

Pilot Monitoring Program

Geologic Input for the Hillslope Component

Thomas E. Spittler
Senior Engineering Geologist
California Department of Conservation
Division of Mines and Geology
1995

The California Department of Conservation, Division of Mines and Geology (DMG) is submitting this report and accompanying maps to the California Department of Forestry and Fire Protection (CDF) to fulfill Interagency Agreement number 8CA38400, Pilot Monitoring Program -- Geologic Input for the Hillslope Component. Under this agreement, DMG has assisted CDF in the development of hillslope monitoring techniques needed to evaluate the effectiveness of the Forest Practice Rules in protecting water quality. The major component of DMG's work involved defining the physical characteristics of the pilot watersheds, including the North Fork of the Gualala River in Mendocino County (McKittrick, 1995A), the portion of the North Fork of the Mokelumne River that is in Amador County (McKittrick, 1995B), and the North and South Forks of Caspar Creek above their weir dams in Mendocino County (Spittler and McKittrick, 1995). Concurrently, DMG also participated in the Monitoring Study Group (MSG) to aid in developing analysis techniques for evaluating for hillslope processes and to develop procedures for selecting and evaluating monitoring locations for a possible long-term monitoring program.

INTRODUCTION:

CDF regulates activities related to the commercial harvesting of timber from private and State lands under the legislative authority of the Z'berg-Negedly Forest Practice Act of 1973 (FPA). This work is done under the guidance of the Board of Forestry (BOF). The principal means of regulation is the requirement that all harvesting be done under a formal Timber Harvesting Plan (THP) that is prepared by a Registered Professional Forester (RPF) and is in compliance with the Forest Practice Rules (Rules). The entire THP process, including the review by an interdisciplinary Review Team chaired by CDF, with participation by the California Department of Fish and Game (DFG) and the Regional Water Quality Control Board (WQCB), is considered to be the functional equivalent to an Environmental Impact Report that would be required under the California Environmental Quality Act (CEQA).

The principal goal of the FPA is to protect, restore, enhance and maintain the productivity of timberlands so that maximum sustained production of high quality timber products is achieved while giving consideration to values relating to recreation, watershed, wildlife, range and forage, fisheries, regional economic vitality, employment, and aesthetic enjoyment. More recently, environmental protection has become the main area of concern. A major issue with timber harvesting is water quality, both with respect to domestic water supplies and as needed for cold water fisheries. To address both CEQA requirements for the protection of water quality, and to obtain certification of the Rules as Best Management Practices under Section 208 of the Federal Clean Water Act, the BOF has established the MSG to develop a program to monitor the effectiveness of the Rules in protecting water quality.

The MSG determined that a 2-year Pilot Monitoring Program (PMP) should be conducted to provide guidance for the development of a long-term monitoring program. The PMP includes an In-Stream Component, conducted by DFG, and a Hillslope Component conducted by CDF under the guidance of Dr. Andrea Tuttle. In order to place the effectiveness monitoring in a larger-scale geologic perspective, DMG was contracted by CDF to define the physical characteristics of the pilot watersheds. The interagency agreement was for DMG to map the geology and geomorphology of pilot watersheds. This work was funded for Year Two of the PMP only.

SCOPE OF WORK

The potential impacts to a watershed from timber harvesting are controlled by the stability of the entire watershed and individual areas within, by physical processes affecting the area, and by land-use actions on the ground surface. In-stream physical habitat conditions are affected by both natural variabilities and by deviations from a norm caused by disruptions within the watercourses as well as from actions on the surrounding slopes. Developing a cause and effect relationship between on-slope activities and stream channel conditions is beyond the scope of the PMP, and may not be possible even under a long-term monitoring program, for three major reasons:

1. Fluvial morphology is dynamic and based on sediment yields from surrounding hillslopes, on rainfall patterns, and on non-linear instream conditions such as input and decay of large woody debris.
2. The instream effects of past timber harvesting, stream clearing, and other land-use activities are long-lived, lasting for decades to centuries.
3. The lag time for an action on a hillslope to result in an effect to a stream channel is generally unknown and impossible to quantify.

Watersheds are open systems that are affected by many processes, including the intrinsic physical properties of the earth materials (strength, cohesion, detachability, permeability, and others) and the extrinsic actions of precipitation and land use. These systems are dynamic. Uplift of the mountains, the rise and fall of the oceans, earthquakes, volcanoes, weathering, major storms, and many other processes all change the potential for hillslope denudation and changes in stream channel form. The geomorphology developed on the parent geology records the recent dynamic processes, and as such, can provide the backdrop upon which to assess THP-related land-use impacts on slope processes.

DMG has prepared maps of geology and geomorphic features of the watersheds of the North Fork of the Gualala River, the private portion of the North Fork of the Mokelumne River, and the monitored North and South Forks of Caspar Creek as part of the hillslope component of the PMP. The mapping for the Gualala River and Mokelumne River areas was done at a scale of 1:24,000, while the Caspar Creek mapping was done at a scale of 1:12,000. Mapping was completed using stereographic aerial photographs supplemented by field work. Small, shallow-seated landslides revegetate fairly rapidly and their physical detail is lost in a few years to decades. Therefore, the location of these features represent their existence at the time of the field mapping and the flights for the aerial photographs.

In addition to the geology and geomorphic features maps, a relative slope stability map was prepared for the Gualala and Mokelumne watersheds. Areas within THPs that are being reviewed under the Hillslope Component of either the PMP or a long-term monitoring program can be checked against the relative slope stability map to see if problems associated with completed THPs are related to the relative slope stability of the area. THPs reviewed by CDF for the Hillslope Component were not compared with the geologic and geomorphic mapping because the results of the CDF reviews were not available during the time of the project.

One task that was proposed to be included with the geologic and geomorphic mapping was the preparation of a map of dominant fluvial processes for the major watercourse reaches within the pilot watersheds. This work was to be general in nature to identify erosional, transport, and depositional stream reaches. Preliminary aerial photographic interpretation of the stream reaches was not successful, in part because of the vegetation. Therefore, information on dominant fluvial processes is not included on the geologic and geomorphic maps. Field mapping of all of the major reaches within the watersheds was beyond the scope of the project, and would have required more time than was allotted in the Interagency Agreement.

The geologic and geomorphic mapping of the North Fork of the Gualala River, the North Fork of the Mokelumne River, and the South Fork of Caspar Creek was conducted by Mary Anne McKittrick, Associate Engineering Geologist with DMG. Thomas E. Spittler, Senior Engineering Geologist, mapped the North Fork of Caspar Creek.

PHYSICAL WATERSHED CHARACTERISTICS

NORTH FORK OF THE GUALALA RIVER

Physiography:

The North Fork of the Gualala River drains a watershed of about 24,000 hectares (60,000 acres) in southwestern Mendocino County. The North Fork joins the South Fork of the Gualala River approximately 10 km (6 miles) upstream from the Pacific Ocean. The confluence of the two forks is the low point in the watershed at an elevation of about 3 m (19 feet). The high point is a peak along Signal Ridge which reaches an elevation of 565 m (1854 feet).

Geology:

The San Andreas Fault zone is the major geologic feature of the region. The Little North Fork of the Gualala River follows the fault zone, separating profoundly different geologic terranes (Wagner and Bortugno, 1982).

Rocks in the fault zone are a highly sheared mixture of the various pre-Quaternary rock types. This material, called fault gouge, is unconsolidated and resembles colluvium. The fault gouge is erodible and poorly exposed so it may be more extensive than mapped (Davenport 1984).

Rock units west of the San Andreas fault include the German Rancho Formation and the Anchor Bay Member of the Gualala Formation. These units are overlain in places by surficial terrace deposits and alluvium.

The German Rancho Formation is a Paleocene to Eocene age marine sedimentary formation of consolidated, coarse-grained sandstones that are interbedded with minor amounts of mudstone and less common conglomerate (Davenport, 1994). The formation is moderately hard and strong and supports steep slopes beyond the limits of the shearing related to the San Andreas Fault.

In Fault Contact with the German Rancho Formation in the northern most portion of the San Andreas Rift Zone is a small area mapped as the Anchor Bay Member of the Gualala Formation of Cretaceous age. This unit was highly sheared in the North Fork of the Gualala River and was not readily distinguishable from the fault gouge.

The Quaternary marine terrace deposits are poorly to moderately consolidated silts, sands, and local quartz-rich pea gravels that form extensive flat benches parallel to the coast. Only portions of the uppermost terraces are in the watershed at the top of the western slopes above the Little North Fork of the Gualala River.

Rocks of the Coastal Belt and the Central Belt of the Franciscan Complex are exposed east of the San Andreas fault. Well-consolidated marine sedimentary sandstone with intergranular clay and silt (graywacke) and feldspathic sandstone, with lesser amounts of siltstone, mudstone, and conglomerate are the dominant rock types of the Coastal Belt of the Franciscan Complex. The sandstones are poorly bedded to massive, and moderately well consolidated. Individual exposures range from coarsely jointed sandstone that is moderately hard and strong to highly fractured to sheared rock that exhibits low strength.

The Central Belt of the Franciscan Complex is a tectonic assemblage, referred to as melange, of pebble- to hectare-sized blocks of graywacke sandstone (sandstone with intergranular clay and silt) interbedded with siltstone, shale, and conglomerate surrounded by a matrix of pervasively sheared argillaceous (clay rich) material. In addition to the sandstone, greenstone (altered volcanic rock), chert, blue schist, and serpentinite are in the melange matrix. The sandstone of the Central Belt differs from that of the Coastal Belt in that it frequently exhibits a post-depositional metamorphic fabric or schistosity. Although some of the individual rock units are very hard and strong, the Central Belt melange has a very low shear strength and readily fails through rotational slumping and earth flow.

The Central Belt of the Franciscan Complex is in fault contact with the Coastal Belt. The degree of activity of this fault is not known, however changes in alluvial deposition across the fault suggest that it may have been active during the Quaternary. The boundary between the Coastal and Central Belts is also the boundary between forest and grassland respectively.

Quaternary alluvium has deposited in low gradient stream reaches throughout the watershed. The alluvium is composed of flat-lying, poorly consolidated sand, silt, and gravel. The alluvium developed from the sedimentary rocks on the west side of the San Andreas Fault differs little from that derived from the Franciscan Complex to the east.

Geomorphology:

The geomorphic setting of the North Fork of the Gualala River watershed is youthful with active downcutting of streams into the relatively soft bedrock during Quaternary time. Stream channels in the mapped area lie in deep, narrow gorges with very steep slopes. First order drainages typically head in amphitheater-shaped basins with steep slopes (in excess of 65 percent). The North Fork channel is sinuous in the lower third of the watershed where it flows within a narrow flood plain of relatively recently deposited silt, sand and gravel. In the central portion of the watershed, flood plain alluvium is less common, and the stream banks and hillslopes are frequently very steep. In the upper portion of the watershed, underlain by the Central Belt of the Franciscan Complex, the topography is more rounded, the slopes are hummocky, and the stream channels flow in relatively small, flat valleys with moderately steep side slopes.

The nature of the bedrock determines the dominant mass wasting processes in the watershed. The areas underlain by the Coastal Belt sandstones have experienced a long history of shallow debris slide and debris flow landsliding. Debris slide slopes dominate the landscape. To the east, where the highly sheared Central Belt forms the hills, mass wasting continues as relatively deep rotational landslides and earth flows. Specific descriptions of the various types of landslides mapped in the watershed are included in the legend for the watershed map (McKittrick, 1995A).

NORTH FORK OF THE MOKELUMNE RIVERPhysiography:

The Mokelumne River flows westward from the central Sierra Nevada to the San Joaquin River in the Great Valley. The North Fork of the Mokelumne River drains a watershed of about 90,000 hectares (220,000 acres) in Amador and Calaveras Counties. Only 17,000 hectares (42,000 acres) in Amador County were mapped as part of the PMP. The lowest point in the mapped part of the watershed is 710 m (2300 feet) at the Tiger Creek Reservoir. The highest point in the mapped area is 1990 m (6500 feet) along the ridge crest north of the Lower Bear River Reservoir.

Geology:

The North Fork of the Mokelumne River is underlain by metamorphosed Paleozoic sedimentary and volcanic rocks, Mesozoic granitic rocks, minor Cenozoic rhyolitic tuffs, and widespread late Cenozoic volcanic mudflows.

Strongly deformed but weakly metamorphosed rocks of the Calaveras Complex include fine-grained, thinly bedded dark siliceous hornfels, derived from siltstone, mudstone, and shale (Bateman and Wahrhaftig, 1966; Wagner and others, 1981). Subordinate to the fine-grained meta-sedimentary rock, are interbeds of metamorphosed limestone (marble), quartzite, chert, calcareous or dolomitic siltstone and lenses of mafic volcanic rock. The Calaveras Complex is hard and strong and has a poorly to moderately developed cleavage (schistosity). The unit

supports steep slopes that are susceptible to rockfall and wedge failure. The thin, rocky, clay-rich soil developed on the metamorphic rocks are not highly erodible. These fine-grained metamorphic rocks are most common in the area mapped in the lower elevations, particularly along the river inner gorge. Local exposures of meta-sedimentary rock are also present as roof pendants within the younger granitic rocks.

The Mesozoic granitic rocks are plutons associated with the Sierra Nevada Batholith. The plutons in the study area include rocks with compositions ranging from quartz diorite to alaskite, with quartz monzonite to granodiorite being the most common. These granitic rock types are composed of quartz, feldspars of varying mineralogy, and dark-colored iron-rich minerals. Where fresh, the granitic rocks are very hard and strong and can support high overhanging slopes. Rock falls are the major slope failures in these areas. Where the granitic rocks are weathered, only moderately inclined slopes are supported. Rotational landslides are the most common types of failures in these areas.

The mineralogy of the dark-colored mineral in the granitic rocks is key to their erosion potential. Where the dark mineral is amphibole, generally hornblende, the rock weathers to quartz, clays, and iron oxides, and the soil only moderately susceptible to surface erosion. Elsewhere, where the dark mineral is black mica (biotite), initial weathering results in expansion and grain-boundary disaggregation. The resulting decomposed granitic soil is deep, cohesionless, and extremely susceptible to erosion.

White rhyolitic tuffs and ashflows of the Tertiary Valley Springs Formation are present as local remnants that survived the major episode of post-depositional erosion. The Valley Springs Formation is only moderately indurated in the watershed and is susceptible to rotational failure

Capping all older rocks over a profound erosional unconformity are andesitic mudflows of the Mehrten Formation. These dark gray-brown volcanic mudflows are composed of cobble- to boulder-sized clasts of andesite and less common pre-volcanic rock of granite and hornfels in a fine-grained andesitic matrix. Locally the Mehrten Formation is well indurated and supports steep slopes. More commonly the volcanic mudflow deposits form a rounded topography that is moderately susceptible to surface erosion. Although landsliding is not common within the Mehrten rocks, the formation is permeable and readily transmits water. Springs are common along the base of the Mehrten Formation, as are landslides within the underlying rock types.

Geomorphology:

The Sierra Nevada were repeatedly scoured by glaciers during the late Quaternary Period, removing weathered bedrock. The North Fork of the Mokelumne River flows through a valley that was formed by Pleistocene glaciation. Moderately inclined glacial slopes in the upper part of the watershed have been cut by post-glacial river erosion that has formed a deep inner gorge in the hard crystalline rocks.

Rock falls and debris slides periodically remove material along the steep inner gorge slopes along the North Fork of the Mokelumne River. Rotational landslides typically occur in areas where weathering has progressed, particularly along the contact between the metamorphic and granitic

rocks and the Mehrten Formation. Rotational landslides are also present in weathered rock along stream canyons.

Although surficial soil erosion was not addressed in this study, it appears to be the dominant denudational process for the watershed of the North Fork of the Mokelumne River.

CASPAR CREEK

The North and South Forks of Caspar Creek have been investigated as part of a paired watershed study by CDF and the Pacific Southwest Forest and Range Experiment Station of the U.S. Department of Agriculture, Forest Service since 1962 (Rice and others, 1979). Engineering geomorphological mapping of the North Fork was begun in 1987, but other DMG requirements precluded completion of the work. The geologic and geomorphic mapping was included with the PMP so that this information would be available for the cumulative effects portion of the Caspar Creek study. The results of the mapping, however, provide insights that are very important to the long-term monitoring program being developed by the MSG.

Physiography:

The North Fork of Caspar Creek above its weir drains a watershed of 500 ha (1225 acres), while the South Fork watershed above the weir is about 425 ha (1050 acres). These small watersheds are about 11 km (7 miles) southeast of Fort Bragg, inland from the central Mendocino County coast. The low point of each watershed is at its weir, 85 m (275 ft) for the North Fork and 50 m (160 ft) for the South Fork, with the high points 310 m (1020 ft) and 320 m (1057 ft), respectively.

Geology:

Both watersheds are underlain by the Coastal Belt of the Franciscan Complex (Kilbourne, 1982, 1983; Kilbourne and Mata-Sol, 1983) that are lithologically similar to that portion of the North Fork of the Gualala River underlain by the same unit.

Geomorphology:

The creeks in both watersheds flow in relatively narrow, bedrock-controlled stream channels. The upper portion of the North Fork of Caspar Creek flows in a narrow trough gullied through Holocene alluvium that is deposited behind an ancient landslide dam. The visible remnant of the dam is an inclined deposit of poorly sorted sand, silt, and gravel that forms a perched bench on the north bank of the North Fork of Caspar Creek. This ancient landslide dam marks the downstream limit to the significant Quaternary alluvium deposits. The narrow canyon formed by the breaching of the old landslide dam was the site of an old splash dam that was used during early timber harvesting of the watershed. Carbon¹⁴ dating of carbonaceous material found in the alluvium upstream from the landslide dam by Stephen Reneau (written communication) indicates that the alluvium slowly filled the valley beginning about 7000 years before present (BP) through at least the late Holocene. Deposition stopped only recently, and sometime after that renewed

downcutting occurred. Apparently the broad (approximately 100 m, 330 feet wide) debris flow deposits formed a long lasting dam that resisted down cutting for thousands of years.

The old growth redwoods that were logged from the watershed near the turn of the century were floated down stream by floods caused by opening the gates of the splash dam. Part of the splash dam structure is still in place, behind which historic alluvium has deposited. Other accumulations of alluvium were mapped elsewhere in the watershed, behind what are inferred landslide dams but none are as extensive as the valley fill behind the splash dam site.

Because the majority of the North Fork of Caspar Creek was never logged with tractors, the details of the surface morphology are well preserved. Debris slides and debris flows, rotational landslides, disrupted, hummocky ground, and inner gorge slopes are all present in the watershed. The lack of ground disturbance allows the landslides to be subdivided into five relative age classes: 1) fresh appearing landslides that were most recently active within the last 20 years; 2) landslides that have affected the second-growth trees but have recovered to some degree -- estimated to be from 20 to 120 years old; 3) landslides that have impacted the old-growth trees or stumps but have not affected the second growth trees -- estimated to be from 100 to 1000 years old; 4) landslides that have not affected the old-growth trees or stumps but have well defined surficial morphologies and are estimated to be from 500 to several thousands of years old; and 5) geomorphic features with morphologies suggestive of landsliding but which are highly modified. These possibly are related to differential erosion of inhomogeneous bedrock, perched ancient erosional surfaces, or ancient landsliding.

None of the landslides observed in the North Fork of Caspar Creek have occurred following the clear-cut logging in the watershed that occurred from 1985 to 1992. Of the 15 landslides in the watershed that are fresh appearing, seven are associated with the existing roads across the upper slopes and eight occurred in areas not adjacent to roads. The landslides in the clearcut blocks appear to predate the timber harvesting based on the age of vegetation growing on the scars. Eight of the fresh appearing landslides have mappable dimensions and are larger than 1/2 acre. Of these, all but one are associated with the older roads.

Mapping in the South Fork of Caspar Creek was handicapped by both the high degree of ground disturbance that occurred as a result of road construction in 1967 and tractor logging between 1971 and 1973, and the very dense vegetation that has grown on the disturbed slopes. Instead of being able to break the landslides into five relative age classes, only large, dormant, rotational landslides and small debris slides and flows were identified. Unlike the North Fork watershed, where none of the landslides were related to the recent predominantly cable clear cut logging, almost all of the smaller, more recent landslides in the South Fork watershed are associated with roads, landings and skid trails constructed from 1967 to 1973.

Interpretation of 1975 aerial photographs of the South Fork of Caspar Creek revealed a total of 66 recently active landslides, all of which appear to be debris slides or debris flows. Of these, 35 are associated with roads, 12 with landings, 16 with skid trails, and three are not associated with ground disturbances and are not within the area that was selectively logged. Seventeen of the post-logging landslides were larger than 1/2 acre. Of the larger landslides, six are associated

with roads, seven with landings, three with skid trails, and one is not associated with the timber operations (Refer to Figures 1 and 2).

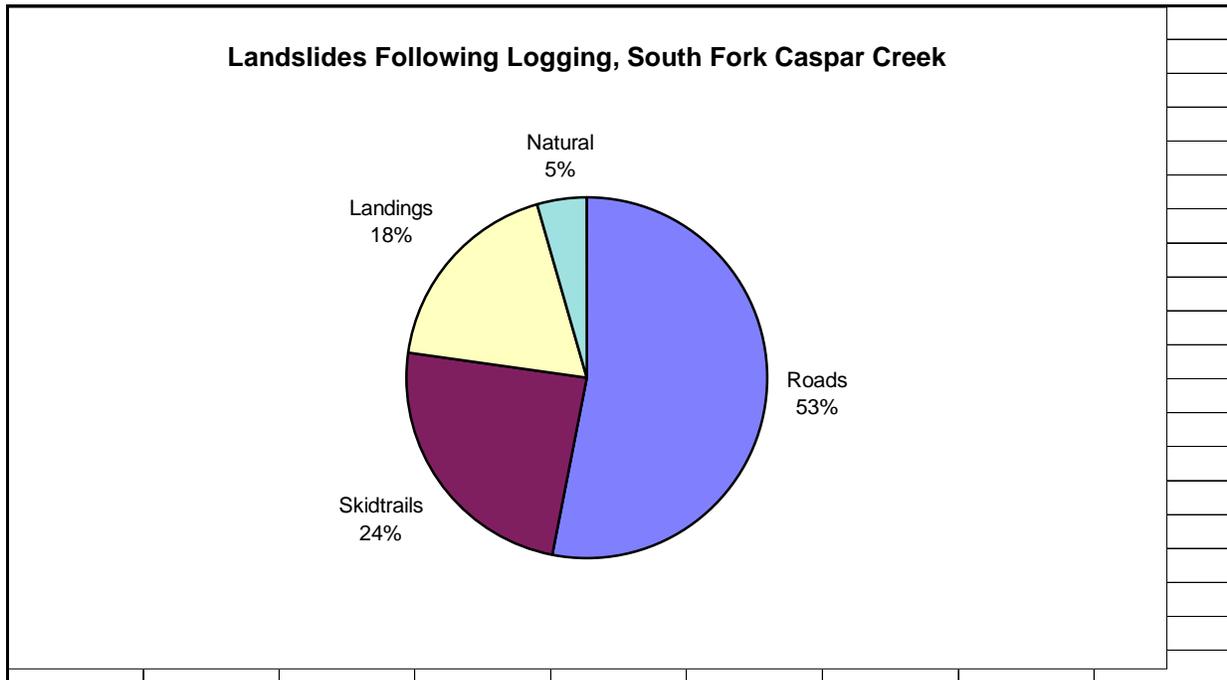


Figure 1. Landslides Following 1967-1973 Roding and Logging Interpreted From 1975 Aerial Photographs, South Fork Caspar Creek

<u>Landuse Association</u>	<u>No. of slides</u>
Roads	35
Landings	12
Skid Trails	16
No Landuse Association	<u>3</u>
Total	66

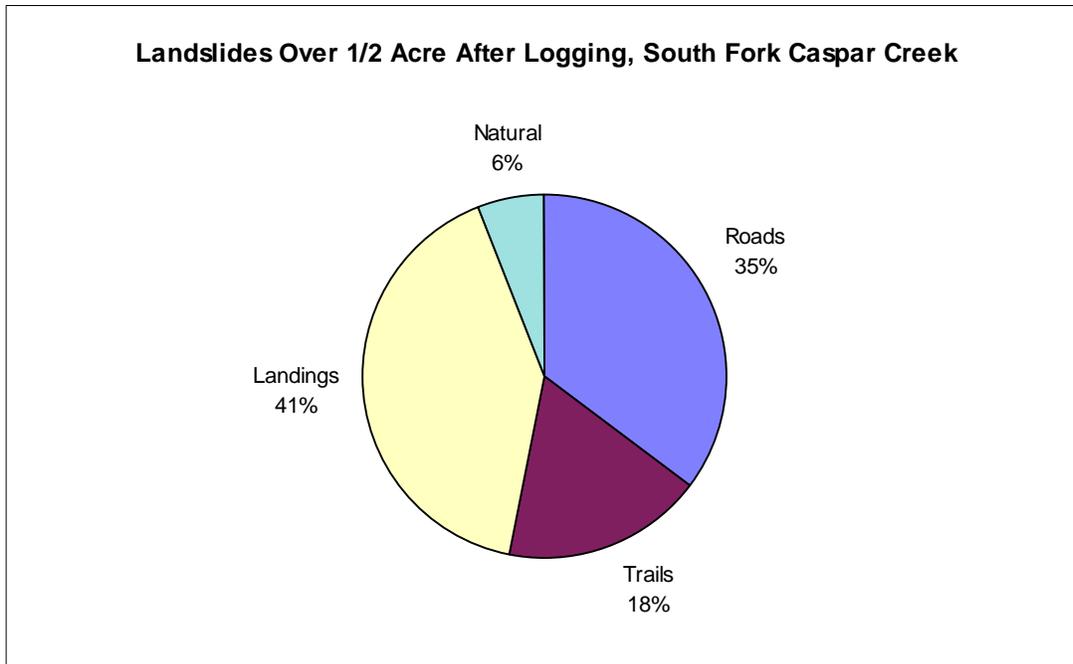


Figure 2. Landslides Over 1/2 Acre Following 1967-1973 Roding and Logging Interpreted From 1975 Aerial Photographs, South Fork Caspar Creek

<u>Landuse Association</u>	<u>No. of slides</u>
Roads	6
Landings	7
Skid Trails	3
No Landuse Association	<u>1</u>
Total	17

GEOLOGIC AND GEOMORPHIC CONTROLS TO MASS WASTING

Landslides and soil erosion are a natural consequence of the factors that lead to the tremendous habitat diversity of the earth. The earth is dynamic. Earthquakes and volcanoes are constantly building mountains which are worn down by landslides and erosion. In general, the more rapid the uplift in an area, the greater the gravitational forces that trigger earth movements. Mass wasting through landsliding and soil erosion is needed to keep up with tectonic uplift. This is definitely the case in the northern California Coast Ranges. An uplifted wave-cut marine platform at Point Delgada near Cape Mendocino has been rising at a rate of up to 1 m/1000 years for the past 44,800 years (McLaughlin and others, 1983). Fission tracks formed by radioactive decay in the mineral apatite observed by Dumitru (1991) indicate that the King Range south of Cape Mendocino has experienced a minimum of 2 to 5 km of uplift and unroofing in the past 1.2 million years. Uplift episodes in the Coast Ranges are also easily identified by the earthquakes that accompany them. The recent series of earthquakes near Eureka are just the most recent examples of this process. The 1992 Cape Mendocino earthquake centered near Petrolia was itself associated with up to 1.4 ± m of uplift (Carver and others, 1994).

The driving force behind the uplift is the movement of the tectonic plates separated by the San Andreas Fault, the Mendocino Fracture Zone, and the Cascadian Subduction Zone. If the current tectonic regime acted relatively consistently for the past 4 million years as suggested in the pattern of magnetic anomalies on the ocean floor (Atwater, 1970), without landsliding and erosion, parts of the northern California Coast Ranges would be about 17 km or 55,000 feet tall. Soil erosion, landsliding, and debris flow/debris torrent activity are natural consequences of uplift in tectonically active areas in the world.

Uplift and down cutting rates are far slower in the western Sierra Nevada than for the Coast Ranges. Therefore, the natural rate of landsliding and erosion will also be lower.

The geomorphic mapping portions of the PMP document that landslide susceptibilities and occurrences in watersheds vary with different geologic and climatic controls, and that the effects of logging (and other land use activities) that occurred prior to the implementation of the current FPA obscure the impacts of more recent activities in some areas. In the Mokelumne River watershed, the effects of mining, although not documented in this study, also has a major impact.

Natural Factors Affecting Landslide Activity:

Approximately 35 active and dormant landslides per 1000 hectares were mapped by McKittrick (1995A) in the watershed of the North Fork of the Gualala River. This contrasts to the five landslides per 1000 hectare identified in the North Fork of the Mokelumne River (McKittrick, 1995B). The most reasonable explanation for this observed difference in landslide frequency is the contrast in geology and geologic history of the two areas.

<u>Watershed</u>	<u>N. Fork Gualala River</u>	<u>N. Fork Mokelumne River</u>
Geology	Marine sedimentary	Igneous and metamorphic
Rock strength	Moderately weak	Strong
Fracturing	Extensive	Local
Uplift rate	Rapid	Moderate
Slope	Very steep	Moderate, locally very steep
Rainfall Intensity	Very high	Moderate to high

DMG recently completed an inventory of watersheds that were intrinsically susceptible to landsliding and soil erosion (McKittrick, 1994). The DMG assessment of natural factors that contribute to mass wasting and soil erosion used a geographic information system (GIS) for susceptibility modeling. Slope, bedrock geology, and precipitation were each assigned integral values for the analysis. The limits of each value was based on literature review and discussions with scientists and resource managers working in the areas analyzed (McKittrick, 1994). Because the GIS model is theoretical and not based on back calculations from controlled watersheds, the GIS uses a simple additive algorithm to calculate relative intrinsic susceptibility for soil erosion, deep-seated landslides, and shallow-seated debris slides and debris flows.

The sum of the variables for both landsliding and debris flow activity for the Gualala River watershed is ten (10), representing Moderate to High intrinsic susceptibility for each. The sum

for the Mokelumne River watershed is six (6), which suggests a moderate to low intrinsic susceptibility. The modeled susceptibility rankings between the two watersheds is consistent with the number of mapped landslides. The modeled values are closer than what the mapping indicates they should be, probably because of the simple algorithm used in the model. Other models that better represent observed differences in landslide and erosion susceptibility could be developed. However, because the base information used for the Erodible Watershed Inventory is general, more complex algorithms could mislead the user into believing that the data support more specific analyses than warranted.

Land Use and Landsliding Incidence:

As determined by the mapping of the North and South Forks of Caspar Creek (Spittler and McKittrick, 1995), timber harvesting activities that occurred prior to the implementation of the FPA were the dominant controls on the number and locations of shallow landslides. In the watershed of the North Fork of Caspar Creek, where timber harvesting this century has followed practices specified under the current Forest Practice Rules, seven fresh appearing landslides are related to the old logging roads and eight are on natural, generally steep slopes. This contrasts with 63 of 66 active landslides in the watershed of the South Fork of Caspar Creek that are directly related to roads, landslides, and skid trails built and used between 1967 and 1973.

Timber harvesting in the monitored portion of the watershed of the North Fork of Caspar Creek was conducted using practices that are consistent with those considered Best Management Practices to reduce sediment production from timber operations (Ziemer and Cafferata, 1992). This contrasts with the harvesting practices that occurred when the watershed of the South Fork of Caspar Creek was harvested (Rice, Tilley, and Dazman, 1979). Changes in forest practices following the implementation of the FPA, particularly where related to road, landing, and skid trail design and placement, are responsible for significant reductions in landslide incidence. As observed in the monitored part of the South Fork of Caspar Creek, land use practices, specifically tractor operations on steep slopes, can obscure and overwhelm intrinsic properties for shallow landslides. In heavily impacted areas, specific small-scale geomorphic features are often compromised by past tractor operations. Where intense ground disturbance has occurred the possibility of developing detailed slope stability maps is reduced.

CONCLUSIONS

The MSG has identified several approaches for long-term hillslope monitoring, including, among other things, monitoring of “demonstration” watersheds and continuing assessment of hillslope transects to develop a statistically significant database. Mapping of geologic and geomorphic features related to landsliding by DMG as part of the hillslope component of the PMP illustrates two key points: 1) landslide activity is intrinsically controlled by the geology, geologic history, geomorphology, ground slope, and precipitation intensity and duration of an area, and 2) land use practices, specifically ground-based yarding operations, can obscure and overwhelm intrinsic

properties for shallow landslides. The most severe impacts observed in the North and South Forks of Caspar Creek occurred prior to 1973 from tractor yarding of steep slopes and tractor operations using small streams for skid trails. These observations will be useful in selecting and evaluating monitoring locations and identifying appropriate procedures for a long-term monitoring program. Specifically, the relative hazards from mass wasting and soil erosion should be used to stratify random sampling of Timber Harvesting Plans for long term hillslope monitoring

For long-term trend monitoring of in-stream parameters, the MSG suggested the establishment of demonstration watersheds that would be repeatedly surveyed. These demonstration watersheds should be selected in a variety of geologic and geomorphic settings. The watersheds should also represent varying degrees of disturbance. The Erodible Watersheds Inventory (EWI) prepared for CDF by DMG (McKittrick, 1994) will be useful in identifying the relative intrinsic failure susceptibilities for candidate demonstration watersheds. The assessment of past disturbance will be more difficult. Identifying areas where tractor operations occurred between the end of World War II and the implementation of the Rules may be key to identifying where above-background sediment yields are likely to occur and where remediations may be needed.

Where ground-based yarding has occurred, it would be helpful if a system could be developed to identify the relative severity of ground disturbance. This ground disturbance index would identify if significant cuts and fills were made across steep hillslopes, if roads and landings were built adjacent to stream channels, or if operations occurred within watercourses. The ground disturbance index would also need to identify the relative degree of recovery of both watercourse channels and hillslopes.

The data developed from transect forms for the hillslope component of the PMP were not available for DMG review. Therefore, the detailed geologic and geomorphic mapping prepared by DMG for the pilot watersheds has not yet been related to problems recorded on the hillslope transect forms by CDF foresters. To judge the need and utility for mapping at the same level as that conducted for the PMP, the results of the monitoring transects should be compared with the geologic and geomorphic features maps. The analysis should segregate data between the North Fork of the Gualala River and the North Fork of the Mokelumne River to evaluate regional geologic controls. The assessment will require several years of post-logging review because major impacts frequently occur only following significant rainfall or snow-melt events. Although the correlation may be affected by mapping problems where roads and other features are only approximately located, or the published topographic maps improperly depict site conditions, the comparison will aid in determining if detailed mapping is cost effective.

If a relationship exists between identified hillslope problems and the PMP geologic and geomorphic map, the need for similar mapping of the demonstration watersheds can be reasonably addressed. Where ground-based yarding equipment has not substantially disturbed hillslopes, and the Erodible Watershed Inventory indicates that a watershed is moderately to highly susceptible to debris flow and debris slide shallow landsliding, compilation of more

detailed geologic and geomorphic maps, similar to those prepared for the PMP and for the Watershed Mapping Project maps (Bedrossian, 1983) may be appropriate. For demonstration watersheds with only a moderate to low susceptibility to landsliding, the time required for developing detailed geologic and geomorphic maps may not be warranted. It may be possible to use a simplified approach, such as the Mass Wasting Module of the Washington Department of Natural Resources (Washington Department of Natural Resources, 1993) to define areas with relatively low slope stability. The reliability of alternative slope stability techniques would need to be evaluated by DMG prior to acceptance and use by the MSG.

Areas that were highly impacted by past tractor operations can be used as demonstration watersheds but it is important that the degree of past impacts is identified. A ground disturbance index should be developed by the MSG for use in comparing various watersheds.

Although DMG's work on the PMP was conducted to evaluate monitoring techniques, similar approaches may be beneficial for development of the watershed assessment portion of Sustained Yield Plans.

Acknowledgments: Many individuals have been helpful in the development of this study. CDF hydrologist Peter H. Cafferata managed the contract between CDF and DMG. Technical input from Mr. Cafferata has been beneficial at every stage of the project. Mapping of the watersheds of the North Fork of the Gualala River, the North Fork of the Mokelumne River, and compilation of the various sources of mapping for the South Fork of Caspar Creek was done by Mary Anne McKittrick. The work was also aided by discussions with Mark Jameson, John Munn, Norman Henry, and Fay Yee of CDF; the members of the MSG, especially Andrea Tuttle; Robert Ziemer of the U.S.D.A. Forest Service; and Trinda Bedrossian of DMG. The map for this project were drafted by Edward L. Foster of DMG. This report received excellent technical review from Peter Cafferata and John Munn of CDF and Trinda Bedrossian and David Wagner of DMG.

REFERENCES

- Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonics of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.
- Bateman, P.C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada: *in* Bailey, E.H., editor, Geology of Northern California, California Division of Mines and Geology Bulletin 190, pp. 107-172.
- Bedrossian, T.L., 1983, Watershed Mapping in Northern California: California Geology, Volume 36, Number 7, p. 140-147.

- Bortugno, E.J., and Wagner, D.L., 1980, Reconnaissance mapping of parts of the Point Arena and Ornbau Valley 15-minute quadrangles, Mendocino County, California: California Division of Mines and Geology, unpublished data, Regional Mapping files, scale 1:62,500.
- Carver, G.A., Jayko, A.S., Valentine, D.W., and Li, W.H., 1994, Coastal uplift associated with the 1992 Cape Mendocino earthquake, northern California: *Geology*, v. 22, p. 195-198.
- Davenport, C.F., 1984, Geologic and Geomorphic Features Related to Landsliding, Gualala 7.5' Quadrangle, Mendocino County, California: California Division of Mines and Geology Open-File Report 84-48 SF, scale 1:24,000.
- Dumitru, T.A., 1991, Major Quaternary uplift along the northernmost San Andreas fault, King Range, northwestern California: *Geology*, v. 19, p. 526-529.
- Georgia-Pacific Corporation, 1975, Natural Color Aerial Photograph: Flight C-GP3-93, Flown 6-6-75; Line C39-10A, Frames 17-19; Line C38-11A, Frames 21-23; nominal scale 1:16,250.
- Kilbourne, R.T., 1982, Geologic and Geomorphic Features Related to Landsliding, Glenblair NW 7.5' (NW 1/4 Comptche 15") Quadrangle, Mendocino County, California: California Division of Mines and Geology Open-File Report OFR 82-25 SF, scale 1:24,000.
- Kilbourne, R.T., 1983, Geologic and Geomorphic Features Related to Landsliding, Mendocino 7.5' Quadrangle, Mendocino County, California: California Division of Mines and Geology Open-File Report OFR 83-15 SF, scale 1:24,000.
- Kilbourne, R.T., and Mata-Sol, A.R., 1983, Geologic and Geomorphic Features Related to Landsliding, Glenblair SW 7.5' (SW 1/4 Comptche 15") Quadrangle, Mendocino County, California: California Division of Mines and Geology Open-File Report OFR 83-20 SF, scale 1:24,000.
- McLaughlin, R.J., Lajoie, K.R., Sorg, D.H., Morrison, S.D., and Wolfe, J.A., 1983, Tectonic uplift of a middle Wisconsin marine platform near the Mendocino triple junction, California: *Geology*, v. 11, p. 35-39.
- McKittrick, M.A., 1994, Erosion Potential in Private Forested Watersheds of Northern California: A GIS Model: California Department of Conservation, Division of Mines and Geology unpublished report prepared for the California Department of Forestry and Fire Protection, 70 p.

- McKittrick, M.A., 1995a, Geologic and Geomorphic Features Related to Landsliding, North Fork Gualala River, Mendocino County, California: California Department of Conservation, Division of Mines and Geology Open File Report OFR 95-05, scale 1:24,000.
- McKittrick, M.A., 1995b, Geologic and Geomorphic Features Related to Landsliding, North Fork River Mokelumne, Amador County, California: California Department of Conservation, Division of Mines and Geology Open File Report OFR 95-06, scale 1:24,000.
- Reneau, Steven, 1989, Unpublished letter communication regarding radiocarbon dates from sediment within the North Fork of Caspar Creek.
- Rice, R.M., Tilley, F.B., and Datzman, P.A., 1979, A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976: U.S.D.A. Forest Service, Pacific Southwest Forest and Range Experiment Station Research Paper PSW-146, Berkeley California, 12 p.
- Spittler, T.E., and McKittrick, M.A., 1995, Geologic and Geomorphic Features Related to Landsliding, North and South Forks of Caspar Creek, Mendocino County, California: California Department of Conservation, Division of Mines and Geology Open File Report OFR 95-08, scale 1:12,000.
- Wagner, D.L., Jennings, C.W., Bedrossian, T.L., and Bortugno, E.J., Geologic Map of the Sacramento Quadrangle: California Division of Mines and Geology Regional Geologic Map Series, Map No. 1A, scale 1:250,000.
- Washington Department of Natural Resources, 1993, Washington Forest Practices Board Manual, Standard Methodology for Conducting Watershed Analysis, Version 2 (includes Mass Wasting Module): Washington Department of Natural Resources, Olympia Washington,
- Ziemer, R.R., and Cafferata, P.H., 1992, The Caspar Creek watersheds: a case study of cumulative effects in a small coastal basin in northern California: Society of American Foresters, Proceedings of the 1991 National Conference, 4-7 August 1991, San Francisco, CA, 2 p.