume to sediment generated by mass movement processes.

CAUSES OF GULLY EROSION

Detailed analyses of gully erosion indicated the diversion of streamflow at logging road and skid trail stream crossings caused 89% (1.0 x 10^6 m^3) of the total measured post-harvest gully erosion in the lower basin (Weaver et al., in press; Hagans et al., 1986). This accounts for 33% of the total lower Redwood Creek sediment production (from all sources) between 1954 and 1980. Based on studies and sample plots from the remaining upper two-thirds of Redwood Creek (419 km^2), gully erosion caused by stream diversions accounts for at least 40% of the total basin-wide sediment production. The importance of stream diversions as a cause of gully erosion and mechanism of drainage basin response to landuse disturbance cannot be overlooked.

Stream diversions typically occur when culverts plug or when storm runoff exceeds their capacity. New gullies form when streamflow is diverted out of a natural channel, down a logging road or skid trail and across the adjacent, harvested hillslopes. The resulting gullies are widespread and form complex, interconnected networks. Gullies on roads are relatively small, with cross-sectional dimensions generally less than 0.5 x 0.5 m. However when diverted waters cascade off the road prism and down the steep hillslopes (>17^{o}), gully dimensions dramatically increase and frequently exceed 2.0 x 2.0 m for the length of the gully. The documented link between the specific land-use practice (i.e. road crossing construction), stream diversions, and consequent gully erosion is quite clear.

Given the overriding importance of stream diversions as a cause of increased erosion from forested steeplands, a simple "diversion

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potential" rating system was developed for stream crossings in Garrett Creek, a 10.8 km^2 tributary basin in the Park Protection Zone (PPZ)(Best et al., in press; Fig. 1, this paper). The diversion potential (DP) is a measure of the probability that streamflow would divert down the road, rather than flow directly across the road, if the culvert were to plug or its capacity were exceeded. The rating system was based solely on the gradient of the road as it crosses a stream channel.

Stream crossings were examined in the field and assigned one of two ratings. For crossings with no DP, the road sloped into and out of stream channel at the crossing (i.e. the road gradient from the stream crossing in either direction was a positive degree). For crossings with a high DP, the road surface was found to slope away from the stream crossing in at least one direction. All crossings with high DP have been inadvertently designed to result in diversions and thereby create extensive gully systems on adjacent hillslopes.

Recorded DP ratings were compared with the frequency of actual stream diversions for 161 logging road stream crossings on five sites. Diversions on the sites occurred in 28-71% of the crossings with a high DP and in none of the no DP crossings (Hagans et al., 1986). An average of nearly 60% of the stream crossings with a high DP had actually diverted at least once since they were originally built, only to be reconstructed with the same high DP.

Study results indicated only on very steep roads (gradient $>7^{o}$) did the magnitude of the road gradient actually affect the diversion frequency. Thus, all 17 streams which crossed very steep roads had diverted at least once. For gradients less than 7^{o}, the relationship between road steepness and diversion frequency was less pronounced. Of 95 inventoried streams which crossed gentle ($<3^{o}$) and moderate ($3\text{-}7^{o}$) gradient roads, just under 50% in each category had diverted since road construction.

Because of their causal link to widespread gully erosion, stream crossings with a high DP represent the most obvious source of future drainage basin response to landuse disturbance. Such crossings are a ubiquitous feature of logging roads in the Redwood Creek basin. For example, in the 121 km^2 PPZ (Fig. 1), over 50% of the stream crossings on the 280 km road network have a high DP, and over 60% have culverts which are too small to pass the 25-year storm flow (Weaver et al., 1987). The potential erosional response is heightened because nearly 80% of the road system has been abandoned and drainage structures are no longer being maintained. These factors guarantee a continuation of the accelerated erosion that has been documented on forest lands in Redwood Creek.

LONG TERM EFFECTS OF LANDUSE-CAUSED FLUVIAL EROSION

Studies in Redwood Creek and in nearby drainage basins such as the Van Duzen (Kelsey, 1980) have identified gullying as a major contributor to increased sediment yields since the advent of modern logging and road building over three decades ago. Fluvial erosion accounts for between 48% (Table 2) and 68% (Kelsey et al., 1981) of all sediment discharged to Redwood Creek and its origin is very clearly linked to specific landuse practices. Most stream diversions occur during moderate or extreme periods of runoff and create large, complex gully systems on hillslopes. These processes have resulted in long-term and persistent increases in hillslope drainage densities and lower order stream channel dimensions.

For example, on seven sites totaling 16.4 km^2, pre-roading and pre-logging "natural" drainage densities averaged 4.8 km/km^2. Post-roading and logging (c. 1980) drainage densities (including gullies and natural stream channels) averaged 8.2 km/km^2. Amongst the sites, drainage densities increased by 6 to 136% ($\bar{x}$ = 71%). The newly formed gullies are now an integral part of the drainage network. Whether they are still actively evolving or are now stable, gullies intercept near-surface storm flow and carry sediment and runoff to higher order stream channels downslope. Their effect on drainage basin storm flow hydrographs has not yet been evaluated.

A second long-term effect is the increase in channel dimensions of many lower order streams. The substantial and relatively rapid adjustments of channel morphology occur as a result of increased discharges and sediment loads carried by some watercourses where streamflow from one natural channel is diverted into another. We found that approximately 20% of the 78 km of natural stream channels on the seven study sites had been permanently widened and deepened.

Because field measurements indicate sediment delivery from fluvial erosion frequently exceeds 90%, numerous downstream manifestations of drainage basin response also occur. These persistent effects are associated with aggradation in higher order stream channels and result in increased incidence of bank erosion, decreased pool frequency, and additions to sediment being stored in channel compartments with long residence times (Hagans et al., 1986).

Madej (this volume) indicates that additions to stored sediment in the lower basin since 1947 have residence times ranging from 9 to 106 years, depending on their proximity to the active channel. Channel bed aggradation has resulted in locally severe channel widening in the main stem of Redwood Creek. In a 30 km reach of Redwood Creek, 51 locations of major bank erosion (greater than 6 m of lateral scour) occurred between 1955 and 1978. At 71% of the locations, the channel has remained wider and not recovered to its pre-aggradation channel configuration. In addition, regression analysis of Redwood Creek thalweg surveys in reaches with similar channel gradients indicates that where some stream bed recovery has occurred since aggradation, pool numbers have increased (Varnum & Ozaki, in press). Presently, there are 15 km of channel in lower Redwood Creek that are actively aggrading. Significantly, the last major input of sediment to Redwood Creek occurred in 1975 during a 10-year flood, yet 12 years later roughly one-third of the lower basin main stem is still responding to and being affected by upslope and upstream sediment inputs.

CONCLUSIONS

Measurements of fluvial erosion on large study plots in the lower Redwood Creek basin indicate gully erosion is responsible for approximately 37% of the total input of sediment to the main stem of Redwood Creek (Table 2). Erosion at stream crossings and by surface erosion processes account for an additional 11%. Although most of the erosion occurred during four relatively large-magnitude storms in 1964, 1972 and 1975, erosion inventories have identified specific land management practices as a major geomorphic influence which can dramatically increase the rate of hillslope erosion. Stream diversions and resultant gully erosion were found to contribute to significant on-site and off-site impacts in Redwood Creek.

Data from hillslopes in Redwood Creek clearly illustrate how past and present landuse practices have "primed" the logged watersheds for additional, future erosional events and subsequent drainage basin response. In addition, the threat of pending erosion is substantially heightened by the common practice of abandoning (not maintaining) logging roads between harvesting cycles.

Although major improvements have been made in forest road construction practices, most large watersheds throughout northern California and the Pacific Northwest already contain hundreds of kilometers of old roads, many of which have been constructed with undersized culverts and have stream crossings constructed with high diversion potentials. Drainage basin response to decades of road building and the construction of thousands of stream crossings with high diversion potentials can be expected to occur over wide geographic areas years after the landuse disturbance. While seemingly a response to the effects of major storms, severe hydrologic events merely trigger a geomorphic response to conditions that have been imposed on the landscape by landuse activities.

REFERENCES

Anderson, H.W. (1979) Sources of sediment-induced reduction in water quality appraised from catchment attributes and land use. In: Proc. of Third World Congress on water resources (23-28 April 1979, Mexico City), 8, 3606-3616.

Best, D.W. (1984) Land use in the Redwood Creek watershed, California. Redwood National Park Tech. Report 9, National Park Service, Arcata, California.

Best, D.W., Kelsey, H.M., Hagans, D.K. & Alpert, M. (in press) Role of fluvial hillslope erosion and road construction in the sediment budget of Garrett Creek, Humboldt County, California. In: Geomorphic process and aquatic habitat in the Redwood basin, northwestern California (ed. K.M. Nolan, H.M. Kelsey & D.C. Marron), USGS Prof. Paper 1454.

Coghlan, T.M. (1984) A climatologically-based analysis of the storm and flood history of Redwood Creek. Redwood National Park Tech. Report 10, National Park Service, Arcata, California.

Hagans, D.K., Weaver, W.E. & Madej, M.A. (1986) Long term on-site and off-site effects of logging and erosion in the Redwood Creek basin, northern California. In: Papers presented at Amer. Geophys. Union meeting on cumulative effects (9-13 Dec. 1985, San Francisco, Ca), Tech. Bull. 490, 38-66, National Council of the Paper Industry (NCASI), New York, New York.

Harden, D.R., Janda, R.J. & Nolan, K.M. (1978) Mass movement and storms in the drainage basin of Redwood Creek, Humboldt County, California - a progress report. USGS Open-File Report 78-486.

Harden, D.R., Kelsey, H.M., Morrison, S.D. & Stephens, T.A. (1981) Geologic map of the Redwood Creek drainage basin, Humboldt County, California. USGS Open-File Report 81-496.

Janda, R.J., Nolan, K.M., Harden, D.R. & Colman, S.M. (1975) Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California, as of 1973, USGS Open-File Report 75-568.

Kelsey, H.M. (1980) A sediment budget and an analysis of geomorphic processes in the Van Duzen River Basin, north coastal California, 1941-1975. Geol. Soc. Am. Bull., 91(4), 1119-1216.

Kelsey, H.M., Madej, M.A., Pitlick, J.C., Coghlan, T.M., Best, D.W., Belding, R. & Stroud, P. (1981) Sediment sources and sediment transport in the Redwood Creek basin, a progress report. Redwood National Park Tech. Report 3, National Park Service, Arcata, California.

Kelsey, H.M., Coghlan, T.M., Pitlick, J.C. & Best, D.W. (in press) Geomorphic analysis of streamside landsliding in the Redwood Creek basin. In: Geomorphic process and aquatic habitat in the Redwood Creek basin, northwestern California (ed. K.M. Nolan, H.M. Kelsey & D.C. Marron), USGS Prof. Paper 1454.

Marron, D.C. (1982) Hillslope evolution and the genesis of colluvium in Redwood National Park, northwestern California; the use of soil development in their analysis. Univ. of California, Berkeley, Ph.D. Dissertation, Berkeley, California.

Marron, D.C., Nolan, K.M. & Janda, R.J. (in press) Effects of logging and geology on hillslope erosion and deposition by surficial processes in the Redwood Creek basin, northwestern California. In: Geomorphic process and aquatic habitat in the Redwood Creek basin, northwestern California, (ed. K.M. Nolan, H.M. Kelsey & D.C. Marron), USGS Prof. Paper 1454.

Nolan, K.M., Harden, D.R. & Colman, S.M. (1976) Erosional landform map of the Redwood Creek drainage basin, Humboldt County, California; 1947-1974. USGS Open-file Report 76-42.

Swanson, F.J. (1981) New directions in assessing human impact on erosion in steeplands. In: Internat. Symposium on erosion and sediment transport in Pacific Rim steeplands, Jour. of Hydro. (N.Z.) 20(1), 3-7.

Varnum, N. & Ozaki, V. (in press) Recent channel adjustments in Redwood Creek, California. Redwood National Park Tech. Report 18, National Park Service, Arcata, California.

Weaver, W.E., Choquette, A.V., Hagans, D.K. & Schlosser, J. (1981) Effects of intensive forest landuse and subsequent landscape rehabilitation on erosion rates and sediment yield in the Copper Creek drainage basin, Redwood National Park. In: Proc., symposium on watershed rehabilitation in Redwood National Park and other coastal areas (24-28 Aug. 1981, Arcata, CA), Center for Natural Resources Studies of the John Muir Institute, Berkeley, California, 341-360.

Weaver, W.E., Hagans, D.K. & Popenoe, J.H. (in press) Magnitude and causes of gully erosion in the lower Redwood Creek drainage basin. In: Geomorphic process and aquatic habitat in the Redwood Creek basin, northern California, (ed. K.M. Nolan, H.M. Kelsey & D.C. Marron), USGS Prof. Paper 1454.

Weaver, W.E., Hagans, D.K. & Madej, M.A. (1987) Managing forest roads to control cumulative erosion and sedimentation effects. In: Proc. California watershed management conference, Report 11 (18-20 Nov. 1986, West Sacramento, CA), Wildland Resources Center, Univ. of California, Berkeley,California.

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