Mattole River Watershed Analysis

Mass Wasting Assessment

Appendix A

Public Review Draft

September 2011

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ACRONYMS

<	less than
>	greater than
km	kilometer
mi^2	square miles
tons/mi^2/yr	tons per square mile per year
tons/mi^2:	tons per square mile
CDMG	California Division of Mines and Geology
CGS	California Geological Survey
co#	Coastal Terrane sub-unit number
CSZ	Cascadia Subduction Zone
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
GIS	Geographic Information System
HCP	Habitat Conservation Plan
LIDAR	Light Detection and Ranging
Ln	Natural Logarithm
LWD	Large Woody Debris
MMI	Modified Mercalli Index
MMU	Morphological Map Unit
MWMU	Mass Wasting Morphological Unit
n	sample number
R^2	coefficient of multiple determination
SHN	SHN Consulting Engineers & Geologists, Inc.
SOPs	Standard Operating Procedures
SRT	Signatory Review Team
WA	Watershed Analysis
y#	Yager terrane sub-unit number
ycgl	Yager terrane conglomerate unit

1.0 ABSTRACT

The Mattole watershed assessment area is a dynamic geomorphic landscape with high rates of mass wasting. The area is characterized by steep terrain and deeply incised drainages due to high regional uplift rates, high rates of seismicity, weak earth materials due to the high levels of tectonic shearing, and large amounts of seasonal rainfall. This mass wasting analysis documents over 3,400 landslides (over 2,700 delivered sediment to watercourses) and nearly 23 million cubic yards of sediment delivery during the air photo analysis period (1948 to 2003). The landslide inventory process and database analysis suggest that a large percentage of the mass wasting in the assessment area occurs as debris slides on steep inner gorge slopes. The unfortunate coincidence of a period of aggressive, first entry logging in portions of the watershed with geomorphically significant storms in 1955 and 1964 resulted in large amounts of sediment delivery during the 1965 air photo period. Although there is a higher frequency of mass wasting features near watercourses, it is apparent that there is an abundance of large and very large landslides in the assessment area that deliver significant volumes of sediment from relatively large distances from streams. Associations between land use and mass wasting are very apparent in the 1965 photo set. These associations become less significant during the later photo periods, including the 16 year "sediment budget" period between 1988 and 2003, and it is difficult to make meaningful correlations due to the relatively minor management associations derived during the landslide inventory process. Breakdown of the mass wasting characteristics of the assessment area into watershed "sub-basins" indicates relatively high amounts of sediment delivery within the Oil Creek, Rattlesnake Creek, Alwardt Creek, and Lower East Branch Mattole sub-basins. The highest rate of sediment delivery occurs in the Lower East Branch Mattole, which appears to be a function of a few relatively large slides in a small sub-basin. A streamside landslide inventory, designed to estimate the rate and amount of sediment input from small near-stream slides that are not visible in air photos suggests an additional input of over 5 million cubic yards of sediment during the sediment budget period when extrapolated over the entire assessment area.

2.0 INTRODUCTION

2.1 PURPOSE

This report presents the results of our assessment of the mass wasting characteristics associated with Humboldt Redwood Company, LLC (HRC) holdings (lands formerly owned by PALCO) within the Mattole River watershed. Mass wasting is a general term used to describe a variety of processes by which masses of earthen material are dislodged and moved downslope by gravity, either slowly or rapidly (Jackson, 1997). For the purposes of this analysis, mass wasting specifically refers to landslide processes; it does not include such processes as soil creep which are covered in the Surface Erosion Assessment (Appendix B) of this Watershed Analysis (WA). The main purposes of this analysis are to estimate landslide rates and distributions (spatial and temporal), to estimate landslide volumes for inclusion in sediment budget estimation, and to evaluate patterns and relationships between landslide occurrence and a variety of influencing factors (e.g., geology, slope, land use, etc.). Ultimately, the analysis is tailored to address a list of “Critical Questions” that have been put forth by the regulatory agencies (Signatory Review Team, or SRT).

2.2 SCOPE OF WORK

The methods used in this mass wasting assessment of the Mattole River watershed are a departure from those used in previous watershed studies on PALCO (now HRC) lands. They reflect an evolution in methodology based on a collaborative dialogue between the consultants, agency representatives, and company representatives that have completed the previous watershed studies. The methods update and improve upon the approach outlined in the *Methods to Complete Watershed Analysis on Pacific Lumber Company Lands in Northern California* (PALCO, 2000a) and *Updated Methods to Complete Watershed Analysis on Pacific Lumber Lands* (PALCO, 2002). The current methods represent an effort to standardize and streamline the mass-wasting module to provide data transparency and better tailor the products to meet the needs of the end users (i.e., the SRT and prescription writing team). The recently completed Bear River mass wasting module was the first to use this standardized approach. This mass wasting module is the second to follow the revised methodology as presented in a series of "Standard Operating Procedures" (SOPs) prepared by PALCO staff with input from consultants and agency representatives.

Previous mass wasting assessments for PALCO watershed studies have followed the guidelines presented in the earlier methods protocols cited above (PALCO, 2000b, 2002), which presented two general approaches, empirical and deterministic analyses. Because deterministic analyses based on inventory-level data are not generally accepted as standard-of-practice, they have not been included in this study. Rather, this study focuses on empirical analysis, which involves the development of landslide inventory maps based on aerial photograph interpretation and field reconnaissance, and interpretation of the trends and patterns that characterize mass wasting specific to an individual watershed. The earlier PALCO watershed manuals prescribe the development of terrain maps (showing Morphological Map Units [MMUs] or Mass Wasting Morphological Units [MWMUs]) and landslide potential maps. Because of a general lack of consensus regarding the accuracy and utility of these maps, however, they have been eliminated from the current methodology.

The work scope for this assessment includes the following:

- **Literature Compilation and Review.** There is a considerable amount of available literature for the Mattole River watershed, and available maps, reports, records, and journal manuscripts were compiled and reviewed. Pertinent to this study are recently completed mass wasting evaluations as part of the North Coast Watershed Assessment Program's analysis of the Mattole watershed (Downie et al., 2003), as well as analyses by the North Coast Regional Water Quality Control Board for determination of the Total Maximum Daily Loads for Sediment and Temperature for the Mattole River watershed (NCRWQCB, 2002).
- **Aerial Photograph Interpretation.** A landslide inventory of the WA area was conducted by stereoscopic interpretation of historical aerial photographs. Photography from 1947/48, 1954, 1965, 1987, 1997, and 2003 was interpreted following the guidelines presented in the "Standard Operating Procedure: Landslide Air Photo Interpretation for PALCO Watershed Analysis, Mass Wasting Module" (PALCO, 2005a). This methodology includes interpretation of the mass wasting feature on aerial photography, plotting of the feature on a scaled topographic base map, and recording of pertinent landslide attributes on a detailed inventory worksheet. A worksheet is filled out for each feature.

- **Geographic Information System (GIS) Data Entry.** Data from the landslide inventory were input into an Excel® database format. This database is compatible with, and ultimately imported into, PALCO's GIS database. Data attribute fields are compiled for each feature, some compiled by air photo analysts and some from PALCO's GIS database.
- **Ground Truthing.** Field reconnaissance was conducted to confirm the accuracy and validity of the air photo interpretation, to provide site-specific data on individual landslides, and to inventory streamside landslides. A fundamental goal of the field verification is to record actual landslide dimensions; these later provide the basis for estimation of air-photo documented landslide dimensions. Ground truthing was completed following the SOP, "Field Verification of Landslides for Watershed Analysis (version 2.2)" (PALCO, 2005b).
- **Streamside Landslide Inventory.** A streamside landslide inventory was conducted to identify the contribution of sediment to streams from landslides that may not be detected on aerial photographs. The streamside landslide inventory was completed in accordance with the SOP, "Reconnaissance Level Streamside Landslide and Bank Erosion Inventory for Watershed Analysis (version 2.2)" (PALCO, 2005c).
- **Data Analysis.** Landslide data were analyzed to estimate the volume of sediment delivery through time across the WA area, and to evaluate patterns of mass wasting relative to a variety of factors, including geology, slope, distance from watercourses, geomorphic associations, and land use. The data provide the basis for interpretation of the unique mass wasting characteristics of the watershed.

2.3 BACKGROUND INFORMATION

Published technical data relating to the Mattole River watershed that was used in this analysis includes:

- published literature regarding the regional geologic setting, including: Aalto and others (1995), McLaughlin and others (1994), Clarke and Carver (1992), Clarke (1992);
- results of the watershed analysis completed by the North Coast Watershed Assessment Program (Downie et al., 2003);
- documents related to calculation of the Total Maximum Daily Loads (TMDL's) for sediment and temperature for the Mattole watershed. This analysis was completed by staff with the North Coast Regional Water Quality Control Board (2002);
- geologic mapping of the region (McLaughlin and others, 2000) at a 1:137,000 scale;
- California Division of Mines and Geology (now California Geological Survey) geologic and geomorphic maps showing landforms associated with landsliding at a 1:24,000 scale;
- landslide compilation maps compiled by the SCOPAC geology department, showing landslide-related landforms identified by geologists during timber harvest plan

evaluations. Maps are at 1:1,000 scale, and are accompanied by a spreadsheet compiling available field data;

- PALCO topographic base maps at 1:1000 scale, based on a Digital Elevation Model (DEM) used in PALCO's GIS database. This map has a 40-foot contour interval. The DEMs are based on 10-meter resolution United Stated Geological Survey 1:24,000 scale topographic maps. During the investigation, we were provided with PALCO's new Light Detection and Ranging (LIDAR) mapping, which has a very high resolution and 10 foot contour interval. Due to the preliminary nature of the LIDAR mapping and its continued refinement, it was only used for field mapping and to determine slope class and other GIS functions;
- slope classes (10 percent intervals) derived from PALCO's LIDAR; and
- various PALCO GIS data layers.

2.4 CRITICAL QUESTIONS

The mass wasting assessment is intended to provide the data necessary to evaluate the distribution of unstable areas within the watershed and the relationships of those areas to various landforms, earth materials, land use practices, and other factors. Specifically, the assessment is designed to address a series of "critical questions" outlined in the *Watershed Assessment Methods for PALCO Lands, Mass Wasting* (PALCO, 2000b).

1. Which landforms or areas of the landscape are susceptible to landslides? What landslide frequencies and landslide types are associated with these landforms? How are they distributed throughout the landscape?
2. What geomorphic or geologic attributes are associated with landslides and landslide density?
3. What is the distribution and rate of natural landslides in comparison with land-use related landslides?
4. Which forest management activities are associated with landslides? What are the relationships between landslide frequency, density, and land use to the extent associations can be identified.
5. Which landslide locations (landform-landslide combinations) deliver sediment to stream channels or other waters? Which types of landslide are most likely to deliver and from what distance? To the extent varying effects can be discerned, what affect does management have on landslide delivery?
6. What is the volume of delivery of sediment by landslides to the stream system in the past 10 to 15 years of the photo record? What proportion of this sediment has resulted from road related sources, and from management activities on hillslopes? Is there any evidence that these management related landslides had higher or lower delivery rates to streams than other landslides during the period?

7. What is the sensitivity of different landforms to various land management activities in the past 10 to 15 years of the photo record?
8. Do landslides in the past 10 to 15 years of the photo record deliver Large Woody Debris (LWD) to streams? If so, where and what is the average distance of delivery?
9. What slopes and areas have experienced the highest rates of road related landslides in the past 10 to 15 years of the photo record?
10. Relative to questions 6 through 9 above, does the pattern of landsliding prior to the past 10 to 15 years following triggering events or periods of intense harvest appear to be consistent with the observations for the past 10 to 15 years? If not, how did they differ?

2.5 KEY ASSUMPTIONS

A number of assumptions are inherent to a watershed-scale mass wasting evaluation of this type. These include the following:

1. Present-day landforms represent a landscape evolving in response to geologic, climatic, and other events. Landslides will initiate naturally on some of these landforms and will contribute to the development of new landforms.
2. Aerial photographs can be used to interpret and document the history of land use and landslide activity associated with different landforms in a watershed over the duration of the photographic record. Although they often become obscured by vegetation, most landslides of significant size (dimensions typically greater than 50 to 100 feet) can be identified on aerial photographs. Documentation of the incidence and frequency of landslide events can be improved with the use of temporal air photos followed by verification in the field.
3. Patterns of past mass wasting are useful in determining areas most susceptible to future mass wasting.
4. Landslides are triggered by natural processes or events (e.g., seismic activity, rainfall). However, logging, road building, and other land use practices often contribute to increases in landslide activity.
5. It is reasonable to extrapolate interpretations (i.e., landslide distribution) from one portion of a watershed to another, as long as the physical characteristics (i.e., geology, geomorphic association, etc.) in the two regions are consistent.

3.0 GEOLOGIC CHARACTERISTICS OF THE WATERSHED

3.1 TECTONIC SETTING

Northern coastal California is characterized by a history of tectonic subduction and accretion that dates to the early Cretaceous Period (approximately 100 to 140 million years ago). The principal tectonic feature in the region is the Mendocino triple junction, the intersection of three crustal plates: the North American, Pacific, and Gorda plates. North of the Mendocino triple junction, the Gorda plate is being subducted in a northeastward direction beneath the North American plate along the Cascadia Subduction Zone. South of the triple junction, transform motion along the San Andreas fault system separates the Pacific plate from the North American Plate. Finally, the Pacific and Gorda plates are separated by the Mendocino fault, an east-west trending, high-angle, right-lateral strike-slip fault.

The location of the Mendocino triple junction is not stationary; due to the complex interaction and relative motions between the various plates, the triple junction is migrating northward. South of the triple junction, strike slip faulting associated with the San Andreas fault has only recently (in geologic terms) developed, and the fault is relatively poorly defined. Because it is essentially a transitory tectonic feature, the Mendocino triple junction is not an easily defined point in the modern landscape. Rather, it is a broad, complex zone of deformation that is likely centered near the town of Petrolia (Clarke, 1992).

The tectonic setting of the Mendocino triple junction region has resulted in extremely rapid uplift rates and a very dynamic geomorphic environment. These strong tectonic influences are manifested in the landscape as steep, rugged topography, deeply incised, high gradient streams, and high rates of mass wasting. Interpretation of uplifted late Pleistocene and Holocene age marine terraces along the coast suggest uplift rates on the order of up to nearly 4 meters per 1,000 years south of the triple junction (Merritts and others, 1992). Near the mouth of the Mattole River, the average uplift rate is estimated at nearly 3.5 meters per 1,000 years.

The leading edge of the over-riding North American plate in the Mendocino triple junction region consists of a series of accretionary wedges of the Mesozoic-Cenozoic age Franciscan

Complex (Blake and others, 1985). “Accretion” is the process by which material that has been scraped off the subducting plate is incorporated onto the overriding plate. The Franciscan Complex forms the basement rock throughout the region. Each accretionary wedge forms an elongate, highly deformed, northwest-trending belt. These belts increase in age and metamorphic grade in an inland direction. There are three principal belts within the Franciscan Complex in the region (from southwest to northeast): the Coastal, Central, and Eastern belts.

3.2 SEISMIC SETTING

3.2.1 SEISMIC SOURCES

There are numerous active seismic sources in the north coast region that are capable of generating moderate- to large-magnitude earthquakes. Historically, northwestern California has been the most seismically-active region in the continental United States. More than 60 earthquakes have produced discernable damage in the region since the mid-1800s (Dengler and others, 1992). Historic seismicity and paleoseismic studies in the area suggest there are at least 6 distinct sources of earthquakes capable of generating strong ground shaking in the region (Dengler and others, 1992):

1. faults within the Gorda Plate;
2. the Mendocino fault;
3. the Mendocino Triple Junction;
4. the northern end of the San Andreas fault;
5. faults within the North American Plate (including the Little Salmon and Mad River fault zones); and
6. the Cascadia Subduction Zone.

Most of these sources are capable of generating earthquakes with magnitudes on the order of 6.5 to 7.5. The Cascadia Subduction Zone (CSZ), however, is capable of significantly larger earthquakes that would be associated with significant regional impacts. The CSZ represents the most significant potential seismic source in the north coast region. A great subduction event may rupture along 200 kilometers (km) or more of the coast from Cape Mendocino to British

Columbia, and may be as large as magnitude 9.5. The devastating Sumatran earthquake of December 2004 is analogous to what might be anticipated during a major CSZ earthquake.

In addition to these regional sources, two poorly understood shear zones are present in the Mattole River area that present unknown levels of seismic potential. The Petrolia and Cooskie shear zones are poorly defined structural anomalies that form terrane boundaries or separate distinct structural domains (Clarke, 1992). Based on the relative landward projections of the CSZ megathrust and Mendocino fault, some researchers have suggested that they continue on-land toward the Petrolia shear zone and Cooskie shear zone, respectively. The Petrolia shear zone is mapped crossing the headwaters of McGinnis Creek (skirting the northeastern edge of the McGinnis Creek block of the study area); the Cooskie shear zone is several miles south of the study area. Should these features represent on-land extensions of these offshore plate boundary faults, they would be significant, potentially active seismic sources capable of generating large magnitude earthquakes.

3.2.2 SEISMICITY IN THE PROJECT AREA

The Mendocino triple junction is a seismically active region. Several recent earthquakes with epicenters in the greater Mattole watershed region effectively illustrate this point. The August 1991 “Honeydew” earthquake (magnitude 6.0 to 6.2) is hypothesized to have occurred along a northwest-trending, southwest-dipping blind thrust fault whose surface projection may daylight just northeast of the town of Honeydew (McPherson and Dengler, 1992). This theorized fault projection lies southeast of the Petrolia fault zone. The earthquake resulted in damage to chimneys and structure foundations, primarily within a 3 mile radius centered near the town of Honeydew. Changes in groundwater and stream flow were reportedly affected over a wide region surrounding the epicenter.

The April 25, 1992 magnitude 7.1 Cape Mendocino earthquake occurred along the southern end of the CSZ, with an epicenter near the town of Petrolia. It was followed over the next day by two magnitude 6.6 aftershocks located offshore, about 16 miles west-northwest of Petrolia. The mainshock of this earthquake sequence generated some of the highest peak accelerations ever measured (in excess of 2 g), and resulted in significant land-level changes in the epicentral region. The main shock resulted in coseismic uplift of some 16 miles of coastline (up to about 5 feet of uplift), and an associated area of coseismic subsidence directly east of the epicenter. Damage from these events was widespread in the Mattole, Bear, and Eel River valley areas, with some damage estimates approaching $70 million.

3.2.3 SEISMIC SHAKING AND ITS RELATION TO MASS WASTING

In this environment, it should be assumed that the watershed will be subject to moderate to strong ground shaking on a relatively frequent basis. Large seismic events and the associated strong ground shaking can be significant geomorphic events that may have impacts similar in magnitude to large storm events. Specifically, strong ground shaking can serve as a triggering mechanism for the initiation of landslides or the reactivation of pre-existing landslides. Recent examples of coseismic landsliding in the watershed have been documented following the 1991 Honeydew earthquake and the 1992 series of earthquakes near Petrolia. In the epicentral regions for these earthquakes, numerous examples of seismically induced landslides were documented (McPherson and Dengler, 1992; Dunklin, 1992). These earthquakes were associated with Modified Mercalli Index (MMI) intensities of VII to VIII+. Studies by Keefer (1984; 2002) show that the threshold of shaking intensity that triggers landslides is generally MMI VI to VIII; although, sometimes intensities as low as MMI IV to V can initiate sliding in particularly susceptible environments. As described above, there are numerous seismic sources in the region that can generate ground shaking sufficient to mobilize landslides.

Seismically induced landslides do not always occur coincident with the actual shaking. Ground cracks and ridge top fissures opened during shaking, and groundwater flow paths disrupted by seismic shaking, may weaken slopes such that the threshold of failure is lowered. These slopes may not fail at the time of the earthquake, but they are susceptible to failure during subsequent wet periods, sometimes several years after the actual earthquake. For example, numerous landslides occurred in the region during wet winters of 1995-96 and 1996-97. The 1995-96 rainy season was the first high precipitation period following the 1992 earthquakes, and it appears that some of the failures during this period were related to seismically weakened slopes.

3.3 GEOLOGIC UNITS

The Mattole River WA area is underlain by bedrock of the Coastal belt of the Franciscan Complex (McLaughlin and others, 2000; Plate 1). The Coastal belt is the youngest of the three belts that comprise the Franciscan Complex of accretionary rocks in northern California. The Coastal belt has been further subdivided into four tectonostratigraphic "terranes," discrete fault-bounded bodies of rock within the larger belt, which are distinguished by lithology, structure, and/or level of metamorphism. The four terranes within the Coastal belt are: the Yager, Coastal, King Range, and False Cape terranes (Aalto and others, 1995; McLaughlin and others 1997). Mapping by McLaughlin and others (2000) indicates that the WA area is underlain by bedrock associated with the Coastal and Yager terranes of the Coastal belt. As described above, Franciscan Complex bedrock comprises the basement rock in the region. These bedrock units are locally unconformably overlain by Quaternary age alluvial and colluvial deposits; although, the distribution of these materials is limited due to the steep topography and narrow, high gradient stream channels.

3.3.1 COASTAL TERRANE

The Pliocene to late Cretaceous age Coastal terrane underlies the vast majority of the WA area. This terrane has been interpreted as an accretionary complex composed of trench- and lower slope-deposits (Clarke, 1992). The unit principally consists of deep-water marine sandstone (greywacke) and argillaceous shale, with lesser amounts of interbedded, dark-gray carbonate beds, and exotic blocks of basalt, and pink to gray limestones present as well (McLaughlin and others, 2000). Although similar in lithology to the Yager terrane, Coastal terrane rocks tend to be more penetratively disrupted and altered. Calcite and laumontite veining are common in Coastal terrane rocks (McLaughlin and others, 2000). Although mélange is present in highly sheared areas within the Coastal terrane near the coast, the inland extent of the unit (i.e., within the study area) is more accurately described as a broken formation with large areas of intact folded strata interrupted by closely- to widely-spaced fractures and faults (McLaughlin and others, 2000).

The Coastal terrane has been subdivided into seven sub-units (co1 through co4, cob, cols, and com) based on the geomorphic expression and its inferred relationship to the distribution of different bedrock lithologies (McLaughlin and others, 2000). Units co1, co2, co3, co4, and cob are all present within the WA area. These units are described as follows in McLaughlin and others (2000):

- co1: Mélange. Predominantly of highly folded argillite and abundant clayey, penetratively sheared rock that exhibits rounded, lumpy, and irregular, poorly incised topography.
- co2: Mélange. Subequal amounts of shattered sandstone and argillite with much clayey, penetratively sheared rock that exhibits generally irregular topography lacking well-incised sidehill drainages.
- co3: Broken sandstone and argillite. Exhibits sharp-crested topography with a well-incised system of irregular sidehill drainages.
- co4: Intact sandstone and argillite. Exhibits sharp crested topography with a regular, well-incised system of sidehill drainages.
- cob: basaltic rocks. Pillow flows, tuffs, flow breccia, and intrusives present as rare blocks or slabs in mélange.

As can be ascertained from the descriptions above, unit co1 is the weakest of the Coastal terrane sub-units, and most susceptible to earthflow-type deformation. Unit co4, by contrast, is associated with the highest strength characteristics, and typically forms steep, resistant slopes subject to shallow, rapid debris slide type failures.

3.3.2 YAGER TERRANE

The Eocene to Paleocene (?) age Yager terrane is thought to have been deposited in an off shore channel-slope setting, or in a series of basins (McLaughlin and others, 1994). Rocks associated with the Yager terrane are generally altered to a zeolite grade, though less so than those associated with the Coastal terrane. Compositionally, the Yager terrane is made up of well-indurated, jointed, fine- to coarse-grained, marine sandstone, argillaceous shale, and large lenses of conglomerate. Sandstone and conglomerate units tend to be massive, whereas finer-grained strata tend to be well-bedded. Much of the Yager terrane consists of turbidite deposits, shelf-slope submarine slide-related sediments laid down in planar, relatively thin interbeds of sandstone and argillaceous shale. Locally, thick channelized sandstone deposits occur within the thin-bedded argillaceous sections. Yager terrane mudstones exhibit rapid weathering and a lack of vein-filling cement, in contrast with mudstones of the Coastal terrane.

The Yager terrane is sub-divided by McLaughlin and others (2000) into three sub-units based on geomorphic expression and outcrop data. Of the three units (y1, y2, and y3), only unit y1 is mapped within the study area, in limited extent at the extreme eastern end of the study area. Unit y1 is described as:

- **y1:** Sheared and highly folded mudstone. Includes minor rhythmically interbedded sandstone, locally with lenses of conglomerate. Exhibits irregular topography lacking a well-incised system of sidehill drainages.

3.3.3 QUATERNARY UNITS

Alluvial Deposits. Alluvium is found in the watershed assessment area as recent deposits along active stream channels, and as older uplifted alluvial terraces found locally throughout the watershed. Recent alluvium found in stream channels consists of loose, unconsolidated deposits of boulders, cobbles, gravels, sand, silt and clay. Older alluvial deposits consist of the same materials, but over time become weathered, resulting in the chemical and mechanical breakdown of smaller fragments, and, eventually pedogenic (soil) development. Uplifted alluvial terraces typically consist of a flat abrasion surface buried by a variable thickness of alluvium. They are mostly Holocene in age, although higher surfaces are likely Pleistocene in age. Terrace formation and preservation is limited in much of the study area due to the steep topography and narrow, v-shaped geometry of most stream valleys. As such, terrace remnants of any significant size are concentrated along the principal tributaries (Alwardt Creek, Oil Creek, McGinnis Creek, etc), and along the main stem Mattole River. A series of older uplifted terraces is mapped along the northeast side of Oil Creek (Spittler Bull Creek and Buckeye Mountain geomorphic maps, 1983 and 1984, respectively), which are highly anomalous for the study area due to their size, elevation, and lateral extent (we note that McLaughlin and others, 2000, map these surfaces as landslide deposits). Terrace remnants in smaller tributary channels are typically small, ephemeral features of limited extent.

Colluvium and Residual Soils. Colluvium and residual soils veneer most hillslopes within the watershed. Residual soils form by means of pedogenic processes as buried rock materials become exposed to the near-surface environment. Detailed description of soil types and their distribution throughout the study area are presented in the "Surface Erosion" module.

Colluvium is weathered material that has moved downslope by gravity-induced processes (creep and landsliding are the main processes). Colluvial thicknesses vary across the landscape, but in general are thin in upland areas and on ridge tops, and thicker downslope, particularly in hollows and at the toes of hillslopes. Because colluvium includes landslide deposits, it can be quite thick in areas where slide debris has accumulated. Colluvial texture is directly related to the texture of the source material. Colluvial deposits tend to be coarse-grained where source material is resistant, blocky bedrock, and fine-grained where source material is weak and/or shaly. Landslide deposits include both coherent masses that move downslope largely intact, and disaggregated masses that become fluid flows that may travel significant distances. Non-slide related colluvial materials are typically Holocene in age; slide-related colluvium may range in age from recent to tens of thousands of years old. Older slide deposits, particularly those of smaller areal extent, may be difficult to distinguish in the modern landscape.

4.0 LANDSLIDE INVENTORY

4.1 METHODS

This assessment of mass wasting in the Mattole River watershed is based on development of a landslide inventory for the past approximately 60 years. The inventory is developed through the interpretation of historic aerial photographs and field reconnaissance, and is used to identify trends and patterns in mass wasting relative to a variety of watershed factors (e.g., slope, geology, land use, etc.). The investigation follows protocols presented in a series of recently developed SOPs. Those documents include:

- Standard Operating Procedure: Landslide Air Photo Interpretation for PALCO Watershed Analysis Mass Wasting Module (PALCO, 2005a);
- Field Verification of Landslides for Watershed Analysis, v2.2: Standard Operating Procedure (PALCO, 2005b); and
- Reconnaissance Level Streamside Landslide and Bank Erosion Inventory for Watershed Analysis, v2.2: Standard Operating Procedure (PALCO, 2005c).

In general, a landslide inventory is generated through the interpretation of historical aerial photographs and field verification. Apparent associations with land use are recorded, as feasible. Landslide dimensions are measured directly for those sites visited in the field. Estimates of landslide volumes are derived for those landslides not visited in the field through a mathematical regression (based on the field-measured slide dimensions), and estimates of sediment delivery to streams are generated. A landslide database for the watershed assessment area is developed, and analysis of trends and patterns relative to spatial distribution, slope, geology, land use, etc. are completed. Because many landslides, especially smaller landslides near streams, can be difficult to observe in aerial photography due to canopy coverage and relatively small size, a streamside landslide inventory is completed. The streamside landslide inventory is intended to provide a sample of the sediment input that may be associated with mass wasting not captured during the air photo-based inventory process. Estimation of streamside landslide volumes is critical because these failures are typically associated with very high delivery potential. The estimates derived from the streamside landslide inventory sampling are extrapolated to the entire stream system. The sum of the contributions of air photo-documented landslides and the streamside inventory represent the total observed input of sediment from mass wasting in the watershed.

Below, we present abbreviated descriptions of the methods used in completing this investigation. For a more complete discussion of the methods, the reader is referred to the SOPs cited above.

4.1.1 AERIAL PHOTOGRAPH INTERPRETATION

Aerial photography from flight years 1947, 1954, 1965, 1987, 1997, and 2003 was interpreted to develop the landslide inventory. Mass wasting features were identified on the photos, and the geometry of the feature recorded on an acetate overlay. Each feature was plotted on a 1:12,000 (1 inch = 1,000 feet) base map, given a unique numerical designation, and described on a detailed data sheet. The air photo interpreted landslides are ultimately digitized into a GIS database.

Characteristics of the mass wasting features recorded on the data sheets include:

- slide type;
- activity status;
- dimensional data (surface area);
- vegetation on the slide and on adjacent slopes;
- canopy cover;
- slide morphology;
- erosional modification;
- geomorphic association (i.e., is the slide associated with an inner gorge, headwall swale, etc.?);
- stream class of affected watercourses;
- sediment delivery estimate; and
- association to various land uses (roads, harvests, etc.).

The minimum size feature mapped is typically about 100 square yards (30 feet by 30 feet) on smaller scale photographs, and as small as about 45 square yards (20 feet by 20 feet) on larger scale photographs. In addition to landslides, we also recorded prominent gullies and noted locations where early ground-based yarding resulted in skid trails along stream channels.

Concurrent with the air photo interpretation, the analyst consulted with other available data sources where available. For the Mattole River, additional data sources include CGS (formerly CDMG) maps showing geomorphic features related to landsliding, and landslide compilation maps prepared by the SCOPAC geology department based on the results of geological reconnaissance for individual timber harvest plans.

There are a number of assumptions and uncertainties inherent to an air photo based geomorphic inventory. These include:

- The ability to interpret landforms in forested terrain is limited. (For discussions on the limitations of this approach, see Robison and others, 1999; Wills and McCrink, 2002; and Ardizzone and others, 2002.) This limitation is more likely to affect one's ability to identify smaller features; large mass wasting landforms are typically visible due to the level of canopy disturbance.
- Land use associations may be difficult to observe where obvious signs of harvest, yarding (cable or tractor) or road building are not evident. Obviously, partial cuts are more difficult to interpret from aerial photography than are clear cuts.
- Estimation of the amount (percent) of sediment delivery from aerial photographs is, by nature, an approximation.
- Sediment input associated with landslides that persist on the landscape for more than one photo period can be difficult to quantify. After a pulse of sedimentation associated with the initial failure, an area of bare soil may be subject to "post-event erosion" at a lower rate, which can be difficult to estimate.
- Impacts from legacy land use effects can be difficult to interpret in air photos.

Due to the intense level of mass wasting occurring in the mid 1960s, an additional mass wasting landform category was created to account for broad areas of debris sliding that affected many steep streamside slopes. Following the intensive first-entry logging of the late 1950s to early 1960s and the 1955 and 1964 storms, broad swaths of inner gorge slope failed in association with one triggering event (an air photo example of one of these areas is shown in Figure A-1).

These features could not be adequately described as simple debris slides because they represented an aggregation of multiple smaller failures, had very large surface areas, were typically deeper than smaller, more confined debris slides, and often encompassed both the sidewalls and headwall of a tributary drainage. Rather than trying to split out a large number of debris slides within these slide complexes, we assigned these areas to a "debris slide slope" category, which greatly simplified the data collection process. These features were characteristically much wider than they were long.

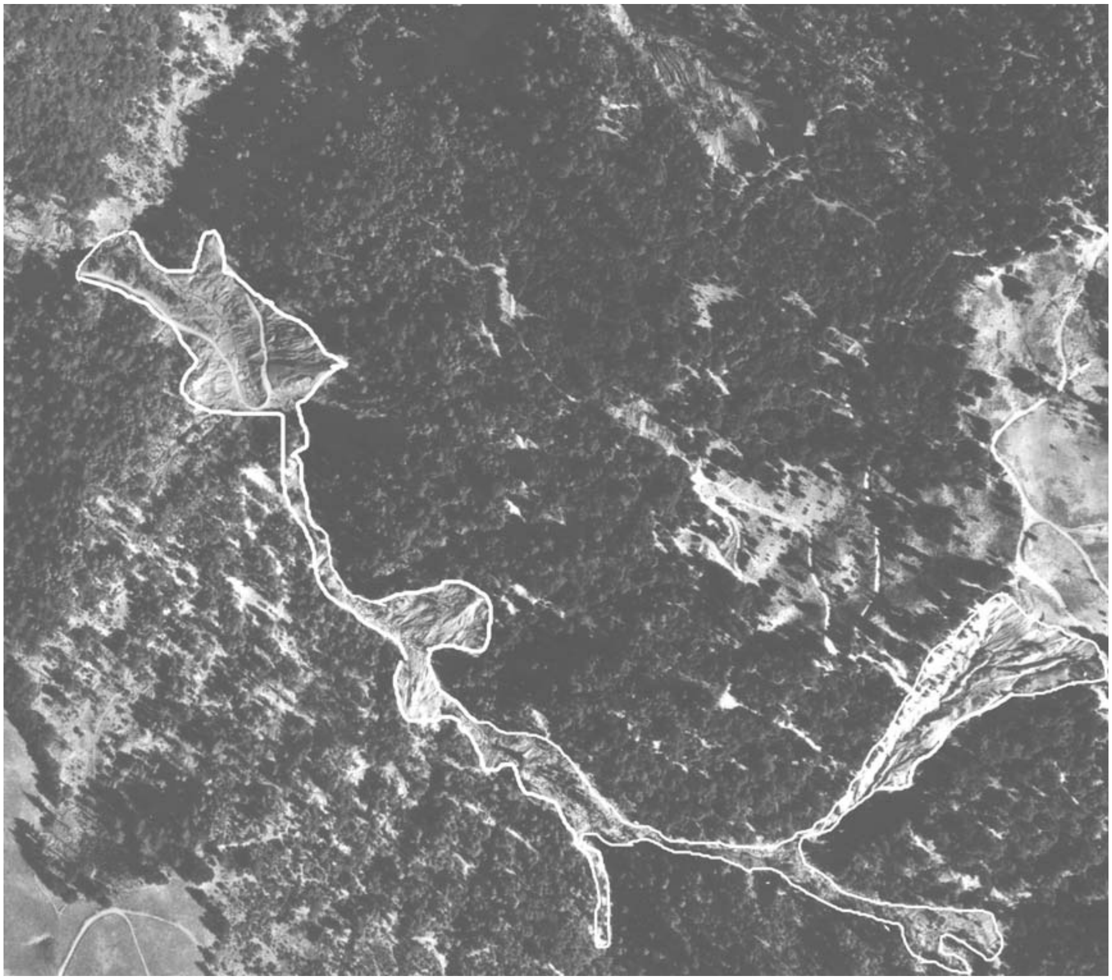


Figure A-1. 1965 Aerial Photograph Showing Extensive Debris Slide Slopes (Highlighted In White) On The Upper North Fork Mattole River

4.1.2 FIELD VERIFICATION

The purposes of the field verification phase of the analysis, as described in the PALCO SOP, include:

- identification of natural and management related site conditions leading to, or associated with, past slope instability;
- measurement of landslide dimensions and other parameters for volume estimates and comparison with parameters measured on aerial photographs or topographic maps (this

especially applies to the measurement of slide depth, which cannot be interpreted from aerial photographs);

- field verification of landslide morphology, mechanisms, and activity levels as identified on aerial photographs;
- field estimates of sediment delivery to watercourses; and
- quality control on aerial photograph analysis.

Specific field data collected includes the following:

- landslide timing;
- harvest history;
- geomorphic association;
- geology;
- mass wasting characteristics, including feature type, age/activity status, hydrologic features, and volume of sediment delivery;
- land use associations, including harvest age/history, and associations to roads, skid trails, or railroads;
- vegetation characteristics (overstory type, estimated Diameter at Breast Height [DBH], spacing); and
- landslide causal mechanisms.

All of this information is collected on field inventory data sheets, which are presented in the SOP. Field sites subject to ground truthing are prioritized based on slide size (the largest slides in the watershed should be field checked), the need to document a suitable range of slide types and sizes, accessibility, geographic distribution, and association with recent management activities.

4.1.3 STREAMSIDE LANDSLIDE INVENTORY

The purpose of the streamside landslide inventory is to complete reconnaissance of streamside landslide and bank erosion sites that are often too small or obscured to observe on aerial photographs. Identification of these sites is critical because of the high sediment delivery potential of streamside mass wasting features. Stream transects are established with the intent to sample the full range of stream classes within the watershed. Mass wasting features initiating within 200 feet of the valley floor are located and documented on a detailed inventory datasheet.

The streamside survey focuses on landslides occurring within the sediment budget period, 1988-2003. Specific field data collected during the streamside survey include:

- geology of site;
- slide type;
- age of feature (by decade);
- slope gradient;
- activity level;
- whether or not Large Woody Debris (LWD) delivery occurred;
- land use associations;
- vegetation characteristics (overstory type, estimated DBH, spacing);
- stream morphology;
- primary and secondary causes; and
- landslide and delivery volumes.

Data from the in-stream inventory are designed to document the frequency and magnitude of mass wasting sites and the amount of sediment delivery that is not detected during air photo analysis. In that regard, the streamside landslide inventory is intended to represent a sample population of mass wasting to be extrapolated to the remainder of the watershed. Those data are an important part of the sediment budgeting process. Data from field-observed streamside mass wasting features are included within the overall landslide database; the data generated by extrapolating the streamside sample, however, are not included in the landslide database due to the absence of site-specific data (e.g., geomorphic and land use associations, etc.).

4.1.4 DATA ANALYSIS

Data analysis as it applies to the mass wasting module describes the process by which the landslide inventory is developed into a database that provides the necessary platform from which to interpret mass wasting relationships within the Mattole River watershed. This analysis phase involves an iterative process wherein the landslide inventory and database were initially generated by SHN Consulting Engineers & Geologists, Inc. (SHN), additional data layers were added by the PALCO GIS department and the data set returned to SHN, and finally, relationships were interpreted by completing a series of data queries.

Each mass-wasting feature identified in the landslide inventory was given a unique identifier, and the attributes associated with the slide were entered into an Excel® database. The mass wasting features were subsequently digitized into GIS as points, lines, and polygons (depending on the size and shape of the feature), and the data attributes were attached to each individual feature. Spatial data were then added to the data set from PALCO’s GIS coverage. These data included slope class, harvest history (post 1988 availability only), geology, and sub-basins. Slope class data were generated by PALCO’s GIS using LIDAR-based topography. The slope class for individual landslides was calculated as an average value derived from 10-foot by 10-foot grid cells (each with an independent slope value) that intersect the landslide polygon that is imported to the GIS layer. Note that the slope class was derived from the undisturbed area surrounding the landslide, and therefore somewhat approximates the gradient of the native slope that existed prior to the failure. Once slope data were known, slope length corrections were calculated (converting map/photo length to slope length using the slope class data).

Sediment volumes cannot be calculated for a landslide from the data derived from the 2-dimensional air photo interpretation until a depth factor can be added. By using the field-measured slides, which include a depth estimate, a mathematical regression was developed between surface area and depth (for all but debris slide slopes, as discussed below). In order to develop a better statistical representation of a best-fit line through widely scattered plots, a series of regression equations was developed for various landslide types (shallow debris slides, translational/ rotational slides, etc.). The series of regression equations was then applied to all the air photo-interpreted slides that were not field checked to provide a depth factor, and in turn, slide volumes. These slide volumes were multiplied by the air-photo estimated delivery (% of slide volume), which was calculated as the median of each delivery category (25% intervals).

The surface area vs. depth regression approach was not used for debris slide slopes. Because these features represent broad zones of coalescing debris slides, they are not necessarily deeper when surface area increases. Therefore, use of the surface area vs. depth regression approach was found to grossly over-estimate delivery volumes for debris slide slopes. To provide a more accurate representation of depth for these features, we use the mean depth of all shallow debris slides (that is, depth = 6 feet) as a constant value when calculating landslide volume for debris slide slopes.

Sediment delivery is typically estimated relative to a series of categories that define the percentage of the total slide volume that is delivered. The percentage categories are in 25% increments (for example, 0-25% of the slide volume was delivered, 25-50%, and so on). For the data analysis phase (discussed below), the actual delivery amount is calculated using the median of each range (that is, the 0-25% category is calculated as 12.5% delivery). This approach was modified in this analysis for earthflow contributions, however, because they tend to be large, deep-seated failures that move slowly and incrementally (rather than catastrophically). An estimation of 12.5% delivery (the lowest value possible based on the methodology outlined in the SOP) for a large earthflow was found to considerably over-estimate the contribution from these features. Further, as a principal mechanism of sediment delivery from earthflows is via shallow sliding from the advancing slide toe, which is tallied independently, we must be careful not to "double-count" the contribution of these failures. The remainder of earthflow sediment delivery presumably occurs as channel narrowing ("squeezing") and subsequent bank erosion, which is not typically tallied in the air photo inventory process. We therefore establish a lower, constant value of the percentage of delivery of 1% to account for the bank erosion contribution, and assume that the majority of the sediment contribution from shallow sliding at the toe of the earthflow is captured during the air photo interpretation.

For mass wasting features that persist on the landscape as erosion areas for more than one air photo period, we developed a specific category to account for erosion that may occur on the body of the slide in the absence of renewed mass failure. This "post-event erosion" was automatically assigned a default depth of 0.5 feet, applied to the slide for each subsequent photo period on which it appears as an active erosion site.

After delivery volumes were calculated, all slides were combined into the database and queries were completed on various combinations of landslide attributes. The queries performed for the Mattole River assessment related the amount of sediment delivered by slide type, photo year, geomorphic association, geology, slope class, stream class, delivery distance, and land use. These queries were completed for the entire area and by sub-basin, and for the entire photo period (1948 to 2003) and for the sediment budget period (1988 to 2003). Delivered sediment volumes (cubic yards) were converted to mass (tons) for subsequent analysis by multiplying the volumes by a conversion factor of 1.53. This value is applied to mass wasting processes to represent an average bulk density of 1.53 tons per cubic yard (North Coast Regional Water Quality Control Board, 2002). Mass wasting processes typically deliver significant rock and subsurface soils, along with a smaller component of lower density near-surface soils, as compared with surface erosion processes involving only near-surface soils that would be represented by a lower bulk density (see Appendix B, Surface Erosion Assessment, for further discussion).

We caution the reader against comparing volume totals between individual tables. Data queries are completed by selecting certain pertinent attributes from the master data set, or by filtering out certain attributes, and these may vary between tables. For example, several of the following tables do not include the field-collected data (they contain only air photo-derived data) because of incomplete data sets, and the volume totals are smaller than those that include all data. Several tables do not include post-event erosion amounts because they do not apply to the particular analysis. Volume totals in the management-association tables are inherently smaller than those that include all landslide sources, because they only include slides with management associations.

4.2 RESULTS

4.2.1 LANDSLIDE STORY OF THE WATERSHED THROUGH THE PHOTO PERIOD

The Mattole River watershed has long been recognized as one of the least stable landscapes in the region (if not the continent), and the results of this analysis are consistent with that assessment. The watershed is a generally steep, tectonically and seismically active area underlain by weak, sheared rock; the entire area is subject to high amounts of annual rainfall, even by Humboldt County standards. Stream gradients are high throughout the study area, which occupies the upland headwaters of many tributaries along Rainbow Ridge, and the geomorphic environment is dynamic.

Topography of the study area is characterized by broad, rolling ridge tops (for example, Rainbow, Long, and Brushy ridges) that break off abruptly to deeply incised stream canyons (Plate 2). Mass wasting tends to be concentrated along streamside slopes throughout the assessment area. Inner gorges, most with high rates of mass wasting, are common along many of the principal watercourses throughout the study area. Due to the abundance of steep, streamside ground, mass wasting (and sediment delivery) estimates are dominated by inputs from debris slides. Owing to its location near the triple junction, however, the study area is more geologically and topographically diverse than neighboring watersheds (e.g., the Bear or Eel river watersheds). This diversity is reflected in the wide range of mass wasting styles observed. Large areas of prairie ground are present within the assessment area, for example, much of which can be considered marginal earthflow terrain. Deep-seated rotational slides were more frequent in this investigation than in the recently completed analysis of the Bear River. Also, large numbers of very large, deep-seated relict landslides can be inferred across much of the study area, as illustrated on the 2003 NCWAP map for the area (Downie et al., 2003).

The geomorphic history of the Mattole River watershed during the post-1947 period is dominated by the unfortunate coincidence of a period of aggressive, first-entry logging and the large storm events of 1955 and 1964. Air photos from 1965 show the managed portions of the watershed in an extremely degraded condition with high concentrations of mass wasting features and excessive amounts of sediment entering virtually every watercourse. Early logging in the watershed included a considerable amount of ground-based yarding, even on the steepest streamside slopes, and in many cases along stream channels. As a result, the effects of the 1955 and 1964 storms were severe along the abundant inner gorge slopes in the Mattole River watershed where vegetation removal and/or ground disturbance had occurred. Large swaths of debris slide slopes activated along the steep streamside slopes throughout managed portions of the watershed. From a mass wasting perspective, the watershed has been in a state of recovery since 1964; a process that, in many places, appears to be still on-going. Many of the larger currently active slides have persisted on the landscape since 1964.

4.2.2 LANDSLIDE VOLUME CALCULATIONS

Because the interpretation of landslide geometry based on aerial photography can yield only an estimate of the landslide's surface area, an estimate of the slide depth must be generated before volume calculations can be completed. The estimate of slide depth is extrapolated to all landslides not directly observed in the field using a mathematical regression based on the dimensions of landslides observed in the field (surface area versus depth). The surface area versus depth regression using all landslide types resulted in a plot with very wide scatter. As such, we attempted to refine the estimate by creating regression equations for individual slide types. The relationships between surface area and depth for various slide types with the best fits are as follows:

- Debris slides/flows (n = 100)
  Depth = $(0.2468)\text{Area}^{0.3549}$ ($R^2 = 0.2867$)

- Earthflows/Trans-Rotational slides (n = 12)

  Depth = $3.3945\text{Ln(Area)} - 20.847$ ($R^2 = 0.6205$)

  Where: n = sample number

Ln = natural logarithm

R^2 = coefficient of multiple determination

4.2.3 GENERAL LANDSLIDE DATA FROM AIR PHOTO INVENTORY AND FIELD VERIFICATION

For the entire air photograph period (1948 through 2003), 3,441 landslides were identified in the Mattole River watershed analysis area (Table A-1; Plate 3). Over 2,700 of those landslides delivered sediment to streams, not counting streamside landslides (discussed in Section 4.1.3 and 4.2.7). These totals consist of the number of recently active slides interpreted for each photo year, and therefore re-count recurrent features that are active over more than one photo period. Nearly 23,000,000 cubic yards of sediment is estimated to have been delivered to streams, which suggests a landslide delivery rate of over 22,500 tons per square mile per year when averaged over the 55-year air photo period. Mass wasting rates are not consistent between photo periods, however, and the average rate is skewed because it includes the 1965 period of very heavy mass wasting. Therefore, the average delivery rate of 22,500 tons/mi^2/year through the study period over-estimates the typical annual rate. The more recent 16-year “sediment budget” period (1988 to 2003), which included the earthquakes of 1991 and 1992 and two significant storm events, produced an average delivery rate of just over 7,300 tons/mi^2/year.

These cumulative totals and delivery rates are significantly larger relative to other watersheds previously analyzed for PALCO mass wasting studies, the exception being the adjacent Bear River watershed. This result is consistent with previous studies that have attempted to inventory landslides (Downie et al., 2003; NCRWQCB, 2002), and our qualitative impression of the high degree of landsliding in this watershed.

Table A-1. Frequency of Landslides in Project Area by Slide Type, Entire Photo Period

Slides	Number of Slides	Number with Sediment Delivery	Sediment Delivered (cubic yards)	Percent of Sediment Delivered	Unit Sediment Delivered (tons per square mile)	Landslide Delivery Rate (tons per square mile per year)
Debris Flow	61	47	155,504	1%	8,466	154
Debris Slide	2,922	2,238	15,645,472	69%	851,807	15,487
Debris Slide Slope	414	395	6,140,170	27%	334,297	6,078
Debris Torrent	3	1	20	<1%	1	0.02
Earth Flow	26	17	139,809	1%	7,612	138
Pure Translational	2	2	80,325	<1%	4,373	80
Translational/ Rotational	13	10	559,672	2%	30,471	554
Totals:	**3,441**	**2,710**	**22,720,973**	**100%**	**1,237,027**	**22,491**

4.2.3.1 LANDSLIDE TYPES

Debris-type landslides make up the vast majority of the mass wasting features identified (Table A-1). Debris slides and debris slide slopes comprise as much as 96% of the interpreted landslides in the study area. Sediment delivery is equally dominated by the contribution of debris type landslides, which represent nearly 96% of the material delivered to watercourses.

The preponderance of debris type landslides in the Mattole River watershed appears to be a function of the geologic and geomorphic conditions within the study area. The combination of steep terrain, frequent earthquakes, weak earth materials, and high levels of rainfall results in a landscape dominated by relatively shallow, rapid moving failures. Aggressive first-entry logging using ground-based yarding left many of these steep streamside slopes in a vulnerable condition that resulted in extreme rates of mass wasting when the large storms of 1955 and 1964 occurred.

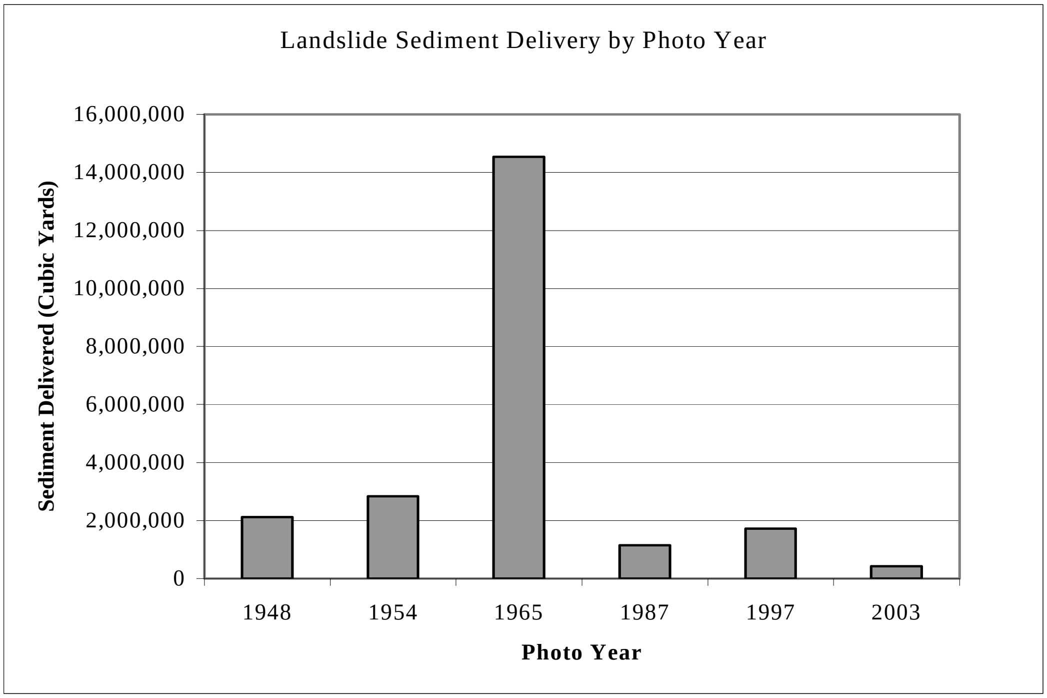
4.2.3.2 LANDSLIDES BY AERIAL PHOTOGRAPH TIME PERIOD

Mass wasting in the Mattole River watershed assessment area during the aerial photograph period (1948 to 2003) is dominated by the huge influx of sediment during the 1965 photo period (Table A-2; Figure A-2, Plate 3).

Table A-2. Landslides in Project Area by Time Period

Photo Year	Number of Slides	Number of Delivering Slides	Sediment Delivered (cubic yards)	Percent of Sediment Delivered	Unit Sediment Delivered (tons per square mile)
1948	101	67	2,058,719	9%	112,085
1954	133	104	2,833,961	12%	154,293
1965	796	632	14,539,882	64%	791,613
1987	861	730	1,150,378	5%	62,631
1997	998	749	1,715,708	8%	93,411
2003	552	428	422,325	2%	22,993
Totals:	**3,441**	**2,710**	**22,720,973**	**100%**	**1,237,027**

Figure A-2. Landslide Sediment Delivery by Photo Year



More than 14.5 million cubic yards of sediment were delivered to streams in 1965 alone, representing 64% of the total sediment delivery. Converting this volume to a unit weight (tons) relative to area suggests delivery of nearly 800,000 tons per square mile for the 1965 photo period. Including the nearly 5 million cubic yards of sediment delivered in the 1948 and 1954 photo periods results in an additional 21% of the total delivery, for a total of 85% in these three early photo periods alone.

Photo periods subsequent to 1965 (1987/1988, 1997, and 2003) show reduced levels of mass wasting, suggesting long-term recovery following the extreme condition in 1965 and a subsequent improvement in land use practices. A relative increase in the sediment delivery in 1997 is inferred to be a result of seismically-induced landsliding associated with the 1992 Cape Mendocino earthquakes. We estimated slightly more than 400,000 cubic yards of sediment delivery for the 1998 to 2003 photo period (managed under the HCP), or just under 23,000 tons per square mile.

Intuitively, mass wasting should be lowest in the earliest photo period (1948), prior to the inception of logging and ground disturbance in the watershed. The data set developed in this study, however, appears to indicate slightly higher rates relative to some later photo periods (for example, 2003). We interpret this result as related to potential differences in storm histories between the two periods, as well as inconsistencies in the mapping of large landslides and the sensitivity of the analysis to inputs from these large slides. The air photo interpreter’s ability to see large landslides is especially sensitive to air photo quality, scale, the sun angle at the time the photo was taken, recent land use, and vegetation conditions that may obscure geomorphic features. The 2003 photo set in particular was subject to limitations relative to photo scale and quality. This interpretation is supported by the analysis below in Section 3.2.3.8 (see Table A-12), which shows a relatively low contribution from large and very large landslides in the 2003 photo set.

4.2.3.3 LANDSLIDE BY GEOMORPHIC ASSOCIATION

Due to the topographic character of the Mattole River watershed (steep, deeply incised stream canyons), mass wasting is dominated by landsliding on inner gorge slopes (Tables A-3 and A-4, Figure A-3, Plate 4).

Table A-3. Landslide Frequency in Project Area by Geomorphic Association

Year	Inner gorge		Headwall Swale	Continuous	Ridge	Encompassing	Break In Slope	Stream Channel	Stream Channel	Stream Channel
	slopes >65%	slopes < 65%							Inner Gorge	Headwall Sale
1948	--	4	12	44	--	5	2	N/A	N/A	N/A
1954	56	23	7	17	--	--	1	N/A	N/A	N/A
1965	332	201	42	53	2	2	--	N/A	N/A	N/A
1987	431	203	28	65	--	2	1	N/A	N/A	N/A
1997	476	187	10	21	0	0	0	21	5	29
2003	265	105	4	17	-0	0	0	17	10	10
Totals:	**1,560**	**723**	**103**	**217**	**2**	**9**	**4**	**38**	**15**	**39**

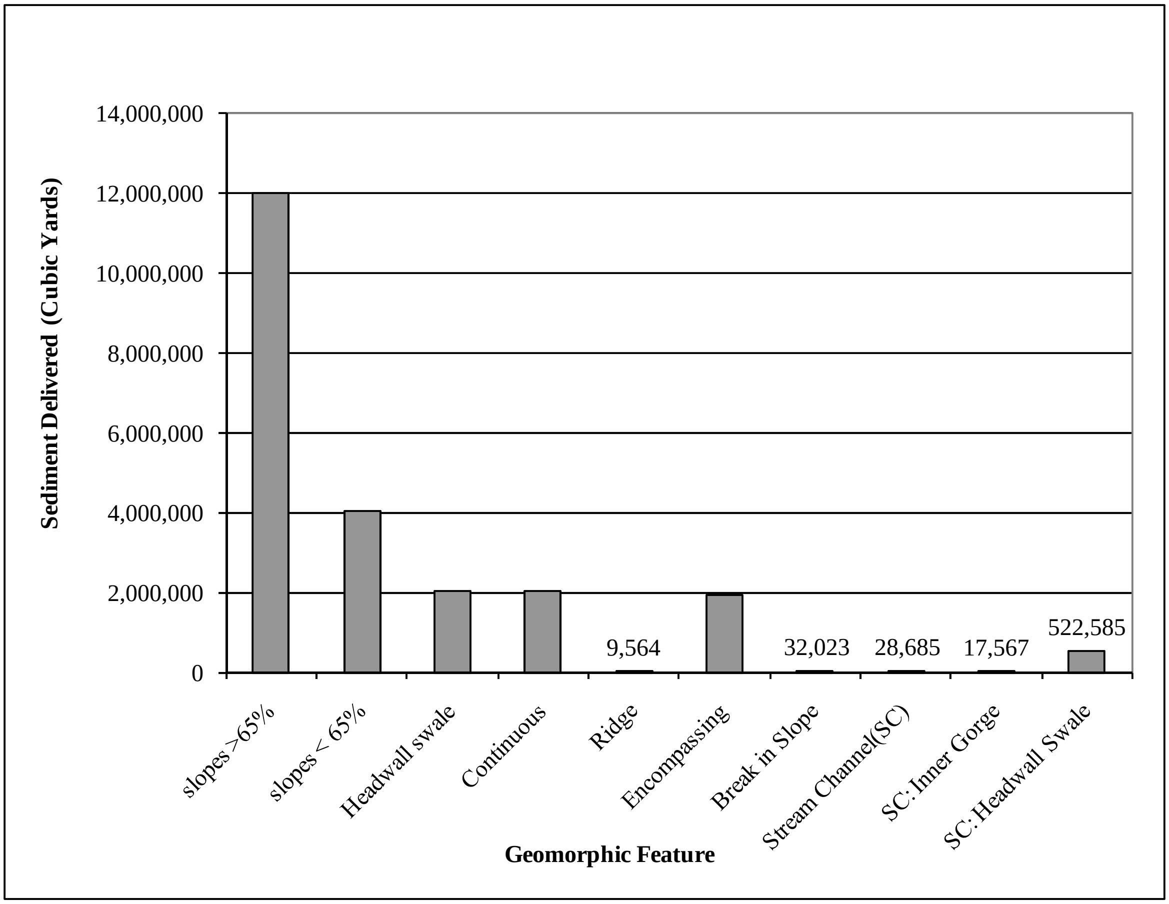
Table A-4. Landslide Delivery (cubic yards) in Project Area by Geomorphic Association

Year	Inner gorge		Headwall swale	Continuous	Ridge	Encompassing	Break In Slope	Stream Channel	Stream Channel	Stream Channel
	slopes >65%	slopes < 65%							Inner Gorge	Headwall Sale
1948	0	321,191	430,695	659,366	0	618,806	28,662	N/A	N/A	N/A
1954	1,596,741	399,163	28,408	806,297	0	0	3,352	N/A	N/A	N/A
1965	8,814,692	2,513,782	1,565,702	324,335	9,564	1,311,806	0	N/A	N/A	N/A
1987	741,197	239,782	31,760	130,487	0	7,145	8	N/A	N/A	N/A
1997	662,659	505,600	11,440	16,067	0	0	0	17,524	8,836	493,582
2003	191,809	55,951	33	125,638	0	0	0	11,161	8,731	29,002
Totals:	**12,007,098**	**4,035,468**	**2,068,037**	**2,062,189**	**9,564**	**1,937,757**	**32,023**	**28,685**	**17,567**	**522,585**

Tables A-3 and A-4 show the frequency (number) and sediment delivery associated with various geomorphic landforms, respectively. “Inner gorge” slopes are broken down on the tables based on slope gradient (steeper than 65% and less than 65% gradient), based on correlations derived from PALCO’s GIS database. These data are somewhat confusing because some definitions of “inner gorge” require slope gradient in excess of 65%. The air photo analyst, however, had no access to slope data during the inventory process, and based the interpretation solely on geomorphic character.

Inner gorge landslides on slopes steeper than 65% are the most common (n=1,560) and generate the most sediment delivery (over 12,000,000 cubic yards). Inner gorge failures on GIS slopes less than 65% represent over 4,000,000 cubic yards of sediment.

Figure A-3. Landslide Sediment Delivery by Geomorphic Association



The temporal pattern of inner gorge landsliding in the assessment area is consistent with the general pattern discussed above, that is, there is a high concentration of mass wasting during the 1965 photo period. In portions of the Mattole River watershed (Rattlesnake and Oil Creek sub-basins), early logging frequently involved ground-based yarding operations and clear-cutting on steep streamside slopes. These early practices left these portions of the watershed in a vulnerable condition, and the slopes responded in a predictable fashion during the high rainfall events in 1955 and 1964. Large swaths of inner gorge slope were subject to debris sliding during the 1965 photo period. Over 11,000,000 cubic yards or more of sediment were derived from inner gorge sliding during this period alone.

Inner gorge landsliding is relatively minor as recorded on the 1948 photo set. Note that only four inner gorge failures were identified on the 1948 photographs. This result is likely a function of the dense canopy cover on these slopes during the pre-logged period, and the inability to view inner gorge conditions under dense canopy on aerial photography.

4.2.3.4 LANDSLIDES BY LITHOLOGIC UNIT

Geology of the watershed assessment area is dominated by bedrock of the Coastal terrane subunit of the Coastal belt of the Franciscan Complex. Because Coastal terrane bedrock underlies about 97% of the study area, there is a high coincidence of landslides occurring on Coastal terrane bedrock (Table A-5).

Table A-5. Landslides in Project Area by Lithologic Unit

Lithologic Unit	Square Miles	Number of Slides	Number of Slides Delivering Sediment	Sediment Delivered (cubic yards)	Percent of Sediment Delivered	Unit Sediment Delivered (tons per square mile)	Landslide Delivery Rate (tons per square mile per year)
Alluvium	0.15	103	99	1,248,821	5%	12,910,109	234,729
Terrace Deposit	0.36	26	22	328,682	1%	1,385,354	25,188
Yager Terrane	0.39	45	39	65,816	<1%	256,517	4,664
Franciscan Coastal Terrane	27.20	3,265	2,548	21,077,266	93%	1,185,683	21,558
Franciscan Coastal Belt Greenstone	0.00	2	2	388	<1%	593,201	10,785
Totals:	**28.10**	**3,441**	**2,710**	**22,720,973**	**100%**	**1,237,008**	**22,491**

Over 21 million cubic yards, or 93% of the total sediment delivery, occurred on Coastal terrane bedrock. This result is not surprising. High sediment inputs are also associated with areas underlain by alluvium and terrace deposits, however, which is not consistent with our observations in the field. This result is likely a function of mapping resolution and the limitations of GIS interpretation, as we did not observe any landslides originating in alluvium in the field. The geologic map base is small-scale relative to the scale of the base map and air photos from which the landslides are interpreted (and the maps tend to over-represent alluvial extent based on our field observations); therefore, slides originating in bedrock on near-stream slopes may register as occurring within alluvium or terraces when queried in the GIS. Therefore, we infer that virtually all of the sediment shown in Table A-5 as originating in Quaternary materials is attributable to Coastal terrane bedrock failures.

Table A-6 shows the total amounts of sediment delivery from near-stream failures interpreted in aerial photographs as occurring on “inner gorge slopes” relative to slope class (gradient greater than 65% and gradient less than 65%, based on LIDAR data) and lithology, in the assessment area, for the 1988-2003 period.

Table A-6. Near-stream Landslides by Slope & Lithology, 1988 to 2003

Sediment Delivered, Tons/Sq. Mile				
Lithology	**Slopes >65%**		**Slopes <65%**	
	1997	**2003**	**1997**	**2003**
Alluvium	358,283	12,605	156,612	146,275
Terrace Deposit	45,158	20	53,285	60
Yager Terrane	2,076	0	29,608	25,948
Franciscan Coastal Terrane	49,057	13,301	42,883	9,216
Franciscan Coastal Belt Shear Zone	61,441	0	0	0
Totals:	**49,980**	**12,940**	**43,429**	**10,053**

This analysis is not particularly informative for the Mattole assessment area due to the uniform distribution of Coastal terrane bedrock. As described above, even sediment contributions shown from Quaternary deposits are likely actually derived from Coastal terrane bedrock adjacent to streams.

4.2.3.5 LANDSLIDE BY SLOPE CLASS

Landslide frequency and magnitude was evaluated relative to slope steepness. Four slope classes (up to 30%, 31 to 50%, 51% to 65%, and greater than 65%) were generated using PALCO’s LIDAR-based digital elevation model (10-foot resolution).

As expected, there is a strong correlation in the Mattole River watershed between landslide frequency and magnitude relative to increased slope steepness (Table A-7, Figure A-4). Both the number of landslides and the amount of sediment delivery increase with slope. By far, the highest number of landslides and the largest amount of sediment originate on slopes with gradients in excess of 65%. These slides represent 67% of the total number of sediment-delivering landslides and 72% of the sediment delivery. Slides originating on slopes between 50% and 65% represent only 24% of the sediment delivery in the assessment area.

Table A-7. Landslides in Project Area by Slope Class, Entire Photo Period

Slope Class %	Area of Slope Class (square miles)	Number of Slides	Number of Delivering Slides	Percent of Delivering Slides	Sediment Delivered (cubic yards)	Percent of Sediment Delivered	Delivery per unit area (tons/sq mi)
<30	2.8	99	74	3%	42,067	<1%	22,987
30–50	8.0	361	241	9%	954,884	4%	182,622
50–65	7.4	772	590	22%	5,406,722	24%	1,117,876
>65	10.0	2,209	1,805	67%	16,317,300	72%	2,496,547
Totals:	**28.1**	**3,441**	**2,710**	**100%**	**22,720,973**	**100%**	**1,232,734**

4.2.3.6 LANDSLIDE SEDIMENT DELIVERY BY STREAM CLASS

There are 271 miles of mapped streams on HRC (formerly PALCO) ownership in the Mattole River watershed assessment area. By length, 50% of these streams are Class IIIs, 36% are Class IIs, and 14% are Class I watercourses. Stream class designations are developed by PALCO fisheries biologists and foresters, and are recorded in the GIS database.

Despite the high percentage of Class III streams in the assessment area, sediment delivery is concentrated along Class I and II watercourses (Table A-8, Figure A-5).

Figure A-4. Landslide Sediment Delivery by Slope Class

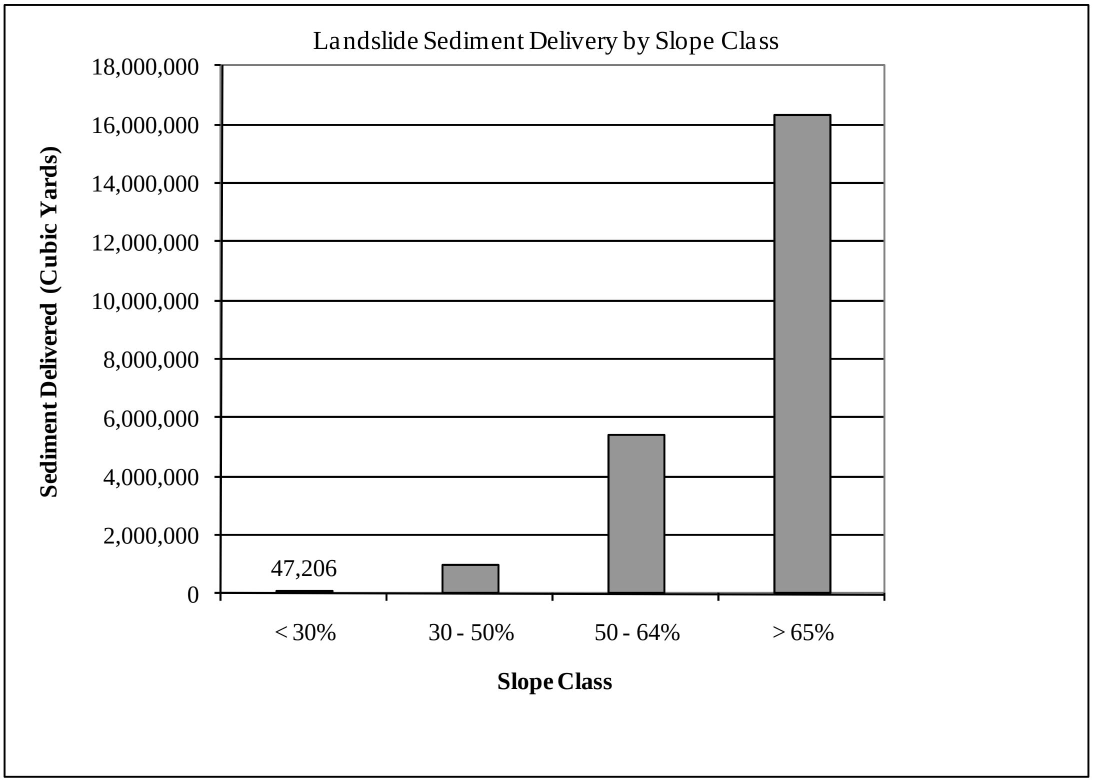
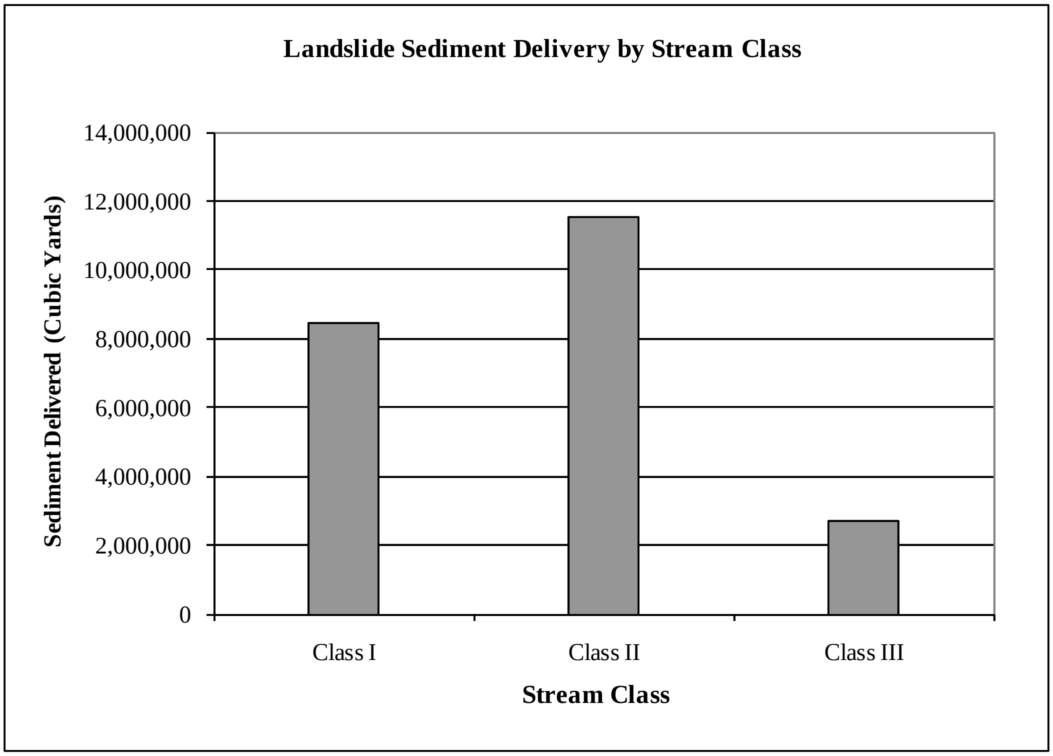


Table A-8. Landslide Sediment Delivery by Stream Class, Entire Photo Period

Stream Class	Length of Stream (miles)	Number of Slides	Number of Delivering Slides	Percent of Delivering Slides	Sediment Delivered (cubic yards)	Percent of Sediment Delivered	Unit Sediment Delivered (tons per mile)	Landslide Delivery Rate (tons/ per mile per year)
I	37.45	1,224	1,011	37%	8,440,664	37%	344,839	6,270
II	97.04	1,368	1,114	41%	11,551,847	51%	182,134	3,312
III	136.55	837	585	22%	2,728,462	12%	30,572	556
Totals:	**271.04**	**3,427**	**2,710**	**100%**	**22,720,973**	**100%**	**128,258**	**2,332**

Figure A-5. Landslide Sediment Delivery by Stream Class



Although Class I streams represent only 14% of the total stream length, landslides delivering to Class I streams represent 37% of the delivering landslides and 37% of the sediment delivery. Landslides along Class II streams account for 51% of the sediment delivery, while slides along Class III streams represent only 12%. The landslide delivery rate for Class III streams is only 556 tons per mile per year, relative to a rate of over 6,000 tons per square mile per year for Class I streams.

The abundance of landslides and sediment delivery to Class I and II streams appears to be a function of the frequency of steep streamside slopes along these principal waterways and active channel erosion at the base of these slopes caused by greater hydrologic power. Class III streams in the assessment area, on the other hand, are located in upland settings where slope gradients are gentler, stream incision is less pronounced, and steep streamside slopes are not as prevalent.

4.2.3.7 LANDSLIDES BY PROXIMITY TO WATERCOURSES

The proximity of landslide initiation to the adjacent watercourse within the assessment area was derived by measuring the distance from the crown (top) of the slide to the stream. Tables A-9 and A-10 show this watercourse proximity based on a series of distance classes, for the entire photo period and for the 1988 to 2003 period, respectively.

Table A-9. Landslides in Project Area by Distance to Stream, Entire Photo Period

Distance to Watercourse (feet)	**Number of slides**	**Number of delivering slides**	**Percent of delivering slides**	**Sediment Delivered (cubic yards)**	**Percent of Sediment Delivered (%)**	**Sediment Delivered (tons/sq mi/yr)**
< 100	906	864	38%	1,045,610	5%	1,035
100-200	804	698	31%	2,153,168	10%	2,132
201-300	408	311	14%	2,107,465	10%	2,086
301-400	228	141	6%	1,389,878	7%	1,376
401-1,000	357	188	8%	5,745,267	28%	5,688
>1,000	145	59	3%	8,255,410	40%	8,173
Totals:	**2,848**	**2,261**	**100%**	**20,696,798**	**100%**	**20,489**

Table A-10. Landslides in Project Area by Distance to Stream, 1988 to 2003

Distance to Watercourse (feet)	Number of slides	Number of delivering slides	Percent of delivering slides	Sediment Delivered (cubic yards)	Percent of Sediment Delivered (%)	Sediment Delivered (tons/sq mi/yr)
< 100	628	592	54%	705,726	34%	2,402
100-200	381	297	27%	321,659	15%	1,095
201-300	182	108	10%	300,793	14%	1,024
301-400	117	58	5%	180,802	9%	615
401-1,000	126	41	4%	452,964	22%	1,541
>1,000	13	5	<1%	124,016	6%	422
Totals:	**1,447**	**1,101**	**100%**	**2,085,960**	**100%**	**7,099**

Over the entire photo period, the greatest number of slides was observed within 100 feet of streams, and the number of slides generally decreases with increasing separation from watercourses. The greatest volume of sediment (just over 14 million cubic yards) was derived from slides originating over 400 feet from the adjacent watercourses. This result partially reflects the greater land area within the 401- to 1,000-foot distance class relative to that within 400 feet of watercourses. By normalizing the sediment delivery of the 401- to 1,000-foot distance class, for example, to the delivery from the 0- to 400-foot distance class (multiplying the delivery from the 401- to 1,000-foot distance class by a factor of 2/3), the sediment delivery for the two slope classes can be directly compared. Using this normalization method, the delivery for the 401- to 1,000-foot distance class is 57% of the sediment delivery of the 0- to 400-foot distance class. (This exercise is not possible for the greater than 1,000-foot band because of its unconstrained width.)

The numerous near-stream slides (distance to watercourse less than 100 feet) are relatively small failures that deliver relatively minor amounts of sediment (38% of the delivering slides contribute only 5% of the sediment). As would be expected, this result becomes inverted for areas farther from the watercourse, due to the preponderance of large and very large landslides that originate in upland areas. For the >1,000 foot distance class, 3% of the delivering landslides produce 40% of the sediment.

In order to filter the effects of the early photo periods, the proximity of landslide initiation to watercourses was evaluated for the 1988 to 2003 photo period (Table A-10). Again, the number of slides generally decreases as the watercourse distance increases. Sediment delivery was highest within 400 feet of watercourses, accounting for 72% of the estimated delivery. The normalized sediment delivery volume of the 401- to 1,000-foot band is 20% the cumulative delivery volume of the 0- to 400-foot band. The sediment delivery rate decreases at distances greater than 1000 feet.

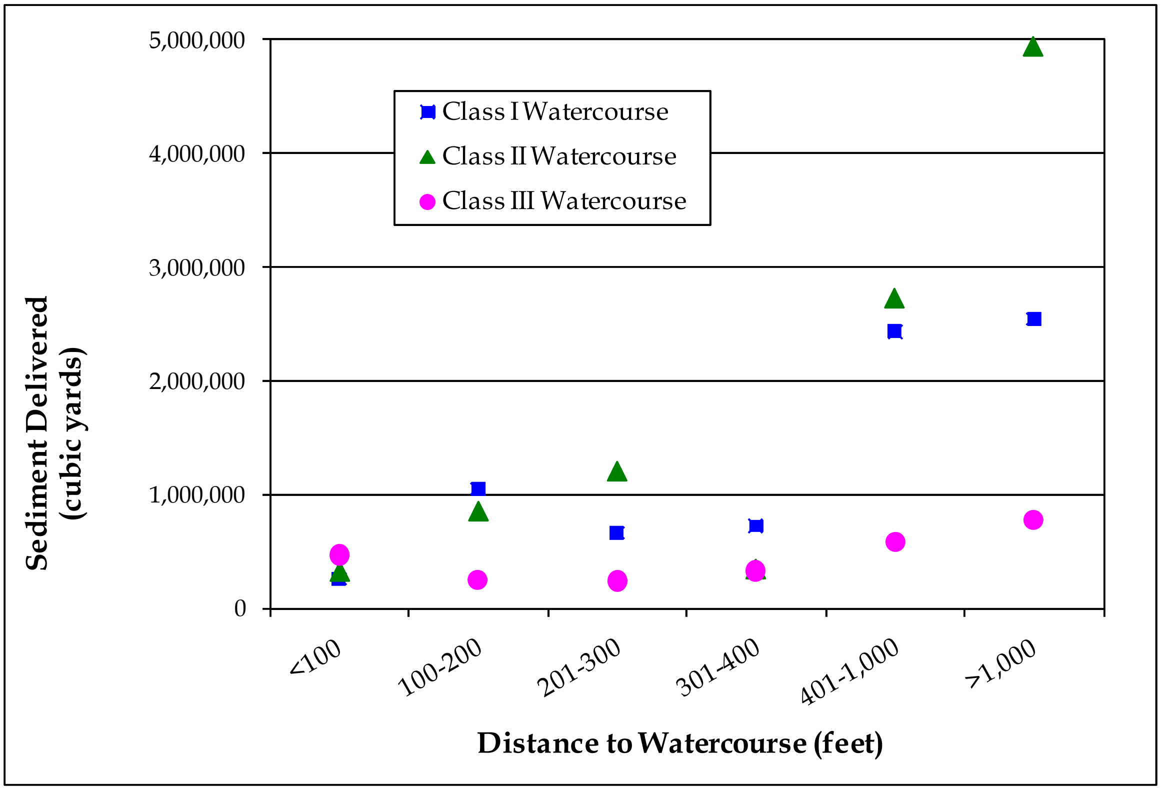
Table A-11 depicts the relationship between landslide initiation distance and slope class. This analysis shows, not surprisingly, that increased sediment delivery occurs from landslides on steeper slopes. All the distance class categories are associated with increased sediment delivery as slope steepness increases (until reaching the >65% class associated with slides over 400 feet from a watercourse, of which there are relatively few). Of note, landslides initiating on slopes greater than 400 feet from streams have a much higher potential to deliver sediment where slope gradient exceeds 51%. All distance classes within 400 feet of a watercourse are associated with greatly increased delivery potential when slopes exceed 65% in steepness.

Table A-11. Matrix Table of Landslide Delivery by Slope Class & Distance to Stream, 1988 to 2003

Distance to Watercourse (feet)	Slopes <30% (cubic yards)	Slopes 31–50% (cubic yards)	Slopes 51–65% (cubic yards)	Slopes >65% (cubic yards)
< 100	4,792	14,036	323,274	363,624
100–200	4,146	9,495	52,652	255,367
201–300	0	5,897	59,653	235,242
301-400	0	7,580	22,615	150,607
401–1,000	0	0	334,430	118,534
>1,000	0	0	113,031	10,985
Totals:	**8,938**	**37,009**	**905,657**	**1,134,357**

Figure A-6 presents sediment delivery by distance to watercourse and stream class, for the entire photo period.

Figure A-6. Sediment Delivery by Distance to Watercourse and Stream Class, Entire Photo Period



4.2.3.8 CONTRIBUTIONS FROM LARGE LANDSLIDES

Because relatively few large landslides can contribute significant percentages of total sediment input, we analyzed the inputs from large (3,000 to 5,000 cubic yards) and very large (greater than 5,000 cubic yards) landslides (Table A-12).

Table A-12. Large & Very Large Landslides in the Project Area

Air Photo Year	Large Landslides		Very Large Landslides		% Delivery From Large and Very Large
	Number	Delivery (cubic yards)	Number	Delivery (cubic yards)	
1948	7	25,185	23	2,011,368	99%
1954	17	64,758	50	2,717,511	98%
1965	43	171,728	175	8,373,318	59%
1987	17	65,780	24	660,053	63%
1997	22	81,988	48	1,199,546	75%
2003	6	25,926	11	282,631	73%
Totals:	**112**	**435,365**	**331**	**15,244,427**	**69%**

We excluded areas mapped primarily in 1965 as “debris slide slopes,” because these are typically debris slide complexes consisting of many shallow landslides that were impossible to distinguish or record as individual features. The intent here is to analyze large, deep-seated landslides.

A large percentage (69%) of the total sediment delivery over the entire photo period is from large and very large landslides. The results indicate that the number of large and very large landslides in the assessment area dramatically increased coincident with impacts of pre-Forest Practice Rules management and the December 1964 storm (23 very large landslides were interpreted in 1948, 50 in 1954, and 175 in 1965). Contributions from the large and very large landslides are greatest relative to smaller landslides in the early photo periods (99% of sediment delivery in 1948; 98% in 1954), presumably because the intact old growth canopy obscured observation and documentation of many small landslides.

Some variation in the number of large and very large landslides interpreted in the different photo periods is a function of the air photo analyst’s ability to discern subtle landscape-scale features. The expression of these large features may be subject to variations in canopy conditions (it is harder to see subtle flow-type failures under heavy canopy), photo scale, sun angle, or quality during particular flight years, or the type and intensity of land use (especially ground-based activity).

Very large landslides are generally associated with weak bedrock related to such conditions as stratigraphic discontinuities, shear zones, or deep weathering. As discussed in Section 2.2.1, seismic shaking may weaken bedrock directly or by affecting deep groundwater hydrology. Table A-12 shows a nearly two-fold increase in delivery from very large landslides between the 1987 and 1997 photo periods that is disproportionate to the smaller increases in delivery from landslides in smaller size categories during the same period.

4.2.4 MASS WASTING RELATIVE TO LAND USE IMPACTS

Landslides that are spatially associated with visible management are recorded during the aerial photograph interpretation and field verification phases. Management practices of interest include road building and the relevant aspects of timber harvest (silviculture and yarding method).

Roads that are visible on or near landslides are conservatively assumed to be contributing to the failure process, and a management "association" is recorded. Landslides that are within or very near a visible harvest unit are recorded as "harvest-associated."

It is important to note that management "associations" do not imply a causal relationship. Determination of landslide causes from aerial photographic interpretation is tenuous at best; even field-based determinations can be problematic due to the variety of influences at work in any mass wasting process.

Below, analyses are presented that explore the associations between landsliding and timber harvest (yarding method and silviculture), and general comparisons of road-related management, non road-related management, and natural landsliding. Because of the significant evolution of management practices during the analysis period, individual analyses are presented for the entire photo period and the 1988 to 2003 sediment budget period. The 1988-2003 interval was selected for the sediment budget in conjunction with the SRT in order to reflect conditions associated with more recent land management.

4.2.4.1 FIRST ENTRY HARVEST HISTORY

Unlike areas in adjacent watersheds, timber harvest entry into the HRC Mattole ownership during the 1950s and 1960s was not universal. While timber harvest began in the Oil Creek, Devils Creek, and Rattlenake Creek portions of the assessment area as early as the 1950's, most of the area in the Taylor Peak, Long Ridge, and Brushy Ridge portion of the ownership was not entered until the 1980's or later (Plate 5). Early entry into the Oil Creek, Devils Creek, and Rattlesnake Creek subwatersheds was thorough and aggressive, with extensive use of ground based yarding methods.

4.2.4.2 LANDSLIDES AND YARDING METHOD

Yarding methods have varied widely since the beginning of the analysis period (1948). Timber harvest was limited prior to the 1954 photo period; while steam donkeys were in wide use in adjacent watersheds, there was limited use of this yarding technique in the analysis area due to its remote location. Initial large-scale logging entries into the watershed assessment area became apparent in 1954, and involved extensive use of ground-based yarding. The Oil Creek, Devils Creek, and Rattlesnake Creek subwatersheds were the primary focus of these early entries. Early tractor use was invasive; no hillslope was too steep and no stream channel was off-limits. Due to the steep topographic conditions, the stream channels were often the easiest access to landings, which themselves were frequently located on small debris fans and/or stream terraces at stream confluences. Cable yarding was first visible in the 1954 photos, but became increasingly prevalent with the advent of the California Forest Practice Rules in 1974.

Associations between yarding and landsliding are applicable for a variable period following a harvest entry, depending on the extent of ground disturbance and soil displacement and until regeneration of the forest diminishes the impacts of the yarding through root development and re-inception of the canopy cover (which facilitates rainfall interception). The time interval criteria for management impacts were developed in conjunction with the SRT to define the length of time associated with various management impacts, based on a review of pertinent literature related to the effects of timber harvest on slope stability. With regard to yarding associations, the time intervals are assumptions adopted for the sake of simplicity. Most available literature pertaining to harvest impacts on slope stability is focused on the effects of tree removal, however, Bawcom (2003) and Cafferata and Spittler (1998) found significant impacts on slope stability related to road and skid trail construction, particularly for pre Forest Practice Rules harvesting, lasting longer than the recovery periods related to reforestation (i.e. root strength and canopy related). More detailed consideration of yarding-related earthwork is provided below in Section 3.2.4.3: Landslides and Management Associations.

For this analysis, we regard the short-term impacts of yarding as occurring during the period generally considered as the recovery period prior to reforestation. Longer-term impacts (so called “legacy” effects) are discussed below in Section “4.2.4.4: Landslides and Management Associations During the Sediment Budget Period.” To reflect the reforestation period, the tables below compare yarding associations for a 15-year period following partial harvest and for a 20-year period following clear cut harvest. Prior to 1988, which is the extent of PALCO/HRC’s GIS harvest history database, harvests are recorded as of the year of the air photo on which they appear. Therefore, additional time had likely elapsed prior to the date of the particular air photo upon which it is recorded, and the temporal categories are inherently extended accordingly. For example, a 1982 partial harvest will be recorded on the 1987 photos, and will be assessed as a “management area” until 2002 (15 years after the photo date), rather than 1997 (15 years after the actual harvest date).

Tables A-13 and A-14 present the associations of yarding methods and landsliding for management-associated landslides during the entire photo period and the sediment budget period (1988 to 2003), respectively. Analysis of the entire photo period further documents the significant impacts related to early ground-based yarding.

Table A-13. Management-Associated Landslide Sediment Delivery in Project Area by Yarding Method, Entire Photo Period

Air Photo Year	Yarding (Sediment Delivered, cubic yards)					
	Ground-based			Cable		
	Number of Delivering Slides	Sediment Delivered	Percent of Sediment Delivered	Number of Delivering Slides	Sediment Delivered	Percent of Sediment Delivered
1948	0	0	0%	0	0	0%
1954	8	66,608	1%	0	0	0%
1965	412	10,619,837	98%	1	659	<1%
1987	0	0	0%	1	6,582	11%
1997	8	140,241	1%	34	50,732	84%
2003	1	780	<1%	7	2,228	4%
Totals:	429	10,827,465	100%	43	60,201	100%

Table A-14. Management-Associated Landslide Sediment Delivery in Project Area by Yarding Method, 1988 to 2003

Sediment Budget Period	Yarding (Sediment Delivered, cubic yards)							
	Ground-based [a]				Cable [a]			
	Acres Harvested	Number of Delivering Slides	Sediment Delivered [b]	Percent of Sediment Delivered [c]	Acres Harvested	Number of Delivering Slides	Sediment Delivered [b]	Percent of Sediment Delivered [c]
1988-1997	516	8	140,241	7%	613	34	50,732	2%
1998-2003	332	1	780	<1%	806	7	2,228	<1%
Total 1988-2003	**848**	**9**	**141,021**	**7%**	**1,420**	**41**	**52,961**	**3%**

[a] Ground based yarding category includes tractor and tractor-cable; cable category includes cable and helicopter.
[b] Delivery occurs within the sediment budget period of 1988-2003 and may include effects of harvest in the years prior to 1988 (see discussion in Section 4.2.4.4).
[c] Percent of sediment delivered is calculated relative to total landslide delivery of 2.1 million cubic yards during the 1988-2003 sediment budget period.

Relative proportions of landslides and sediment delivery associated with ground-based and cable yarding vary with the prevalence of the yarding technique used in each photo period. Direct comparison of sediment delivery impacts associated with each yarding method is shown in Table A-14 with normalized data relative to the amount of ground harvested using each yarding method and the percentage of delivery relative to the overall sediment delivery.

There is a clear relationship in the data between ground-based yarding and landsliding, particularly during the initial entry period. While only eight slides were interpreted with ground-based yarding associations in 1954, accounting for over 66,000 cubic yards, there were 412 in

1965, estimated to have yielded nearly 11 million cubic yards of sediment. That just over 14.5 million cubic yards of sediment were estimated for all slides in 1965 indicates the pervasive extent (and impact) of tractor use in the Mattole assessment area during this period. There are not significant numbers of landslides with associations to cable-yarded areas in the study area until 1997 due at least in part to the reported minimal use of this method prior to the 1980s.

Landslide associations to yarding in the sediment budget period are most prevalent in 1997, and suggest continued correlation to ground-based yarding. Although there are a larger number of landslides associated with cable-yarded areas in 1997 (n=34) relative to ground-based yarding areas (n=8), the ground-based yarding associated slides delivered nearly 3 times the sediment (140,241 cubic yards versus 50,732 cubic yards). Again, the largest component of the increase in sediment delivery seen in the 1997 photo period is in the very large landslide category, and is inferred to be a result of seismogenically induced landslides occurring during or following the 1992 Cape Mendocino earthquake sequence (and therefore may not be associated with management at all). Impacts associated with ground-based yarding in 1997 were concentrated in the Lower East Branch Mattole sub-basin; the largest sediment yield associated with cable yarding occurred in Alwardt Creek (although this delivery is significantly reduced when contributions from large/v. large landslides are removed). It should be noted that cable yarding occurs in modern forest practices on the steepest slopes, which are also the most inherently slide prone (regardless of management intensity or style).

Yarding-associated landslides in the 2003 photo period were negligible. Implementation of the PALCO HCP mass wasting avoidance strategy along with utilization of helicopter yarding methods on steeper slopes may be partially responsible for the decline in yarding associated landslides over the last photo period (1998-2003). However the passage of additional time and subsequent completion of future landslide inventories (i.e. watershed analysis re-visitation) is required to confirm or disprove this assumption.

4.2.4.3 LANDSLIDES AND SILVICULTURE

Landslide occurrences in harvested areas were documented relative to silviculture (clear cut vs. partial cut). Silviculture was estimated on aerial photographs from all photo periods based on the degree of canopy removal. Harvest history for timber operations after 1988 is available in PALCO's GIS database.

As discussed above, the effects of silviculture are considered relevant to mass wasting processes for a variable period, depending largely on the degree of harvest. For this analysis, criteria addressing the duration of these impacts were developed by a collaborative effort of a scientific review team (consisting of involved consultants, agency representatives, and company scientists) based on review of pertinent literature. Recent literature relating timber harvesting to soil mechanics and hydrologic processes stems from the work of Gray (1970), who proposed a reduction in effective soil cohesion from diminished root reinforcement (due to root die-off) and increased soil moisture (due to the loss of evapotranspiration) as harvest-related impacts that result in decreases in slope stability. The hydrologic impacts of timber harvesting have been documented by Jones (2000), in an analysis of paired watershed studies performed between the early 1960s and late 1990s. Keppeler and others (1994) documented changes in groundwater levels after logging in the Caspar Creek watershed. Iverson and Major (1987) document seasonal and storm influences on shallow and deep groundwater levels. Ziemer (1981) proposed a model of root strength depletion and recovery after harvest that is used to derive estimates of the duration of harvest impacts. The mechanics of root reinforcement are summarized by O'Loughlin and Ziemer (1982). Abe and Ziemer (1991) provided experimental data on shear reinforcement by root systems. Detailed analyses of root cohesion, stand structure, and landsliding are provided in Krogstad (1995), Schmidt and others (2001), and Roering and others (2003).

For the purposes of this analysis, landslides are considered "associated" with partial harvests for a period of 15 years, and with clear cuts for 20 years. Longer-term effects ("legacy" effects) are considered below in Section "4.2.4.4: Landslides and Management Associations."

Landslide associations with harvested areas are shown in Tables A-15 and A-16 for the entire photo period and photo years 1988 to 2003, respectively.

Table A-15. Management-Associated Landslide Sediment Delivery in Project Area by Silviculture, Entire Photo Period

Air Photo Year	Silviculture (Sediment Delivered, cubic yards)					
	Clear Cut			Partial Cut		
	Number of Delivering Slides	Sediment Delivered	Percent of Sediment Delivered	Number of Delivering Slides	Sediment Delivered	Percent of Sediment Delivered
1948	0	0	<1%	0	0	0%
1954	7	4,425	<1%	1	62,183	1%
1965	90	1,310,743	95%	323	9,309,752	98%
1987	1	6,582	0%	0	0	0%
1997	31	50,481	4%	11	140,491	1%
2003	4	2,142	<1%	4	867	<1%
Totals:	**133**	**1,374,373**	**100%**	**339**	**9,513,294**	**100%**

Table A-16. Management-Associated Landslide Sediment Delivery in Project Area by Silviculture, 1988 to 2003

Year	Silviculture (Sediment Delivered, cubic yards) [a]							
	Clear Cut				Partial Cut			
	Acres Harvested	Number of Delivering Slides	Sediment Delivered [b]	Percent of Sediment Delivered [c]	Acres Harvested	Number of Delivering Slides	Sediment Delivered [b]	Percent of Sediment Delivered [c]
1988-1997	237	31	50,481	2%	892	11	140,491	7%
1998-2003	754	4	2,142	<1%	384	4	867	<1%
Total 1988-2003	**992**	**35**	**52,623**	**3%**	**1,276**	**15**	**141,358**	**7%**

[a] Note that a 730-acre salvage harvest in 1992 (included in this table as “partial cut”) was similar in many ways to a clear cut due to the previous fire.
[b] Delivery occurs within the sediment budget period of 1988-2003 and may include effects of harvest in the years prior to 1988 (see discussion in Section 4.2.4.4).
[c] Percent of sediment delivered is calculated relative to total landslide delivery of 2.1 million cubic yards during the 1988-2003 sediment budget period.

Similar to the results for the yarding associations described above, the landslide associations to silviculture document the impacts resulting from the coincidence of intensive early management and the geomorphically significant storm events in 1955 and 1964. The vast majority of harvest-associated landslides (for both partial and clear cuts) occur in the 1965 photo set. Ninety slides were documented with associations to clear cut areas in 1965, resulting in delivery of an estimated 1.3 million cubic yards of sediment. 323 landslides were associated with partial cut areas in 1965, with an estimated 9.3 million cubic yards of sediment delivered.

Sediment inputs from landslides associated with harvest areas (clear cut or partial cut) are generally low in both the 1997 and 2003 photo periods. There was an increase during the 1997 photo period, as has been described previously above, again presumably in response to the 1992 earthquakes and the 1996-1997 storms. Sediment delivery amounts are greater for partial cut areas in 1997, reflecting both the larger area harvested under this method and the location of most partial cuts on steeper slopes that are more naturally prone to seismically induced landsliding. The majority of this non-road, harvest related sediment delivery occurred in the Oil Creek and Alwardt Creek sub-basins. More detailed discussion of the sediment budget period harvest history is provided in the Surface Erosion Module (Appendix B).

4.2.4.4 LANDSLIDES AND MANAGEMENT ASSOCIATIONS

For the purposes of developing a sediment budget for the period of 1988 through 2003, landslides given some form of management association are categorized as “recent” management (including both recent harvest units and the entire contemporary road system),“legacy” management (including harvest units generally pre-dating the 1974 Forest Practice Act, and abandoned roads, once used to access historic logging sites), or as “natural/ background” where significant time has elapsed since the last harvest. These land-use association categories were developed by the scientific review team based on review of available literature, as described above (see literature citations in Sections 4.2.4.2 and 4.2.4.3). This analysis provides data critical to construction of an accurate sediment budget for the assessment area.

“Management-related” landslides are defined as:

1. landslides occurring on hillslopes that have been clear cut harvested (>50% canopy removal) less than 20 years prior (typically relative to the air photo date);
2. landslides occurring on hillslopes partially harvested (<50% canopy removal) less than 15 years prior;
3. road-related landslides associated with any roads subject to the 1999 PALCO Habitat Conservation Plan (HCP) (generally any roads within PALCO’s GIS system).

"Legacy" effects are typically those associated with management that pre-dates the 1974 Forest Practice Rules, or that may be associated with the lingering impacts of tractor disturbance. Sediment delivery which occurred during the sediment budget period (1988-2003) from landslides associated with legacy management effects are not accurate predictors of future management impacts on mass wasting, but can indicate the extent to which these historic practices continue to contribute sediment, and can identify sources of sedimentation that may be correctable. Landslides associated with legacy effects are:

1. landslides occurring on hillslopes that have been clear cut and tractor yarded between 20 and 30 years prior (again, typically relative to the air photo date);
2. landslides occurring on hillslopes that have been partially harvested and tractor yarded 15 to 30 years prior;
3. all landslides associated with pre-1975 earthwork (including skid trails and yarding corridors); and
4. all landslides associated with roads that were not recognized at the time of the adoption of the 1999 HCP (old, abandoned roads, generally impassible by motorized vehicle; *not* recognized in PALCO's GIS database).

"Background" landslides are defined as:

1. landslides that are not management associated ("naturally" occurring);
2. landslides occurring on hillslopes that were clear cut harvested more than 20 years prior, with non-ground based yarding;
3. landslides occurring on hillslopes that were partially harvested more than 15 years prior, with non-ground based yarding; and,
4. landslides occurring on harvested hillslopes that were tractor yarded more than 30 years prior.

Tables A-17 and A-18, Figure A-7, and Plates 6 and 7 present data on slide frequency and sediment delivery amounts for road-related and non-road-related (management) landslides relative to the various management associations and time periods. Note that Table A-17, which presents data from the pre-sediment budget period (1948-1987), does not include a "legacy" category because the concept is not yet relevant. The legacy category is present in Table A-18, which presents data from the sediment budget period, 1988-2003. Over the entire analysis period, management-associated landslides are again most prevalent in the 1965 photo period. Overall, the record reveals a high level of management-related impacts in the 1965 photo period, moderate levels in the 1954 and 1997 photo periods, and low levels in 1987, and 2003. Road and non-road-related management landslides delivered more than 11 million cubic yards in 1965, nearly 7,000 cubic yards in 1987, over 200,000 cubic yards in 1997, and just over 3,000 cubic yards in 2003. Since 1988, delivery from legacy impacts is moderately significant, with about 102,000 cubic yards delivering. Virtually all of the “legacy” slides are associated with now-abandoned roads, originally constructed and used for timber harvest access in the 1950s and 60s.

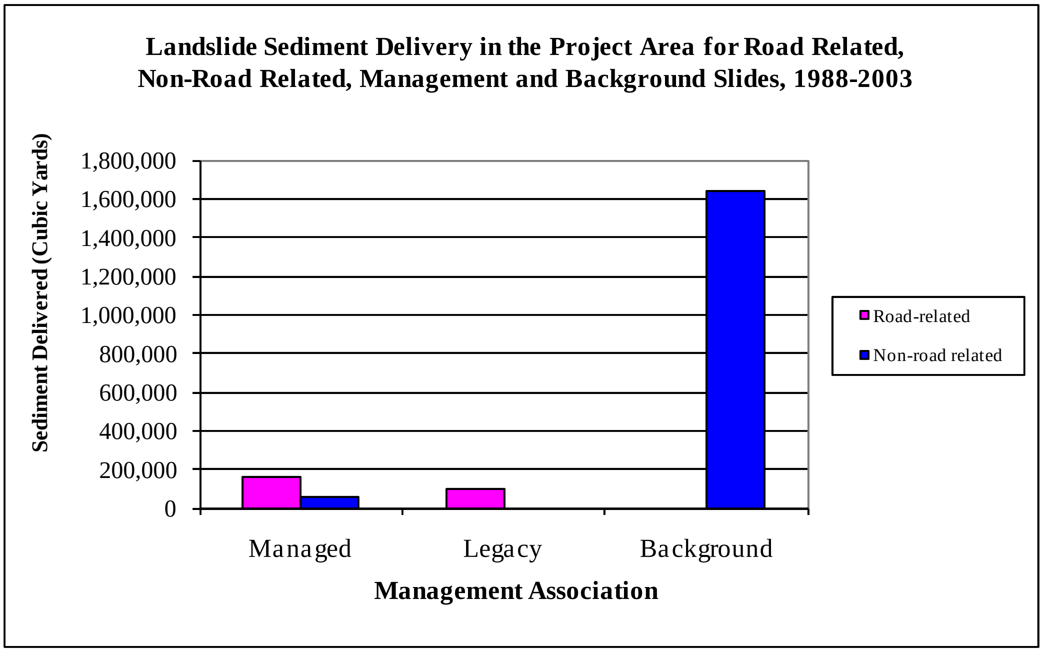
Table A-17. Landslide Sediment Delivery in Project Area for Road-Related & Non-Road Related Slides Relative to Management Association versus No Management Association, 1948 - 1987

Year		Management		Legacy		Background	
		Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)
1948	Road	0	0	0	0	0	0
	Non-road	0	0	0	0	67	2,058,719
1954	Road	10	97,918	0	0	0	0
	Non-road	6	64,366	0	0	88	2,671,678
1965	Road	129	7,239,218	0	0	0	0
	Non-road	303	4,089,925	0	0	200	3,210,739
1987	Road	0	0	63	196,582	0	0
	Non-road	1	6,582	191	556,500	88	273,671
Totals:		**449**	**11,489,008**	**254**	**753,082**	**4,433**	**8,214,807**

Table A-18. Landslide Sediment Delivery in Project Area for Road-Related & Non-Road Related Slides Relative to Management Association, 1988 to 2003

Year		Management		Legacy		Background	
		Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)
1997	Road	7	156,564	13	94,554	0	0
	Non-road	36	49,021	0	0	344	1,312,181
2003	Road	0	0	4	7,585	0	0
	Non-road	8	3,009	0	0	89	330,947
Totals:		**51**	**208,594**	**17**	**102,139**	**433**	**1,643,128**

Figure A-7. Landslide Sediment Delivery in the Project Area for Road Related, Non-Road Related, Management and Background Slides, 1988-2003



Tables A-19 and A-20 and Figure A-8 present the management association again, but without the contributions from large and very large landslides. These large and very large slides (3,000 to 5,000 cubic yards and greater than 5,000 cubic yards, respectively) are less likely to be caused by management impacts because their basal shear surfaces are typically too deep to be affected by changes in root reinforcement, shallow grading, or minor hydrologic changes. The intent here is to focus on the smaller debris slides that are typically more sensitive to management.

Table A-19. Landslide Sediment Delivery in Project Area for Road-Related & Non-Road Related Slides Relative to Management Association, 1948 to 1987, Minus Large & Very Large Landslide Contributions

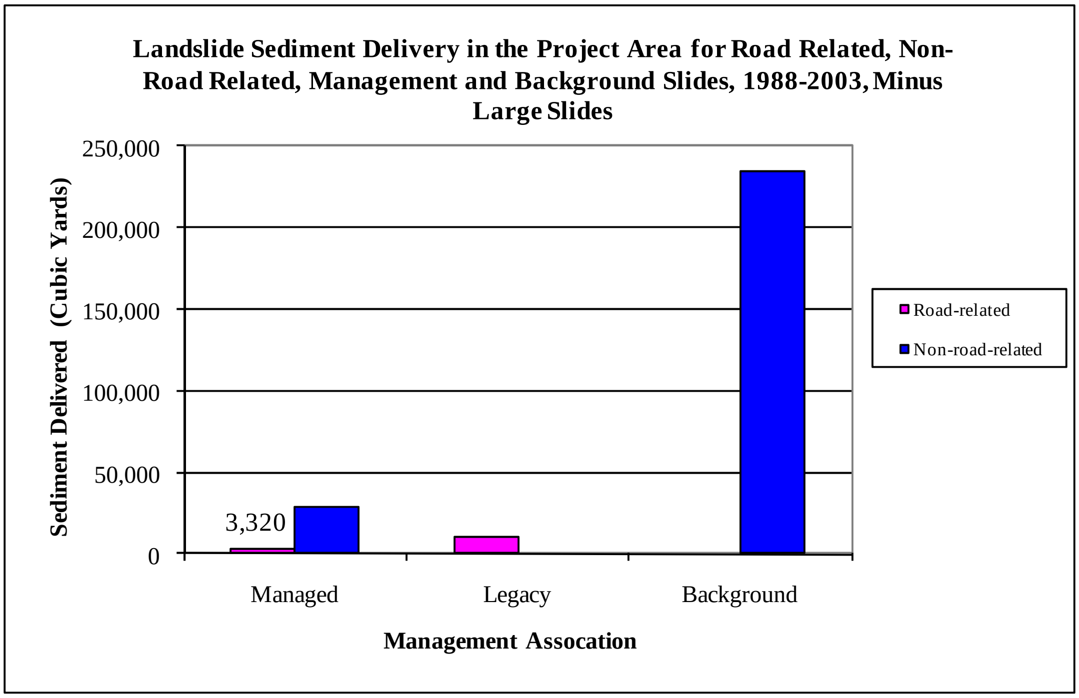
Year		Management		Legacy		Natural	
		Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)
1948	Road	0	0	0	0	0	0
	Non-	0	0	0	0	37	22,166
1954	Road	4	7,766	0	0	0	0
	Non-	5	2,183	0	0	28	41,744
1965	Road	45	45,829	0	0	0	0
	Non-road	161	147,752	0	0	104	123,902
1987	Road	0	0	54	37,600	0	0
	Non-road	0	0	162	114,980	71	42,954
Totals:		**215**	**203,530**	**216**	**152,581**	**240**	**230,765**

Table A-20. Landslide Sediment Delivery in Project Area for Road-Related & Non-Road Related Slides Relative to Management Association, 1988 to 2003, Minus Large & Very Large Landslide Contributions

Year		Management		Legacy		Natural	
		Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)	Number of Landslides	Sediment Delivered (cubic yards)
1997	Road	3	3,320	9	7,121	0	0
	Non-road	33	26,393	0	0	281	197,908
2003	Road	0	0	3	2,723	0	0
	Non-road	8	3,009	0	0	75	36,181
Totals:		**44**	**32,722**	**12**	**9,843**	**356**	**234,088**

In general, road-related mass wasting associations are relatively minor within the watershed assessment area, especially during the sediment budget period (1988-2003). This result is a function of the topography of the area, and the general absence of low slope roads. The road network in the watershed is relatively limited, and most roads are located in ridge top settings with low failure and sediment delivery potential, in contrast to the road system associated with the first harvest entry of 1954-1965. Legacy roads delivered more sediment than management roads during the sediment budget period.

Figure A-8. Landslide Sediment Delivery in the Project Area for Road Related, Non-Road Related, Management and Background Slides, 1988-2003, Minus Large Slides



4.2.5 SUB-BASIN ANALYSIS

In order to identify spatial mass wasting patterns within the watershed assessment area, the landslide database was broken down by sub-basin, and evaluated in a series of database searches in a similar fashion to that presented above for the entire watershed. The analyses presented below focus on the 1988 to 2003 period.

There are seven California planning watersheds within the study, with areas ranging from just under 0.25 square mile to nearly 7.5 square miles (Table A-21). These watersheds provide the first level of sub-basin differentiation. Several of these larger watersheds (Rainbow and Camp Mattole) are further subdivided. This breakdown results in a total of 11 sub-basins.

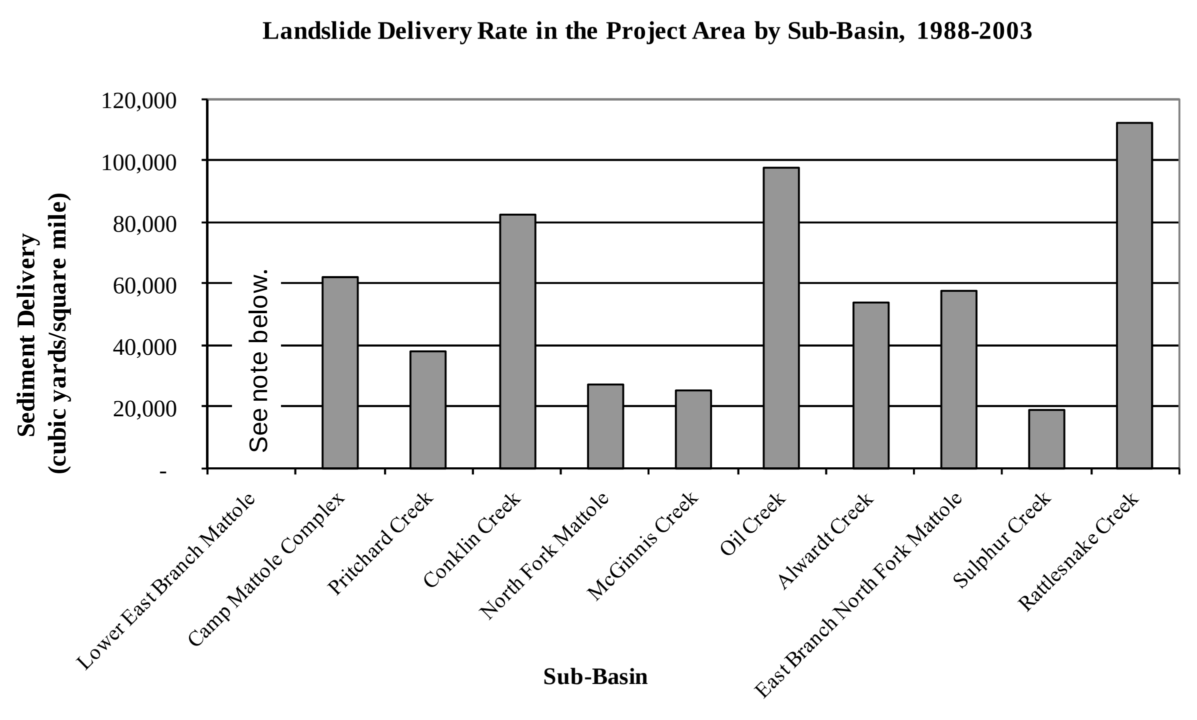
4.2.5.1 LANDSLIDES BY SUB-BASIN

Table A-21 and Figure A-9 present the distribution of landslides and sediment delivery amounts by sub-basin during the sediment budget period. The results indicate concentrations of mass wasting in the Oil Creek and Rattlesnake Creek sub-basins. Landslides in the Rattlesnake Creek sub-basin represent 38% of the total number of slides during the sediment budget period, and 39% of the sediment delivery. Landslides in the Oil Creek sub-basin represent 24% of the slides and 29% of the sediment delivery. Other sub-basins exhibit a lower rate and relatively even distribution of mass wasting. When landslide delivery rates are calculated in the project area, it suggests a very high rate of delivery in the Lower East Branch Mattole sub-basin. This result appears to reflect the presence of a few large slides (7 slides interpreted) within a relatively small area (0.25 square miles).

Table A-21. Landslide Sediment Delivery in Project Area (HCP Covered Lands), by Sub-basin, 1988 to 2003

PWS Name	Sub-basin	Slides	Percent of Number of Slides	Area (square mile)	Sediment Delivered (cubic yard)	Percent of Sediment Delivered	Delivery per Unit Area (cubic yard/sq mi)
Apple Tree	Lower East Branch Mattole	7	1%	0.25	139,181	7%	561,213
Camp Mattole	Camp Mattole Complex	20	2%	0.56	34,537	2%	62,005
	Pritchard Creek	61	5%	1.28	48,168	2%	37,749
Cow Pasture Opening	Conklin Creek	22	2%	0.80	65,216	3%	82,033
Long Ridge	North Fork	46	4%	2.14	58,571	3%	27,382
McGinnis Creek	McGinnis Creek	85	7%	3.42	86,592	4%	25,341
Oil Creek	Oil Creek	281	24%	6.29	613,148	29%	97,542
Rainbow	Alwardt Creek	99	8%	2.73	146,170	7%	53,464
	East Branch North Fork	42	4%	1.33	76,606	4%	57,816
	Sulphur Creek	72	6%	1.84	34,919	2%	18,978
Rattlesnake Creek	Rattlesnake Creek	442	38%	7.43	834,925	39%	112,342

Figure A-9. Landslide Delivery Rate in the Project Area by Sub-Basin, 1988-2003



Note: 561,213 cy/sq mi value not shown for Lower East Branch Mattole due to very small sub-basin area (<0.25 sq mi).

4.2.5.2 LANDSLIDES BY SUB-BASIN AND LITHOLOGY

Table A-22 presents the relationship between landslide occurrence and lithology, broken down by sub-basin. As would be expected based on the predominance of Coastal terrane bedrock in the watershed, mass wasting is most common in that bedrock type within the sub-basins shown above as being the most active mass wasting sites. Because of the uniformity of lithology throughout the study area, it is difficult to draw significant conclusions from this analysis. Of note, we would reiterate that the inputs from alluvial sites (alluvium and terrace deposits) are probably near-stream bedrock failures that appear as alluvial sites due to differences in map scales and resolution.

Table A-22. Landslide Sediment Delivery by Lithologic Unit & Sub-basin, 1988 to 2003

Sub-basin	Alluvium (cubic yards)	Terrace Deposits (cubic yards)	Yager Terrane (cubic yards)	Franciscan Coastal Terrane (cubic yards)	Franciscan Coastal Terrane-Sheared
Lower East Branch Mattole	0	0	0	139,181	0
Camp Mattole Complex	0	0	0	34,537	0
Pritchard Creek	0	0	0	48,168	0
Conklin Creek	525	0	0	64,692	0
North Fork	2,426	0	0	56,145	0
McGinnis Creek	738	0	0	85,853	0
Oil Creek	0	23,375	0	589,773	0
Alwardt Creek	3,037	0	0	143,133	0
East Branch North Fork	49,100	0	0	27,506	0
Sulphur Creek	236	0	0	34,683	0
Rattlesnake Creek	9,113	0	14,787	810,985	40
Total	**65,176**	**23,375**	**14,787**	**2,034,655**	**40**

4.2.5.3 LANDSLIDES BY SUB-BASIN AND GEOMORPHIC ASSOCIATION

Table A-23 presents the relationship between landslide occurrence and geomorphic association, broken down by sub-basin.

The results are dominated by sediment delivery from landslides initiating on slopes identified in the air photo interpretation as “inner gorges.” Subsequent slope class analysis by means of PALCO’s GIS database distinguishes slopes less than and greater than 65%. Streamside slopes in the Mattole River watershed are by far the most significant contributors of sediment-delivering landslides. Interestingly, relatively small contributions are derived from headwall swales, which in other watersheds in the region can be sensitive geomorphic features that contribute large amounts of sediment. There is also a significant contribution from slides originating on “continuous slopes,” that is, open slopes above the inner gorge. These slides are principally larger failures (many earthflows) that occupy large portions of valley wall slopes.

Table A-23. Landslide Sediment Delivery by Geomorphic Association & Sub-basin, 1988 to 2003

Sub-basin	Inner Gorge (cubic yards)		Headwall Swale (cubic yards)	Continuous Slope (cubic yards)	Stream Channel	Stream Channel	Stream Channel
	GIS slopes >65%	GIS slopes <65%				Inner Gorge	Headwall Swale
Lower East Branch Mattole	11,888	82	0	0	0	0	127,211
Camp Mattole Complex	5,794	1,522	0	0	0	0	27,222
Pritchard Creek	28,030	4,920	0	2,403	1,657	0	11,158
Conklin Creek	53,051	6,352	0	5,813	0	0	0
North Fork	36,522	20,972	0	373	323	0	381
McGinnis Creek	41,928	9,556	6,797	1,350	6,553	0	20,408
Oil Creek	312,412	245,840	109	10,619	8,171	5,285	30,712
Alwardt Creek	76,233	43,626	4,567	55	8,151	174	13,365
East Branch North Fork	53,630	16,131	0	6,503	0	0	342
Sulphur Creek	22,348	12,253	0	125	10	0	182
Rattlesnake Creek	212,632	200,298	0	114,464	3,819	12,109	291,603
Total	**854,468**	**561,551**	**11,473**	**141,705**	**28,685**	**17,567**	**522,585**

4.2.5.4 LANDSLIDES BY SUB-BASIN AND DISTANCE TO STREAM

Table A-24 presents the data regarding the initiation points of landslides relative to watercourses in the project area, broken down by sub-basin. As described above in Section 3.2.3.6, the distance to the watercourse is measured from the top of the landslide. The results reinforce the interpretation presented earlier that significant amounts of landslide sediment delivery in the Mattole River watershed are derived from landslides initiating in upland areas greater than 400 feet from the stream. Significant upland sediment contributions are apparent in the Oil Creek, Rattlesnake Creek and the lower east branch Mattole sub-basins. 99% of the sediment delivery from watercourse distances greater than 1,000 feet was contributed by landslides in the Rattlesnake Creek sub-basin, with the remaining 1% occurring in the Oil Creek sub-basin.

As noted in Section 3.2.3.6, the larger sediment delivery volumes associated with the 401- to 1,000-foot distance class relative to the other distance classes is in part, a function of its increased width. Normalized sediment delivery for the 401- to 1,000-foot distance class typically decreases to just a few percent to 61% of the 0- to 400-foot distance classes for the sediment budget period. For example, sediment delivery from the 401- to 1,000-foot class is 33% and 61% of the delivery from the 0- to 400-foot class in the Oil and Rattlesnake Creek sub-basins, respectively. The exceptions are the Lower East Branch Mattole sub-basin (7 times the delivery rate of the 0- to 400-foot class), the Camp Mattole Complex sub-basin (2 times the delivery rate of the 0- to 400-foot class), and the Conklin Creek sub-basin (rates roughly equivalent). These are also the three smallest sub-basins in the assessment area (0.25 to 0.8 mi^2), which are difficult to compare to the larger sub-basins due to their sensitivity in terms of calculations of sediment input rates (that is, a single slide in a small sub-basin can considerably skew the sediment input rate). The upland sediment delivery appears to reflect the frequency of large landslides in the watershed. As discussed above, large landslides in the region are often seismically-induced features. Note that the 1988 to 2003 analysis period described in Table A-24 includes the 1992 Petrolia earthquake sequence, which generated many co-seismic landslides throughout the region (Dunklin, 1992) and may have instigated the generation of large landslides during the next sustained wet winter (1996-97).

Table A-24. Landslide Sediment Delivery by Distance to Stream & Sub-basin, 1988 to 2003

Sub-basin	< 100 feet (cubic yards)	101–200 feet (cubic yards)	201–300 feet (cubic yards)	301–400 feet (cubic yards)	401–1,000 feet (cubic yards)	> 1,000 feet (cubic yards)
Lower East Branch Mattole	128,593	2,470	0	8,118	0	0
Camp Mattole Complex	32,415	2,074	47	0	0	0
Pritchard Creek	19,684	7,530	9,244	10,868	842	0
Conklin Creek	2,452	5,971	18,068	0	38,725	0
North Fork	6,569	13,336	13,466	23,848	1,353	0
McGinnis Creek	41,622	18,415	11,362	14,237	81	0
Oil Creek	82,918	140,034	140,401	55,553	179,429	1,021
Alwardt Creek	34,658	26,181	27,508	17,533	31,079	0
East Branch North Fork	12,117	21,272	18,247	24,970	0	0
Sulphur Creek	9,105	7,935	15,109	2,557	213	0
Rattlesnake Creek	335,594	76,440	47,340	23,119	201,243	122,995
Total	**705,726**	**321,659**	**300,793**	**180,802**	**452,964**	**124,016**

4.2.5.5 LANDSLIDES BY SUB-BASIN AND YARDING METHOD

Table A-25 presents the relationship between landslides and yarding in the project area between 1988 and 2003. Significant associations between landslides and yarding are present in the Lower East Branch Mattole, Oil Creek, Alwardt Creek, and East Branch North Fork. However, based on comparison with the management association tables presented below (A-27 and A-28), it is apparent that these sediment inputs are associated with large and very large landslides (note that the values do not appear in the “managed” columns in Table A-28). Because these sediment contributions appear to be related to recent large or very large landslides, they are more likely to be related to seismicity (1992 Petrolia earthquake sequence) and are less likely to be management-related. Without the contributions of these large or very large slides, there are few associations between yarding and landsliding in the study area (see non-road, managed column in Table A-28).

Table A-25. Management-Associated Landslide Sediment Delivery in Project Area by Yarding Method, 1988 to 2003, by Sub-basin

	Yarding (Sediment Delivered, cubic yards)					
	Ground-based			Cable		
Sub-basin	Number of Delivering Slides	Sediment Delivered	Percent of Sediment Delivered	Number of Delivering Slides	Sediment Delivered	Percent of Sediment Delivered
Lower East Branch Mattole	6	139,016	98%	0	0	0%
Camp Mattole Complex	0	0	0%	0	0	0%
Pritchard Creek	0	0	0%	2	494	<1%
Conklin Creek	0	0	0%	0	0	0%
North Fork	0	0	0%	3	754	1%
McGinnis Creek	2	1,225	1%	4	3,027	5%
Oil Creek	1	780	<1%	12	10,132	17%
Alwardt Creek	0	0	0%	11	26,424	50%
East Branch North Fork	0	0	0%	4	9,704	16%
Sulphur Creek	0	0	0%	5	2,427	4%
Rattlesnake Creek	0	0	0%	0	0	0%
Total	**9**	**141,021**	**100%**	**41**	**52,961**	**100%**

4.2.5.6 LANDSLIDES BY SUB-BASIN AND SILVICULTURE

Table A-26 presents the relationship between landslides and silviculture in the project area between 1988 and 2003. Significant silviculture associations appear related to clear cuts in Oil and Alwardt Creeks, and the East Branch North Fork Mattole, as well as a partial cut in the Lower East Branch Mattole. As described above, however, much of this sediment contribution is the result of large and very large landslides that are most likely related to the strong seismicity that affected the region in 1992. Without the contributions of these large or very large landslides, there are few associations between silviculture and landsliding in the study area (see non-road, managed column in Table A-28 below). The exception in the data set appears to be the silviculture associations in Oil Creek, which do not appear to be associated with large or very large landslides.

Table A-26. Management-Associated Landslide Sediment Delivery in Project Area by Silviculture, 1988 to 2003, by Sub-basin

Sub-basin	Clear Cut (cubic yards)	Partial Cut (cubic yards)
Lower East Branch Mattole	0	139,016
Camp Mattole Complex	0	0
Pritchard Creek	0	494
Conklin Creek	0	0
North Fork	0	754
McGinnis Creek	3,414	837
Oil Creek	10,654	258
Alwardt Creek	26,424	0
East Branch North Fork	9,704	0
Sulphur Creek	2,427	0
Rattlesnake Creek	0	0
Total	**52,623**	**141,358**

4.2.5.7 LANDSLIDES AND MANAGEMENT ASSOCIATIONS BY SUB-BASIN

Tables A-27 and A-28 present the relationship between landslides and management associations, by sub-basin, including large landslide contributions and without large and very large landslide contributions, respectively. Because large and very large landslides in the watershed are less likely to be management-induced, Table A-28 is considered more relevant than Table A-27 regarding potential management impacts. Note that most large sediment volumes drop out of the analysis when large and very large landslides are excluded.

Table A-27. Landslide Sediment Delivery in Project Area for Road-Related and Non-Road Related Slides Relative to Management Association, 1988 to 2003, by Sub-basin

Sub-basin		Management	Legacy	Natural
Lower East Branch Mattole	Road	135,330	0	0
	Non-road	3,686	0	0
Camp Mattole Complex	Road	0	0	0
	Non-road	0	0	33,961
Pritchard Creek	Road	0	2,102	0
	Non-road	494	0	41,402
Conklin Creek	Road	0	0	0
	Non-road	0	0	64,957
North Fork	Road	0	0	0
	Non-road	754	0	49,081
McGinnis Creek	Road	728	34,972	0
	Non-road	3,523	0	44,915
Oil Creek	Road	0	7,802	0
	Non-road	10,912	0	546,510
Alwardt Creek	Road	20,506	0	0
	Non-road	20,531	0	93,945
East Branch North Fork	Road	0	0	0
	Non-road	9,704	0	65,209
Sulphur Creek	Road	0	0	0
	Non-road	2,427	0	29,508
Rattlesnake Creek	Road	0	57,264	0
	Non-road	0	0	673,640
Totals:		**208,594**	**102,139**	**1,643,128**

Table A-28. Landslide Sediment Delivery in Project Area for Road-Related and Non-Road Related Slides Relative to Management Association, 1988 to 2003, Minus Large and Very Large Landslide Contributions, by Sub-Basin

Sub-basin		Managed	Legacy	Natural
Lower East Branch Mattole	Road	0	0	0
	Non-road	3,686	0	0
Camp Mattole Complex	Road	0	0	0
	Non-road	0	0	8,549
Pritchard Creek	Road	0	2,102	0
	Non-road	494	0	16,365
Conklin Creek	Road	0	0	0
	Non-road	0	0	8,391
North Fork	Road	0	0	0
	Non-road	754	0	13,367
McGinnis Creek	Road	728	625	0
	Non-road	3,523	0	29,339
Oil Creek	Road	0	2,939	0
	Non-road	10,912	0	54,425
Alwardt Creek	Road	2,592	0	0
	Non-road	5,930	0	26,460
East Branch North Fork	Road	0	0	0
	Non-road	1,676	0	10,379
Sulphur Creek	Road	0	0	0
	Non-road	2,427	0	14,855
Rattlesnake Creek	Road	0	4,178	0
	Non-road	0	0	51,959
	Totals:	**32,722**	**9,843**	**234,088**

4.2.6 FIELD VERIFICATION OF AIR PHOTO-IDENTIFIED LANDSLIDES

Seventy landslides identified from aerial photography were field verified to assess the accuracy of the landslide attributes collected during the photo interpretation. Landslides were generally chosen for field verification based on accessibility (a major factor in the Mattole River watershed), size, proximity to other slides, and slide type. Also included were several slides that we had visited previously during previous timber harvest plan layouts, if the field data collected at the time provided sufficient information.

As is anticipated due to the documented limitations of aerial photograph interpretation, there was considerable variability between the attributes recorded on the photos and those measured in the field. There is no apparent pattern or trend to the discrepancies (they are not universally too small or too large in any predictable way). The greatest variability is clearly associated with the estimate of depth and the percentage of sediment delivery. Inaccuracies in the depth estimates are attributable to the method in which they are generated. The extrapolation of the field measured depths to a surface area versus depth mathematical regression is by nature going to be an approximation. Further, due to considerable scatter in the surface area vs. depth plots, the best-fit line is not typically very statistically robust; thus regressions are associated with relatively low R^2 (coefficient of multiple determination) values (values range from 0.287 to 0.621).

The percentage of sediment delivery is inherently a difficult attribute to generate through interpretation of aerial photographs. The shortcomings in this approach are generally attributable to the difficulties in interpreting the nature of the accumulation zone. Because the accumulation zone and depletion zone can appear similar in aerial photography (as a high albedo [light reflectance] feature devoid of vegetation), it can be impossible to determine whether the area was merely scoured by passing debris that delivered to the adjacent watercourse, or whether all or part of the debris was deposited on the slope. Further, if the slide has a long run-out, the accumulation zone or torrent track may be largely obscured by canopy.

We have high confidence in the ability to accurately identify and locate landslides during the aerial photograph inventory process. Very few slides identified on the air photos were determined to not be slides during the field verification. Further, the locations of slides depicted on air photos were generally accurate when visited in the field. Confidence in identification of mass wasting features increases with the size of the failure; obviously, small features are more easily obscured by surrounding canopy.

We have moderate confidence in the estimation of landslide volumes and delivery percentages based on interpretation of aerial photographs. As described above, landslide volumes are generated from a mathematical regression based on a surface area versus depth plot derived from a limited number of field sites. The surface area versus depth plot has considerable scatter, and the best-fit line is of poor statistical quality. The inherent limitations in estimating sediment delivery amounts are described above.

4.2.7 STREAMSIDE LANDSLIDE INVENTORY

An inventory of streamside landslides was conducted for the purpose of identifying small landslides that may not be detected on aerial photographs, yet potentially producing a significant portion of the landslide sediment delivery to streams. Field inventory of streamside landslides was completed for a variety of main stem and tributary streams in the project area. Stream transects were developed along Class I, II, and III streams. The primary consideration in selection of transect locations was accessibility. Due to a general absence of road access to valley bottoms throughout the study area, it is not possible to drive to many potential streamside survey sites. As such, we selected sites that could be accessed in a reasonable timeframe and in a safe manner. We surveyed a total of 6.6 miles of stream, including 2.4 miles of Class I, 2.1 miles of Class II, and 2.1 miles of Class III streams. Transect locations are depicted on Plate 8.

4.2.7.1 RESULTS OF STREAMSIDE LANDSLIDE INVENTORY

Table A-29 presents the results of the streamside landslide inventory. Relatively significant amounts of streamside sediment delivery were documented in the Oil Creek, Alwardt Creek, and Rattlesnake Creek transects. Twenty-two undetected streamside landslides were recorded in the Oil Creek transect, representing an estimated 14,000 cubic yards of sediment delivery; 23 were recorded in the Alwardt Creek transect, delivering an estimated 9,000 cubic yards; and 24 streamside slides in the Rattlesnake Creek transect were estimated to have delivered just over 17,000 cubic yards. Sediment delivery rates in these areas range from about 2,000 cubic yards/mile to nearly 8,000 cubic yards/mile. There were no undetected streamside landslides in the Sulphur Creek transect, which encompassed the heads of four short Class III streams.

Table A-29. Streamside Landslides by Hillslope Gradient and Sub-basins

		Slopes < 65%			Slopes > 65%		
Sub-basin	**Length of transect surveyed (miles)**	**Number of slides**	**Sed Delivered (cubic yards)**	**Unit sediment delivered (cubic yards per mile)**	**Number of slides**	**Sed Delivered (cubic yards)**	**Unit sediment delivered (cubic yards per miile)**
McGinnis Creek	1.0	0	0	0	5	874	874
Oil Creek	2.1	10	12,981	6,134	12	1,129	534
Alwardt Creek	1.2	6	6,154	5,309	17	3,148	2,716
Sulphur Creek	0.2	0	0	0	0	0	0
Rattlesnake Creek	2.1	3	531	254	21	16,650	7,960
Total	**6.6**	**19**	**19,666**	**2,980**	**55**	**21,801**	**3,304**

A relatively low level of undetected streamside landsliding was documented along a 1 mile stretch of lower McGinnis Creek, where only 5 additional slides were noted, representing a unit sediment delivery rate of about 800 cubic yards/mile. McGinnis Creek is unique from the remainder of watercourses within the study area due to its lower topographic setting and the width of the valley bottom. The surveyed stream reach is near the lower extent of the sub-basin, along the main stem of McGinnis Creek. The stream canyon in this area is characterized by a broad, flat-floored valley where the stream rarely encounters the sidewalls. Valley sidewalls are not as steep or high as those found in more upland settings in the remainder of the watershed assessment area.

Few streamside landslides were documented along the Class III streams included in our survey. From nearly 11,000 lineal feet of stream survey, just over 1,000 cubic yards of sediment delivery was documented. In general, due to the steep nature of the terrain in the project area, Class III streams represent short upland segments that quickly transition downslope into Class II streams. The Class III streams typically occupy swales with relatively low relief and minimal landslide potential, and do not generate sufficient flow to initiate hillslope failures.

Results from the limited stream reaches surveyed in the streamside landslide inventory are extrapolated to the remainder of the watershed assessment area to provide an estimate of sediment input that is not captured in the aerial photographic landslide inventory. Table A-30 presents the results of that extrapolation process. The data suggest significant additional sediment input from small landslides along Class II streams, moderate additional sediment input along Class I streams, and relatively small sediment input along Class III streams. Input from streamside landslides along Class I streams may be underestimated due to the inclusion of the McGinnis Creek transect, which yielded relatively low rates of undetected sediment input. In all, extrapolation of the streamside landslide survey data suggests nearly 2 million cubic yards of additional sediment delivery during the sediment budget period. Note that even though the sediment input rates along Class III streams is relatively minor, the extrapolated sediment contribution to these streams is significant because of the large number of Class III stream mileage in the assessment area (136 miles).

Table A-30. Streamside Landslide Delivery Extrapolation from Survey Area to Streams in Project Area

Stream Class	Feet of Stream Class	Sediment Delivered (cubic yards)	Miles of Stream Class	Sediment Delivered//Mile (cubic yards/mile)	Total Miles of Stream Class in Watershed	Total Sediment Delivery (cubic yards)	% of Total Stream Miles
I	12,815	3,794	2.4	1,563	37.45	58,544	14%
II	11,030	36,644	2.1	17,541	97.04	1,702,189	36%
III	10,998	1,029	2.1	495	136.55	67,529	50%
Totals:	**34,843**	**41,467**	**6.6**	**6,286**	**271.04**	**1,828,262**	**100%**

5.0 CRITICAL QUESTIONS

Below, we provide responses to the critical questions from the (HRC) PALCO watershed analysis manual.

1. **Which landforms or areas of the landscape are susceptible to landslides? What landslide frequencies and landslide types are associated with these landforms? How are they distributed throughout the landscape?**

   In general, the Mattole watershed assessment area is an area characterized by high rates of tectonic uplift, steep topography, high levels of seasonal precipitation, commonly weak sheared bedrock, and frequent strong seismic shaking; all factors that lead to some of the highest mass wasting rates in the region. Relative to other watersheds within the HRC ownership that have been analyzed by the “watershed assessment” methodology, rates of mass wasting are significantly higher in the Mattole and adjacent Bear River watersheds. In this study, over 3,440 landslides were identified, which were estimated to account for nearly 23 million cubic yards of sediment delivery.

   Mass wasting is strongly concentrated on steep streamside slopes in the Mattole watershed. The topographic setting of the watershed is characterized by deeply incised, narrow stream canyons, so inner gorge slopes are nearly ubiquitous within the project area. Due to the propensity of steep slopes along watercourses, mass wasting is dominated by shallow debris sliding; landslides interpreted as debris slides represent up to 96% of documented mass wasting (see Table A-1). Landslides initiating on inner gorge slopes account for 71% of the sediment delivered to streams (Table A-4). Mass wasting rates increase significantly on slopes in excess of 65% (Table A-7). Because of the length of steep streamside slopes throughout the assessment area, there has been significant sediment delivery from landslides that may originate hundreds of feet from the watercourse (some in excess of 1000 feet). This condition was more prevalent earlier in the photo period (see discussion in Section 4.2.3.7 and Table A-9); during the later “sediment budget period” (1988-2003), sediment delivery generally decreases with distance from the watercourse (Table A-10).

2. What geomorphic or geologic attributes are associated with landslides and landslide density?

Steep streamside slopes interpreted as “inner gorges” are by far the most frequent geomorphic feature associated with landsliding. Regarding geologic associations, the assessment area is dominated by Coastal terrane bedrock, occupying 97% of the landscape (Table A-5). Data analysis for this study indicate that most mass wasting related sediment inputs in the Mattole River watershed assessment area are derived from debris slides (Table A-1) occurring on steep inner gorge slopes (Table A-3) underlain by Coastal terrane bedrock (Table A-5).

3. What is the distribution and rate of natural landslides in comparison with land-use related landslides?

Land-use related landslides were a significant contributor in the 1954 and 1965 air photo periods, but have since become a relatively small component of overall mass wasting. During the 1965 photo period alone, landslides with management associations were responsible for more than 11 million cubic yards of sediment input (78% of total sediment delivery for the 1965 photo period; see Table A-17). During the sediment budget period, management contributions dropped to just over 200,000 cubic yards (10% of the total sediment delivery) including large and very large landslides, or just over 37,000 cubic yards (<2% of the total sediment delivery) excluding large and very large landslides. The portion of management-associated sediment delivery drops further when the sediment delivery from streamside landslides is considered (which is generally not associated with management due to the limited operations occurring within 200 feet of streams).

4. Which forest management activities are associated with landslides? What are the relationships between landslide frequency, density, and land use to the extent associations can be identified.

The aggressive, intensive forest management practices of the early post-war era had dramatic impacts on the watershed, especially in combination with the geomorphically significant storm events in 1955 and 1964. 64% of the total sediment interpreted to have been delivered to streams via mass wasting is attributed to the 1955 to 1965 photo period alone (over 14.5 million cubic yards of sediment, 11 million of which have "management associations"; see Tables A-1 and A-17). Modern forest management practices appear associated with much reduced impacts within the assessment area. Landslides with management associations during the sediment budget period (1988-2003) delivered just over 200,000 cubic yards of sediment (Table A-18). Management associated impacts in the Rattlesnake Creek subbasin are relatively low, for example, despite a concentration of harvesting in that area in the late 1990's, and suggesting reduced impacts associated with HRC's HCP measures.

5. **Which landslide locations (landform-landslide combinations) deliver sediment to stream channels or other waters? Which type of landslide are most likely to deliver and from what distance? To the extent varying effects can be discerned, what affect does management have on landslide delivery?**

As described above, there is a very strong correlation in the watershed assessment area between debris slides on inner gorge slopes as sediment delivering mass wasting features. Because of the highly incised topography resulting from high rates of tectonic uplift, the inner gorge slopes can extend several hundred feet upslope; therefore, significant sediment contributions are derived from areas in excess of 400 feet from streams. No distinction could be drawn between specific modern forest management activities relative to landslide sediment delivery.

6. **What is the volume of delivery of sediment by landslides to the stream system in the past 10 to 15 years of the photo record? What proportion of this sediment has resulted from road related sources, and from management activities on hillslopes? Is there any evidence that these management related landslides had higher or lower delivery rates to streams than other landslides during the period?**

The 16-year period between 1988 and 2003 has been designated as the sediment budget period. This period encompasses the two most recent air photo sets (1997 and 2003). For this period, slightly less than 2 million cubic yards of sediment is estimated to have been delivered to streams in the assessment area (Table A-2). Small streamside landslides not detected on aerial photographs are inferred to have contributed an additional 2 million cubic yards of sediment (Table A-30). There were 7 landslides given road associations during the sediment budget period in the assessment area, which were estimated to have delivered just over 150,000 cubic yards of sediment (Table A-18). All of these landslides were documented in the 1997 photo set; there were no road-related landslides noted in the 2003 photo set. The relatively low level of road-related sedimentation, which is often prevalent in other watersheds, is due to the relatively sparse road network, and a general absence of low slope roads and watercourse crossings in recent times (these were more common earlier in the study period). Non-road related (management) landslides during the sediment budget period were estimated to have delivered just over 50,000 cubic yards of sediment. Note that all these management-associated inputs drop significantly when large and very large landslide contributions (which are less likely to be related to surficial management activities) are excluded. In general, the management-associated landslides are a minor source relative to “background” landslides that have occurred in previously managed areas, which are estimated to have delivered in excess of 1.6 million cubic yards during the sediment budget period.

7. What is the sensitivity of different landforms to various land management activities in the past 10 to 15 years of the photo record?

Steep streamside slopes remain the most susceptible landforms in the assessment area, although there has been very little “management” on these slopes. Most management in the watershed has occurred in upland areas away from sensitive landforms. The sensitivity of steep streamside slopes to management is reflected in the relative amount of sediment delivery associated with cable yarding, which although less disruptive than ground based yarding, frequently occurs on steep streamside slopes (Table A-13).

8. Do landslides in the past 10 to 15 years of the photo record deliver LWD to streams? If so, where and what is the average distance of delivery?

Although LWD recruitment was noted during the field studies, the distribution of source areas or its extent in streams was not evaluated. In general, the slides we observed, particularly during the streamside landslide inventory, are delivering large quantities of

LWD. The LWD appears to have the best chance to form favorable log jams and other habitat features in narrow Class II watercourses where the key pieces can wedge into the channel walls or across the channel. As described above, however, stream gradients throughout the assessment area are generally steep, and LWD is not typically retained in larger channels where it is readily flushed downstream. LWD retention in Class I streams is rare, typically offering only seasonal benefits before the following season's high flows.

9. What slopes and areas have experienced the highest rates of road related landslides in the past 10 to 15 years of the photo record?

This question is not relevant to the Mattole River watershed assessment area due to the low density of roads and the low degree of mass wasting that was detected with road associations.

10. Relative to questions 6 through 9 above, does the pattern of landsliding prior to the past 10 to 15 years following triggering events or periods of intense harvest appear to be consistent with the observations for the past 10 to 15 years? If not, how did they differ?

It is difficult to compare the two periods because the amount of management and mass wasting during the 1954 and 1965 photo periods was so extreme. Mass wasting inputs during the sediment budget period have been relatively minor. Large and very large landslide inputs (that meet management associated criteria) during 1997 appear to be associated with the primary triggering event for the period, the combination of 1992 seismicity and the geomorphically significant storms of 1996 to 1997. In general, however, the patterns and distribution of mass wasting appear constant through the photo period. Most mass wasting is concentrated along the steep streamside slopes, with significant contributions from larger slides that initiate relatively high on the slope.

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