FRESHWATER CREEK TMDL
SEDIMENT SOURCE ASSESSMENT
PHASE I

Prepared for

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FRESHWATER CREEK TMDL SEDIMENT SOURCE ASSESSMENT PHASE I

I. Introduction

A. Purpose/Background

The Freshwater Creek TMDL study area is located in Humboldt County in the vicinity of Eureka, California (Figure1). The study area is comprised of three main watersheds including Freshwater Creek, the Ryan Slough planning watershed and the Fay Slough planning watershed. The entire TMDL study area is approximately 57.9 mi^2 in area. The Freshwater Creek watershed comprises approximately 53% (30.7 mi^2) of the TMDL study area. The Ryan Slough planning watershed includes 26% (14.7 mi^2) of the TMDL study area, and the Fay Slough planning watershed comprises 21% (12.4 mi^2) of the TMDL study area.

Approximately78% of the Freshwater Creek watershed and the Ryan Slough planning watershed are managed for commercial timber harvesting operations by the Pacific Lumber Company (Freshwater Creek) and Green Diamond Resource Company (Ryan Slough). Land use within the remaining 22% of the area within Freshwater Creek and the Ryan Slough planning watershed, as well as the Fay Slough planning watershed includes urban development, rural subdivision, recreation, and smaller private industry.

Under the Clean Water Act Section 303(d), the Freshwater Creek watershed was listed by the North Coast Regional Water Quality Control Board (Regional Water Board) and the U.S. Environmental Protection Agency (EPA) as a sediment impaired water body. Space Imaging was granted a CMAS contract to conduct the sediment source analysis for the Freshwater Creek TMDL sediment study. Space Imaging partnered with Pacific Watershed Associates and landslide modeler Bill Haneberg, to complete the work elements necessary to conduct the project. Subsequently, Sanborn was spilt from Space Imaging and has assumed continued management of the project.

The original work plan submitted by Sanborn for the Freshwater Creek sediment source assessment includes four main tasks. Task 1 involves compiling the historic aerial photography and LIDAR imagery (Task1.1) and developing a comprehensive GIS library (Task 1.2) with the necessary GIS coverages and shapefiles required to run the slopes stability and road surface erosion models.

Task 2 involves conducting a comprehensive landslide inventory using the 1987, 1997 and 2003 historic air photo sets. In addition, Task 2 work elements include a field verification study of a sample of air photo identified landslides to verify landslide type, size, sediment delivery and land use association. Finally, Task 2 includes an air photo identified landslide and field inventoried landslide comparison study designed to determine how many landslides were not detected in the

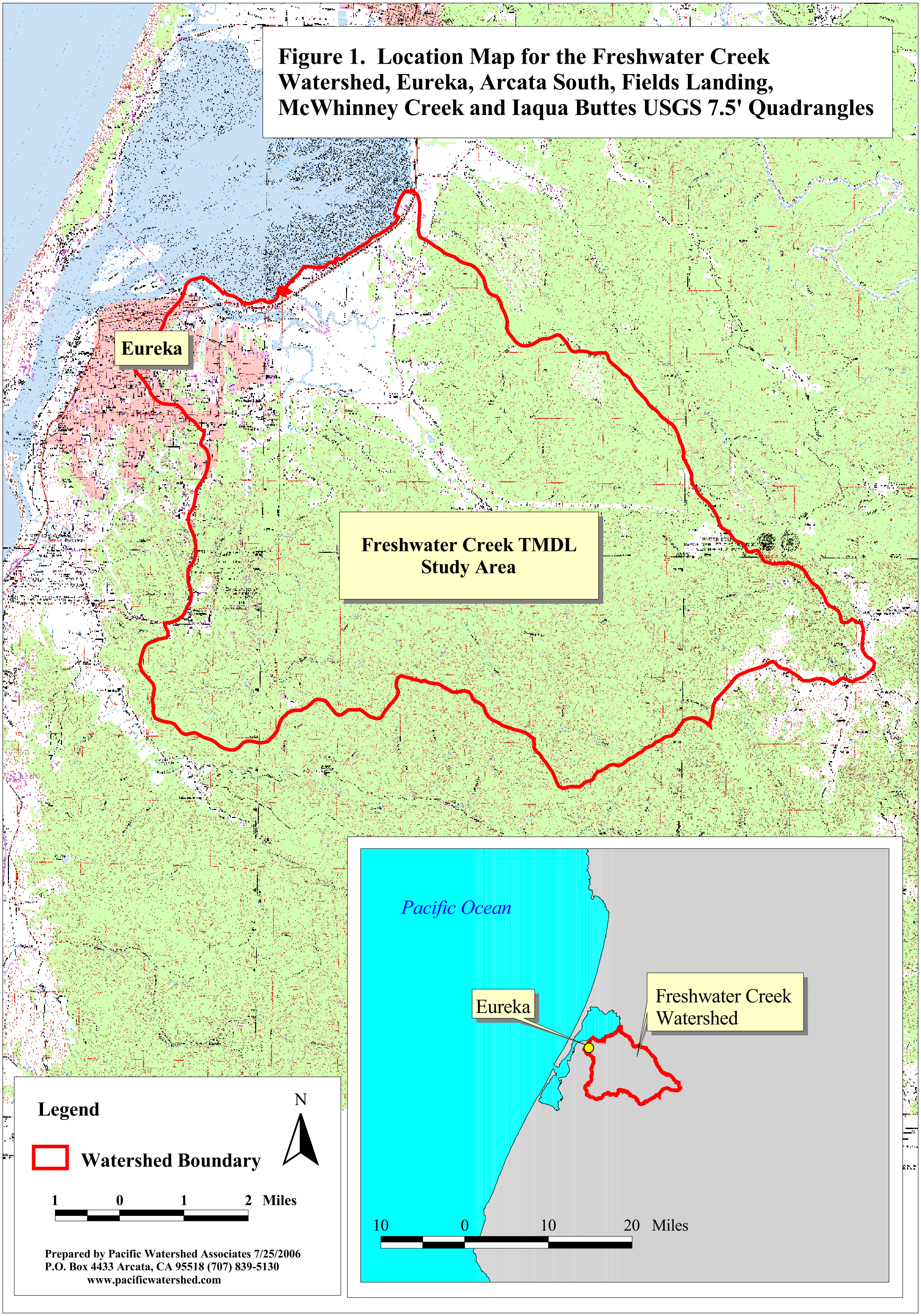
Figure 1. Location Map for the Freshwater Creek Watershed, Eureka, Arcata South, Fields Landing, McWhinney Creek and Iaqua Buttes USGS 7.5' Quadrangles
Eureka
Freshwater Creek TMDL Study Area
Pacific Ocean
Eureka
Freshwater Creek Watershed
10 0 10 20 Miles
Legend
N
Watershed Boundary
1 0 1 2 Miles
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air photo analysis due to obstruction by the forest canopy within old-growth, mature second-growth (>30 years old) and "young" forest (<30 years old) sample plots. Two sample plots for each timber age class category were proposed for the air photo landslide and field identified landslide comparison study.

Task 3 involves conducting geologic slope stability modeling to identify varying landslide hazard throughout the Freshwater Creek TMDL study area. Geologic hazard models include: Shalstab (Dietrich and Montgomery, 1998); PISA – Probabilistic Infinite Slope Analysis (Haneberg, 2001); and SMORPH (Vaugeois and Shaw, 1999). In addition, the study will involve modeling at least one type of landslide triggering event (i.e. rainfall or seismic input).

Task 4 includes developing road surface erosion estimates using SEDMODL2. SEDMODL modeling was conducted by Kathy Dube in Freshwater Creek as part of the 2000 PALCO Watershed Analysis. As part of this project, SEDMODL2 will be run on areas outside of the Freshwater Creek Watershed Analysis Area (i.e. Fay Slough and Ryan Slough planning watersheds. Road surface erosion estimates developed by Kathy Dube for the Freshwater Creek Watershed Analysis will be combined with the road surface erosion estimates calculated as part of this study in order to provide an estimate of total road surface erosion for the entire Freshwater TMDL study area.

Task 5 involves conducting a watershed assessment of the Freshwater Creek TMDL study area. This task involves using spatial databases and model outputs to categorize and rank sub-watersheds by their erosion and mass wasting potential based on watershed characteristics including geology, vegetation, drainage area, roads harvest history and landslide history.

Due to delays beyond the control of the contractor and subcontractors, including final CMAS contract development and feedback from the Regional Board staff regarding study design, the work conducted on the project was not initiated until April, 2006. The final CMAS contract end date was determined to be May 26, 2006. This left little time to conduct all of the work elements outlined in the work plan. As a result, only a subset of the work elements was completed by the end of the CMAS contract end date.

Completed work tasks for Phase I of the Freshwater Creek TMDL Sediment Source Study are being addressed in this summary report include: 1) Task 1 involving the compilation of GIS data library and other data sources; 2) Task 2 including the air photo analysis landslide inventory, field verification of a sample of air photo identified landslides, and the air photo identified landslide and field inventory identified landslide comparison study; and 3) Task 4 involving the development of surface erosion estimates for the Freshwater Creek TMDL study area.

B. Scope of Work

The scope of the work conducted as part of Phase I of the Freshwater Creek TMDL Sediment Source Assessment included identification and documentation of the following:

- The types and rates of landslides occurring in the watershed.
- Landforms having similar inherent physical characteristics relative to landslide activity.
- The effects of land use practices on landslide activity (rates) on different landforms.

- The relative contribution of sediment to streams by landslides, over the TMDL study time period (1987 -2003).
- The rate of sediment delivery from road surface erosion over the TMDL study time period (1987 -2003).
- The comparison of the accuracy and results from air photo landslide analysis and field landslide inventory on three different timber age stands in the Freshwater Creek and Elk River watersheds.

The Freshwater Creek TMDL Sediment Source Assessment Phase I report is organized into 5 sections. The first section provides the introduction to the TMDL sediment source assessment report including the purpose, scope of work, background information and reference materials used in the study.

Section 2 of the summary report describes the geologic characteristics and tectonic setting of the Freshwater Creek TMDL study area. Section 3 describes the methodology, results and confidence in analysis for the mass wasting air photo analysis and field verification of air photo identified landslides. Results for the air photo analysis of mass wasting are organized to: 1) describe each air photo analysis component (i.e. road construction history, land use history, landslide history); 2) provide general landslide information including landslides by landform type, geology, erosion process, etc., and; 3) discuss the relationship between mass wasting and land use association.

Section 4 describes the methodology and results for the air photo comparison study conducted on 3 different timber age stands (old growth, advanced or mature second growth (stand age >30 years old), and "young" forest (stand age <30 years). Section 5 describes the methodology and results from the SEDMODL analysis conducted to determine past sediment delivery from road surface erosion for the TMDL study time period (1987-2003). Results are presented by the three main planning watersheds in the TMDL study area (Freshwater Creek, Ryan Slough and Fay Slough).

Phase I of the Freshwater Creek TMDL sediment source study involved four discrete steps. The first step involved a comprehensive aerial photograph inventory of the land use history, road construction history, and landslide history for the TMDL study area. Second, a subset of air photo-identified landslides was field verified to determine the accuracy of landslide attributes. Third, roads identified in the road construction history were used to develop road surface erosion rates for the TMDL study area. Finally, a field study was conducted to compare the accuracy of air photo identified landslide identification and classifications with detailed ground-based landslide inventories conducted within 3 timber stand age plots. All air photo analysis and field inventories were conducted under the supervision of Eileen Weppner, Professional Geologist #7587 and Dr. William Weaver. Final analysis and report writing were conducted by Eileen Weppner and Dr. William Weaver.

C. Background Information/Reference Materials

Source and reference information for the Freshwater Creek TMDL study included:

- PALCO historical aerial photography for the Freshwater Creek TMDL study area (including the 1987, 1997 and 2003 air photo sets).
- Digital elevation model (DEM) based on LIDAR imagery from Sanborn.
- USGS Digital elevation model (10 meter DEM) for the Arcata South and Eureka topographic quadrangles (used to develop slope layer and stream layer for the Fay Slough planning watershed).
- PALCO data attributes for Freshwater Creek air photo identified landslides
- PALCO GIS data layers.
  - GIS shape file of Freshwater Creek 1987, 1997 and 2003 landslides.
  - GIS shape file of Freshwater Creek Watershed Analysis area sub-basins
  - GIS shape files of 1987, 1997 and 2003 road construction history
- Geology of the Cape Mendocino, Eureka, Garberville, and Southwestern Part of the Hayfork 30 x 60 Minute Quadrangles and Adjacent Offshore Area, Northern California (McLaughlin et al., 2003)
- California Department of Forestry timber harvest GIS shape files from 1986-2003
- California Department of Forestry and Fire Protection, Fire and Resource Assessment Program 1:24000 GIS road layer
- North Coast Watershed Assessment Program landslide maps developed by the California Geological Survey for Freshwater Creek.

Previous landslide mapping conducted by the California Geological Survey (CGS) for the North Coast Watershed Assessment Program (NCWAP) was used to develop the landslide data set for the Mass Wasting Module component of the Freshwater Creek Watershed Analysis in 2000. Landslide data sets from PWA and CGS were compared independently to identify gaps in landslide identification for the 1954, 1966, 1974, 1987 and 1997 air photo time periods. The two data sets were combined to derive the final landslide data set used in the Freshwater Creek Watershed Analysis Mass Wasting Module. Only a few small landslides uniquely identified by CGS were added to the larger PWA data set to complete the Freshwater Creek Watershed Analysis Mass Wasting Module landslide inventory.

The NCWAP landslide data was only used as a landslide location tool for the Freshwater Creek Watershed Analysis landslide inventory. Unfortunately, the NCWAP landslide data does not contain attribute information needed for the TMDL analysis, including specific landslide volume or dimension information, or information relating to the amount of sediment delivery, specific land use association or geomorphic association. In addition, the NCWAP landslide mapping includes historic and relict landslide features that may be greater than 150 years old.

The focus of the landslide inventory for the 2000 Freshwater Creek Watershed Analysis was to identify and quantify recent landsliding (i.e., that occurring in the last 50 – 60 years). Landslides identified in the 2000 Freshwater Creek Watershed Analysis were attributed by the land use history, as well as other specific landslide attributes (i.e. geomorphic association), in order to more fully identify causal mechanisms and associations with management. Other than landslide location, the NCWAP landslide data attributes were not applicable to the PWA 2000 Freshwater Creek air photo inventory landslide data.

Like the air photo landslide inventory for the 2000 Freshwater Creek Watershed Analysis Mass Wasting Module, the air photo landslide inventory for the Freshwater Creek TMDL sediment study is primarily focused on identifying and quantifying recent landslides, and in determining their magnitude and cause(s). In addition, the TMDL study is interested in other specific attributes such as land use history, geomorphic association, and geology. As described above, the PWA air photo landslide inventory methods have been found to successfully identify the majority of the recent landslides identified on NCWAP landslide maps of the same area. Because of this, and because the PWA data includes specific and useful attribute information that is not collected by CGS, the NCWAP landslide data was not used in conjunction with the PWA air photo landslide inventory data for the Ryan Slough and Fay Slough planning watersheds or for the 2003 PALCO landslide forensic study.

II. Geologic Setting of the Freshwater TMDL Study Area

Coastal California north of Cape Mendocino lies within the tectonically active convergent margin of the North American plate. Since the Mesozoic Era, the geologic development of Northern California has been dominated by plate convergence. During the last 140 million years, subduction and the resulting continental accretion have welded a broad complex of highly deformed oceanic rocks to the western margin of the North American plate. These accreted rocks now comprise the Franciscan Complex, which constitutes the basement of the north coast region (Carver and Burke, 1992). Throughout the latest geologic period, major uplift of the Coast Ranges and erosional stripping of the regionally extensive forearc sediments are postulated to have resulted from the combined effects of the eastward subduction of the Gorda plate and the northward migration of the Mendocino triple junction (Nilsen and Clarke, 1987). Today, geologically youthful cover sediments are preserved in a series of structural settings such as those found within and around the greater Humboldt Bay region (Clarke and McLaughlin, 1992; Nilsen and Clarke, 1987; Carver, 1987).

The distribution of lithologic units within the Freshwater Creek TMDL study area is illustrated in Table 1 and Map 1. The lithology for the study area was compiled from the Geology of the Cape Mendocino, Eureka, Garberville, and Southwestern Part of the Hayfork 30 x 60 Minute Quadrangles and Adjacent Offshore Area, Northern California developed by McLaughlin et al. (2000).

The Freshwater Creek TMDL study area is comprised of the following lithologies:

Franciscan Complex –Central Belt and Coastal Belt units of the Franciscan Complex are found in the study area (Table 1 and Map 1).

> **KJfm** – The Franciscan mélange consists of a matrix of clayey, penetratively sheared meta-argillite and blocks of metasandstone.. Twenty-four percent (24%) of the study area is underlain by this unit, which exhibits rounded, poorly incised, lumpy and irregular topography (McLaughlin et al., 2000). The Franciscan mélange is found primarily in the eastern half of the Freshwater Creek watershed, and in isolated areas in the Fay Slough planning watershed.

KJbf – The Broken Formation consists of bedded to massive, locally folded, rarely conglomeratic, meta-sandstone and meta-argillite. The Broken Formation typically exhibits sharp crested topography with regular well incised side hill drainages (McLaughlin et al., 2000). Less than 1% of the Freshwater Creek TMDL study area is underlain by the Broken Formation, and these rocks crop out along the eastern side of the Freshwater Creek Fault in the Freshwater Creek watershed.

Table 1. Lithology of the Freshwater Creek TMDL Study Area.

Lithology	Ryan Slough		Freshwater Creek		Fay Slough		Total	
	Area (mi^2)	% area	Area (mi^2)	% area	Area (mi^2)	% area	Area (mi^2)	% area
Qal	0.3	2%	1.0	3%	4.5	36%	5.7	10%
Qt	4.2	28%	0.5	1%	3.2	26%	7.8	14%
QTw	9.9	67%	14.9	49%	4.4	36%	29.3	51%
TKy	0.4	3%	0.8	3%	0.0	0%	1.2	2%
KJfm	0.0	0%	13.5	44%	0.2	2%	13.7	24%
KJbf	0.0	0%	0.1	<1%	0.0	0%	0.1	<1%
Total	**14.7**	**100%**	**30.7**	**100%**	**12.4**	**100%**	**57.9**	**100%**

Coastal belt – The Coastal Belt underlies the majority of the Freshwater Creek TMDL study area, comprising approximately fifty-three percent (53%) of the study area (Table 1 and Map 1). The Coastal Belt is divided into two structural and lithologic terranes.

TKy –The Yager terrane consists of thin to medium bedded argillite and arkosic sandstone and massive to thickly bedded arkosic sandstone with minor interbeds of argillite. The Yager terrane is divided into 3 subunits based principally on topographic expression: "y1" sheared and highly folded mudstone with irregular topography; "y2" highly folded broken mudstone, sandstone, and conglomeratic sandstone with sharp ridge crests and well incised drainages; and "y3" highly folded, broken sandstone, conglomerate, and mudstone with sharp ridge crests and well incised drainages. Only the "y1" subunit is located in the TMDL study area and represents approximately 2% of the TMDL study area. The "y1" subunit is found primarily in the incised stream channels in Freshwater Creek and locally in the Ryan Slough planning watershed (Table 1 and Map 1).

QTw – The undifferentiated Wildcat Group consists predominantly of weakly to moderately well lithified marine sandstone, siltstone, mudstone, and minor conglomerate. Fifty-one percent (51%) of the study area is underlain by this geologic unit (Table 1 and Map 1).

Quaternary Terrace Deposits (Qt) – Terrace deposits consist of Holocene and Late Pleistocene undifferentiated non-marine terrace deposits. Specifically, Qt consists of dissected and uplifted gravel, sand, silt and clay deposited in fluvial settings. In addition, Qt consists of minor shallow intertongues and warped tilted beds of Late Pleistocene Hookton Formation (McLaughlin et al., 2003). Approximately 14% of the Freshwater Creek TMDL study area is underlain by Qt. In the Ryan Slough planning watershed, Qt primarily consists of the Hookton Formation.

Quaternary Alluvial Deposits (Qal) -Alluvial deposits are found along the low elevation areas of the main stem reaches of Freshwater Creek and the Ryan Slough planning watershed, and throughout the low elevation alluvial fan and floodplain areas of the Fay Slough planning watershed. They comprise approximately 10% of the TMDL watershed assessment area (Table 1 and Map 1). These deposits consist of Holocene clay, silt, sand, gravel and boulders deposited in stream beds, alluvial fans, terraces, floodplains and ponds (McLaughlin et al., 2003).

III. Air Photo Interpretation/Field Verification

A. Methods

1. Air Photo Interpretation

A comprehensive air photo analysis was conducted to identify all landslides with sediment delivery that occurred in the Freshwater Creek TMDL study area on three historic sets of air photos. Aerial photographs were obtained for the 1987/1988, 1997 and 2003 air photo years. Analysis of past landslides does not show where future debris slides will develop, but it can be used to help evaluate the location of slopes or geomorphic settings which are most susceptible to shallow mass wasting in the watershed. Landslides identified on aerial photographs are considered to be largely triggered by significant storms. Aerial photo years were chosen to capture the effects of major storms in the 1983, 1997 and 2003 water years. However, the effects of more than one major storm are represented on the 1987/1988, and 2003 aerial photographs. The air photo analysis conducted as part of this project was focused on areas within the Freshwater Creek TMDL study area where no existing data was available. Existing data from the Palco Freshwater Creek Sediment Source Investigation (PWA, 1999) and the Freshwater Creek Watershed Analysis (2000) were used to supplement air photo analysis data for the 1987 and 1997 air photo years. In addition, PALCO forensic landslide data from the 2003 aerial photography was used to provide landslide data for the 2003 air photo time period. As a result, air photo analysis as part of this project was only conducted on the 1987, 1997 and 2003 aerial photography for the Fay Slough and Ryan Slough planning watersheds.

Air photo interpretation involved the development of a comprehensive land use and landslide history for the Freshwater Creek TMDL study area including: 1) harvesting history, 2) road construction history, and 3) landslide history. The land use history for Fay Slough, Ryan Slough and Freshwater Creek were compiled from California Department of Forestry THP maps dating back to the earliest available time period (1986). The road construction history for the Ryan Slough and Fay Slough planning watersheds was developed by mapping the roads by first appearance on the aerial photography for each year analyzed. Roads were mapped as line features on the air photo mylars. The road construction history for Freshwater Creek was derived from air photo analysis conducted as part of the Palco Freshwater Creek Sediment Source Investigation (PWA, 1999) and the Freshwater Creek Watershed Analysis (2000).

For the landslide history conducted in the Ryan Slough and Fay Slough planning watersheds, each new landslide which appeared on the photographs was assigned a unique site number and characterized using a variety of factors. Specifically, all visible recent or active landslides that deliver sediment to streams with a minimum area of 400 ft^2 were mapped on mylars overlying air photos and attributes were recorded on a standardized dataform. Mass wasting attributes collected from air photo interpretation included:

- Unique identification number
- Air photo year
- Sub-basin
- Feature type (as per Cruden and Varnes 1996 classification nomenclature)
- Certainty of identification
- Approximate landslide width
- Approximate landslide length
- Sediment delivery to streams
- Delivery certainty
- Aspect
- Stream type
- Land use association
    - Road location (RD)
    - Skid trail location (SK)
    - Tractor clearcut (TC) - <2% crown density remaining
    - Cable clearcut (CC) -<2% crown density remaining
    - Seed tree tractor cut (STT) – 2%-20% crown density remaining
    - Moderate partial cable harvest (MPC) – 20%-50% crown density remaining
    - Light partial cable harvest (LPC) - > 50% crown density remaining
    - Moderate partial tractor harvest (MPT) - 20%-50% crown density remaining
    - Light partial tractor harvest (LPT) - >50% crown density remaining
    - Grazing (GZ)
    - No apparent management activities (NO)
- Approximate stand age - the age of the stand at the point of failure (upper-most point on landslide).
- Geomorphic association at crown of the landslide (upper-most point on landslide)
    - Inner gorge slope (IG) (slopes formed by coalescing scars originating from mass wasting and stream erosion processes)
    - Steep stream side slopes (SSS) (>65% hillslopes continuous to stream, slopes not formed by coalescing landslide scars and stream erosion)
    - Stream side (SS) 50-64% hillslopes continuous to stream)
    - Stream channel (ST)
    - Swale channel (SW)
    - Headwall area (HD)
    - Major break-in-slope on hillslope, not inner gorge (BIS)
    - Other
- Slope (%) - Hillslope steepness passing through the mass wasting feature crown scarp point. Hillslope steepness was derived from LIDAR imagery

All landslides were mapped as polygons on the mylars overlying the historic aerial photography. All information mapped on air photo mylars for road construction history and landslide history was transferred to 1:24,000 USGS topographic quadrangle base maps. The base maps were scanned and “rubber sheeted” or geo-referenced, and air photo identified landslides were digitized using ArcGIS software. Attribute data collected for the mass wasting features were collected on a standardized data form and entered into a relational database.

Existing Palco data for Freshwater Creek landslides occurring during the 1987, 1997and 2003 time periods was compiled for the Freshwater Creek TMDL project. Additional landslide attributes such as landslide delivery % and land use association were collected for landslides identified on the 2003 aerial photography by PALCO as part of their forensics landslide study. All air photo landslide data was compiled into one master database for analysis purposes.

Landslide depths were estimated by testing statistical relationships between landslide length, width, area and depth. For Freshwater Creek, landslide depths were determined by using a linear regression equation developed for the Freshwater Creek Sediment Source Investigation (PWA, 1998). The equation is based on the relationship between landslide surface area using field data collected during the field verification phase of the 1998 Freshwater Creek Sediment Source Investigation. The field-verified landslides were used to develop a linear regression equation (Depth=0.00024*Area + 1.426, R^2=0.52) to estimate depth for landslides that were not field verified. Freshwater Creek shallow landslide volumes were calculated from the air photo measured areas and depths derived from the regression curve.

Estimated depth for shallow landslides in the Ryan Slough and Fay Slough planning watersheds was estimated from field verified 1997 and 2003 air photo identified landslides, as part of the Freshwater Creek TMDL Study. Statistical analyses were conducted to determine the relationship between landslide area and depth, as well as other relationships between other landslide dimension parameters. No statistical relationship existed between landslide depth and landslide area. The only significant statistical relationship (R^2 = 0.92) existed between landslide volume and landslide area. This suggests that landslide depth does not vary, regardless of landslide size or volume. An estimated landslide depth of 3.5 feet was determined by averaging field verified depth measurements for the 34 field verified landslides.

Volumes for debris flow (torrent) tracks were estimated using a unit erosion estimate of 2.91 yds^3/ft developed from previous studies conducted on PALCO lands in the Jordan Creek (PWA 1998b) and Bear Creek (PWA 1998a) watersheds. The unit erosion estimate was applied to the length of scoured (torrented) channel identified in the air photo analysis.

Earthflow erosion and sediment delivery were estimated using an earthflow toe retreat or movement rate of approximately 1.82 ft/yr developed from previous studies in the Middle Fork Eel River (Department of Water Resources, 1982). A number of other past studies conducted in Redwood National Park (Nolan and Janda 1995; Swanston, Ziemer and Janda 1995; Harden, Colman and Nolan 1995) and the Van Duzen River (Kelsey, 1977) were reviewed for the development of the earthflow toe retreat rate. An average rate of 4.3 ft/yr was estimated for the Van Duzen River and Redwood Creek earthflows. These earthflows are much larger and more active than the earthflows identified in the Freshwater Creek TMDL study area. The Middle Fork Eel River earthflow toe retreat rate was more applicable to the size of the earthflows in the study area.

The earthflow toe retreat rate was applied to high annual precipitation years between 1988 and 2003 with a maximum earthflow displacement time period of 2 years for each high precipitation year. In order to be classified as a high annual precipitation year, annual rainfall had to exceed mean annual precipitation by at least 10%. Annual precipitation estimates were delineated from historic records from the Scotia, California gage.

Previous studies have shown that the duration of earthflow displacement can occur over a period of days to years (Harden, Colman and Nolan 1995). Based on studies conducted on the Minor Creek earthflow in Redwood Creek (Iverson 1984) and the Davilla Hill earthflow complex (Keefer and Johnson 1983), a duration of 2 years for cumulative earthflow displacement was applied to each high annual precipitation year to estimate earthflow sediment delivery in the Freshwater Creek TMDL study area.

2. Field Verification of Air Photo Identified Landslides

Field verification of mass wasting features included:

- Field-verify all air photo mass wasting attributes, including: location, morphology, geomorphic association and mass wasting mechanisms.
- Measure mass wasting dimensions and other parameters for volume estimates and comparison with parameters measured on aerial photographs.
- Estimate sediment delivery to watercourses.
- Identify natural and management-related site conditions leading to or associated with slope instability.

Thirty (30) percent of the air photo-identified mass wasting features on the two most recent aerial photo years (1997 and 2003) were selected for field verification in the Ryan Slough planning watershed. Only one landslide was identified on air photos in the Slough area. Since the landslide was located on private property, no attempt was made to field verify the site. No 1997 or 2003 landslides were field verified in the Freshwater Creek Planning Watershed as part of this study. A sample of landslides identified on the 1997 air photos were field verified as part of the 1998 Freshwater Creek Sediment Source Investigation. We chose to use the existing information for field verified landslides in Freshwater Creek.

Field verified mass wasting features were chosen to reflect all lithologic types identified in the Freshwater Creek TMDL study area, as well as road and non-road related associations. Due to time and budgetary constraints, field verified features were also chosen based on their accessibility. In addition to the field verification of mass wasting attributes identified during the air photo analysis, a number of field-observed attributes were also collected, including:

- Primary cause of landslide
    - Natural
    - Harvest
    - Road
    - Railroad
    - Skid trail

- Grazing
- Diverted/Concentrated flow
- Other

- Secondary cause (see above)
- Mid-feature hillslope gradient
- Activity level including percent active and activity indicators

Field data was collected on a standardized data form and entered into a relational database.

B. Results

1. Air Photo Analysis

The air photo analysis component of the Freshwater Creek TMDL sediment source study involved a comprehensive air photo analysis to determine the road construction, timber harvest, and landslide history for the TMDL study area. The road construction, land use and landslide histories for the Fay Slough and Ryan Slough planning watersheds were developed from the 1987/1988, 1997 and 2003 historical aerial photographs. Existing road construction, land use and landslides history data from previous PALCO studies in the Freshwater Creek watershed were used in the Freshwater Creek TMDL study. The 1987 photo year was used as the baseline for the Freshwater Creek TMDL study area, even though portions of the Fay Slough, Ryan Slough and Freshwater Creek planning watersheds had been previously harvested and roaded.

Road Construction History

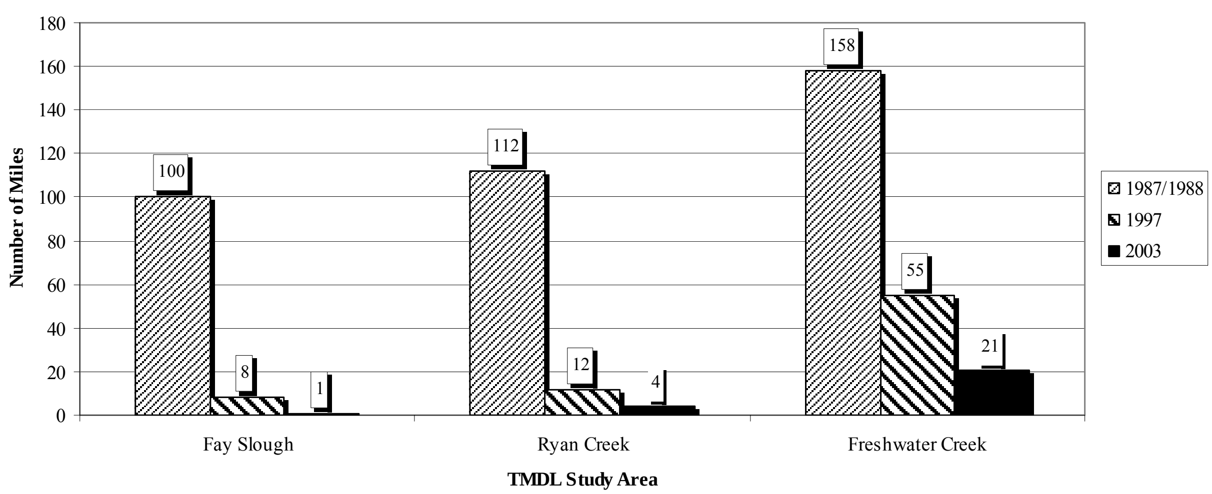
The road construction history documented the first occurrence of each road on the historic aerial photos. The first occurrence of the road does not imply that the road was constructed in the air photo year it was observed in. Rather, it implies that the roads were constructed during the time period between the historic air photo years analyzed. For roads identified on the 1987/1988 historic aerial photography, road construction occurred previous to 1987/1988 and could extend as far back as the early 20th century in some locations (i.e. Eureka area).

Figure 2 and Map 2 depict the general road construction history for the Freshwater Creek TMDL study area, as derived from the current and past analysis of historical aerial photography. A total of 408 miles of road were constructed in the TMDL study areas by the time of the 2003 aerial photography. The new road construction visible in each air photo year was used to develop an accurate representation of the road system during the time period of the Freshwater Creek TMDL study for use in SEDMODL analysis.

As of 1987/88, air photo analysis indicates 370 miles of road (79% of the total air photo identified road mileage) had already been constructed throughout the TMDL study area. Between 1988 and 1997, an additional 76 miles of road were built (7.6 mi/yr). Approximately 18% of the roads in the watershed were constructed between 1988 and 1997, with the vast majority of new roads being constructed in Freshwater Creek (Figure 2). Between 1997 and 2003 road construction continued at approximately 4.3 mi/yr, with approximately 26 miles of road constructed in the Freshwater Creek TMDL study area.

Between 1987 and 2003, the highest road densities in the Freshwater Creek TMDL study area were observed in the Fay Slough and Ryan Slough planning watersheds (8.8 mi/mi^2 and 8.7 mi/mi^2, respectively). The overall road density for Freshwater Creek was nearly 15% (7.6 mi/mi^2) lower than the road densities observed in the Fay Slough and Ryan Slough planning watersheds. The high road densities in the Fay Slough and Ryan Slough planning watersheds reflect the higher density of urban and rural subdivision roads.

Figure 2. Road Construction History for the Freshwater Creek TMDL Study Area



Land Use History

Figure 3 and Map 3 describe the harvesting and re-harvesting history for the Freshwater Creek TMDL study area as derived from CDF timber harvest plan GIS layers. The CDF timber harvest plan layers date back to 1986. Fortunately, the time period for the land use history for the Freshwater Creek TMDL study area spans 1986 to 2003.

In order to develop a harvest history, the CDF layers were analyzed based on the year of the timber harvest plan submission and the year of timber harvest completion. According to CDF timber harvest rules, all timber harvest plans must be completed within 3 years of THP submission and approval (the "effective" period), with up to five years after the completion of operations to meet stocking requirements. CDF THP layers provide attribute data for the date of THP submission and the year the THP was completed. Unfortunately, there is no record of when the harvesting activity actually occurred for each THP.

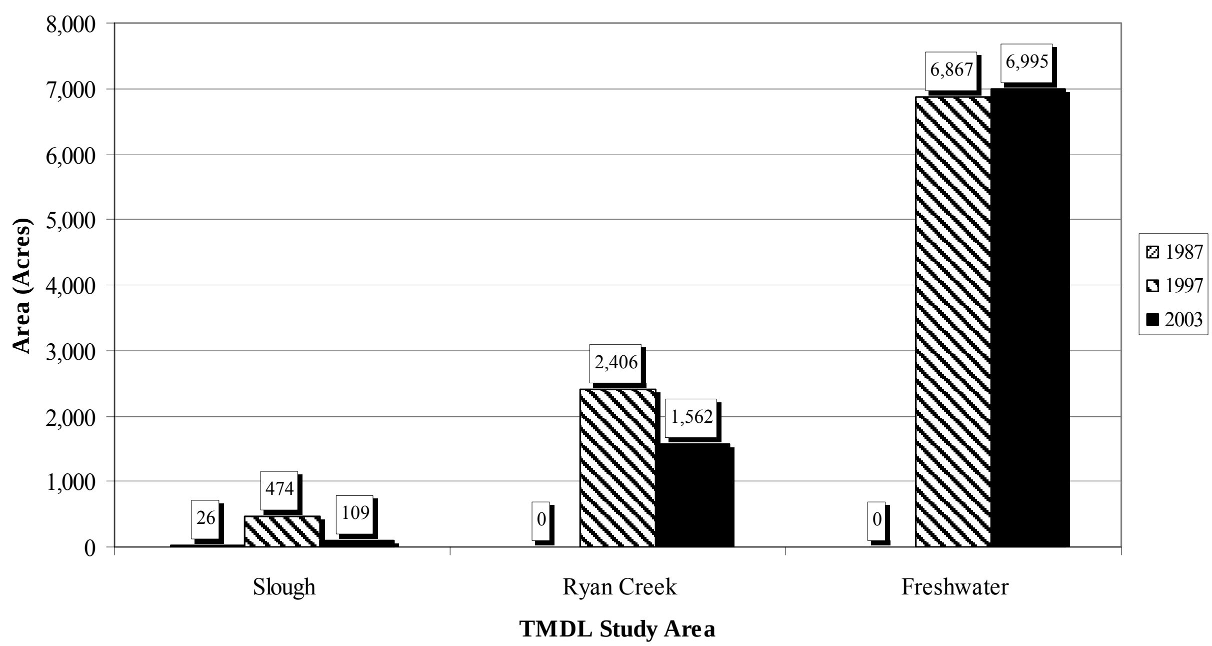
Several assumptions had to be made in order to construct the actual harvest history for the TMDL study area from the CDF THP GIS layers and attribute data. In viewing the CDF data, the average time period between THP submission and THP completion was estimated at 3 years including 1 year for re-stocking and THP completion procedures. For THPs with a date of completion provided in the attribute table, the estimated year of harvest activity was assumed to be 1 year prior to the THP completion date. For THPs with no completion date provided in the attribute table, the estimated year of harvest activity was determined to be 2 years after the year of the THP submission. Any THPs with an estimated submission date of 2002 or later were thereby eliminated from the THP GIS layer and attribute data set because their likely harvest date would have been after 2003.

Between 1986 and 1987, approximately 26 acres of the Freshwater Creek TMDL study area was harvested for timber. All 26 acres of the timber harvesting conducted between 1986 and 1987 occurred in the Fay Slough planning watershed. The rate of timber harvesting in the Fay Slough planning watershed was estimated at 13 acres/year. The low timber harvest rates recorded between 1986 and 1987 reflect the short time period (2 years) and the lack of THP data for this time period.

Between 1988 and 1997, the rate of timber harvesting increased in the Fay Slough, Ryan Slough and Freshwater Creek planning watersheds (Figure 3). Overall, the rate of timber harvesting increased from 12.8 acres/year between 1986 and 1987 to 956 acres/year between 1989 and 1997. The highest rate of timber harvesting during this time period was observed in the Freshwater Creek watershed (668 acres/year). The Fay Slough and Ryan Slough planning watersheds continued to have lower rates (93% and 80% lower, respectively) of timber harvesting as compared to Freshwater Creek (Figure 3).

Between 1998 and 2003, timber harvesting decreased in the Ryan Creek and Fay Slough planning watersheds (Figure 3). The highest rate of timber harvesting occurred in the Freshwater Creek watershed. Timber harvesting in Freshwater Creek increased from 668 acres/year between the 1988 and 1997 to 1,166 acres/year between 1998 and 2003.

Figure 3. Timber Harvest History for the Freshwater Creek TMDL Study Area



Landslide History

Landslides observed on the 1987/1988, 1997 and 2003 historical aerial photographs were used to construct a history of landsliding for the analysis period. Landslides tend to be triggered during major storm events. The December 21-22, 1964 storm (3.04"/2 days at Eureka according to National Weather Service records) is commonly used as a benchmark for a significant landslide-triggering storm. A total of 22 significant storms have been recorded at Eureka in the 1956, 1959, 1965, 1969, 1975, 1976, 1981, 1982, 1983, 1997, 1999, and 2003 water years, based on 3"/2 day and 4"/3 day rainfalls as threshold standards for significant storms. The storm of record in Eureka is the December 27, 2002 storm (6.79"/1 day). Other particularly large storms are recorded at 4.84"/1 day (Feb 1959), 5.91"/2 days (Jan 1975), 4.86"/1 day (Dec 1996), 4.60"/2 days (Dec 1996- Jan 1997), 4.12"/1 day (Oct 1997), 4.37"/1 day (Nov 1998), and 5.86"/2 days (Dec 2002). Local variability of storms does not allow direct comparison of intensities between storms in the study area based on Eureka rainfall records, only inclusion of an event in the general class of significant storms.

Landslide sediment delivery is expressed as total sediment delivered to watercourses (yds^3) and sediment delivery rate ($tons/mi^2/yr$). A soil bulk density of 1.4 $tons/yd^3$ was used to convert sediment volume to mass. Landslide sediment delivery rates can be derived as annual rates or as storm event-related rates. For the purposes of this study, annual delivery rates are determined by assuming the erosion occurs uniformly over the entire analysis time period, rather than variably from year to year. Annualized annual rates of sediment delivery ($tons/mi^2/yr$) have been the traditional unit used for depiction of mass wasting sediment delivery derived from air photo analyses. In this method, annualized sediment delivery rates are calculated by dividing the total unit sediment delivery ($tons/mi^2$) for a specific time period by the number of air photo years in the time period. Clearly, sediment is episodically generated and delivered during storm events and not as an average annual rate. The landslide sediment delivery discussion in this summary report refers to annualized rates, so as to be consistent with traditional sediment budget calculations, and with previous studies conducted in the Freshwater Creek TMDL study area.

A total of 190 landslides with past sediment delivery to streams were identified in the Freshwater Creek TMDL study area (Table 2 and Map 4). Air photo identified landslides generated approximately 87,600yds^3 of sediment to streams over the analysis period (1987-2003). Approximately 65% (n=123) of the observed landslides were observed in the Ryan Slough planning watershed (Table 2). Landslides observed in Ryan Slough account for 71% (62,380 yds^3) of the sediment delivery and the highest sediment delivery rate (228 $tons/mi^2/yr$) in the Freshwater Creek TMDL Study area. Approximately 78% of the Ryan Slough planning watershed is managed by the Green Diamond Timber Management Company. Of the 123 landslides observed in the Ryan Slough planning watershed, 116 (94%) were located within the Green Diamond ownership and account for 98% of the sediment delivery in the Ryan Slough planning watershed.

Nearly 35% (n=66) of the air photo identified landslides were observed in Freshwater Creek and account for 27% (24,333 yds^3) of the sediment delivery in the TMDL study area, and a sediment delivery rate of 43 $tons/mi^2/yr$. Similar to Ryan Slough, 78% of Freshwater Creek is managed by the Pacific Lumber Company. Of the 65 observed landslides in Freshwater Creek, only 1 landslide was observed on non PALCO property. Observed landslides on PALCO property represent 99 % of the landslides and 96% (23,469 yds3) of the sediment delivery to Freshwater Creek. Finally, only one landslide was observed in the Fay Slough planning watershed and represent 1% of the sediment delivery in the TMDL study area (Table 2).

Landslide type

Debris landslides (n=107) represent 56% of the landslides identified in the TMDL study area and 67% of the sediment delivered (58,686 yds^3). Other landslides types identified in the air photo analysis included 9 debris flows, 6 debris flow torrent tracks and 2 earthflows. Estimated sediment delivery from these other landslide types is approximately 28,951yds^3 (33% of the total sediment delivered by mass wasting processes) (Table 2).

Table 2. Frequency and Sediment Delivery from Air Photo Identified Landslides by Landslide Type, Freshwater Creek TMDL Study Area (1987-2003).

Feature Type	Ryan Slough		Freshwater Creek		Fay Slough		Total	
	#	Sediment Delivery (yds^3)	#	Sediment Delivery (yds^3)	#	Sediment Delivery (yds^3)	#	Sediment Delivery (yds^3)
Debris slide	107	43,753	53	14,009	1	924	161	58,686
Debris flow	9	10,566	7	6,249	0	0	16	16,815
Debris flow track	6	5,136	5	1,489	0	0	11	6,625
Earthflow	1	2,925	1	2,586	0	0	2	5,511
Total	**123**	**62,380**	**66**	**24,333**	**1**	**924**	**190**	**87,637**

Landslides by Air Photo Time Period

Approximately 66% (n=126) of the landslides identified in the air photo analysis in the Freshwater Creek TMDL study area were identified on the 1997 historic aerial photography (Table 3 and Map 4). Landslides identified in this time period were estimated to deliver approximately 65% (56,646 yds^3) of the total sediment delivered to streams during the 1987 to 2003 air photo time period. Three major storms occurred in 1996 including the 1996-1997 storm. Part of the difference in observed sediment delivery between the 1997 and 1987 photo periods may be attributable to the fact that the major storms of the 1987 period occurred earlier relative to the photo year and their effects may be less detectable.

The antecedent influence of three large earthquakes in 1992 may also have influenced sediment delivery in the 1988 to 1997 time period. The three earthquakes had epicenters located in the Cape Mendocino area. The first earthquake had a magnitude of 7.1M and occurred on April 25, 1992 approximately 6 miles north of the town of Petrolia. The second and third earthquakes occurred on April 26, 1992 and were located offshore approximately 6 miles west of the first earthquake epicenter. The magnitudes of the second and third earthquake were estimated at 6.6M and 6.7M, respectively.

Table 3. Landslides by Air Photo Time Period, Freshwater Creek TMDL Study Area								
Air Photo Time Period	Ryan Slough		Freshwater Creek		Fay Slough		Total	
	#	Sediment Delivery (yds3)	#	Sediment Delivery (yds3)	#	Sediment Delivery (yds3)	#	Sediment Delivery (yds3)
1987	18	15,227	11	3,088	0	0	29	18,315
1997	90	42,244	35	13,478	1	924	126	56,646
2003	15	4,909	20	7,767	0	0	35	12,676
Total	**123**	**62,380**	**66**	**24,333**	**1**	**924**	**190**	**87,637**

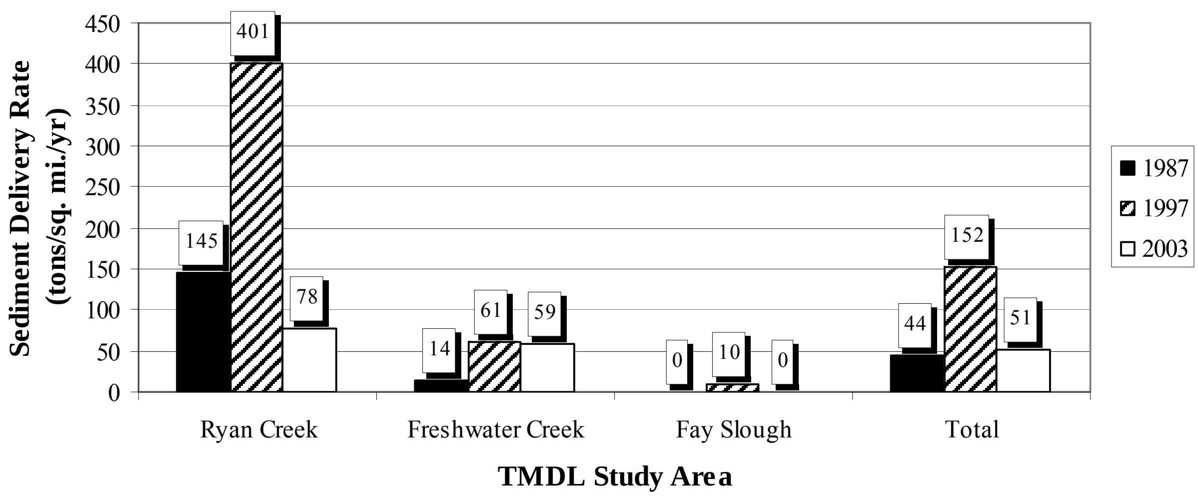
Landslides observed in the 1987 air photo time period represent 15% of the total number of observed landslides and approximately 21% of the overall sediment delivery (Table 3). The 1987 period contains eight major storm events and the wettest year of the entire analysis period (1982-1983; 1983 water year). The lower sediment delivery (18,315 yds^3) and sediment delivery rate (44 $tons/mi^2/yr$) may be attributable to improved management practices after implementation of Forest Practice Rules (Table 3 and Figure 4), and lower rates of timber harvesting in the period (Figure 3). Likewise, landslides observed in the 2003 air photo time period represent 18% of the observed landslides and nearly 14% of the overall sediment delivery. Lower sediment delivery (12,676 yds^3) and sediment delivery rate (51 $tons/mi^2/yr$) during this time period may reflect improved road construction and timber harvesting practices required under the PALCO and Green Diamond Habitat Conservation Plans (HCPs), or lower geomorphic response due to storm variability and the lack of a significant antecedent seismic event affecting the storm response in this period (Table 3 and Figure 4).

Landslides by Geomorphic Association

Between 1987 and 2003, over 54% (n=103) of the 190 observed landslides with sediment delivery occurred on inner gorge slopes, steep streamside slopes, streamside slopes and other streamside slopes (Table 4). These landslides account for approximately 40% (35,049 yds^3) of the total sediment delivery from air photo identified landslides in the TMDL study area. For the purposes of this study, inner gorge slopes are located below the last major break-in-slope, and formed by coalescing scars originating from mass wasting and stream erosion processes. Steep streamside slopes are areas located below the last major break-in-slope and not formed by coalescing landslide scars with slope gradients greater than or equal to 65%. Streamside slopes are also located below the last major break-in-slope, but are not formed by coalescing landslide scars and have slopes gradients between 50% and 64%. Other streamside slopes are located below the last major break-in-slope and have slope gradients less than 50%.

Of the 103 observed landslides occurring below the last major break-in-slope, forty-six (46) occurred on steep streamside slopes (non inner gorge slopes with >= 65% slope gradient) (Table 4). Landslides occurring on steep streamside slopes account for 18% (15,847 yds^3) of the total sediment delivery to streams within the TMDL study area. By far, the Ryan Slough planning watershed had the highest frequency (n=42) of landslides and the highest sediment delivery (14,756 yds^3) occurring on steep streamside slopes as compared to Freshwater Creek (n=4, 1,091 yds^3 sediment delivered).

Figure 4. Sediment Delivery Rate by Air Photo Time Period, Freshwater Creek TMDL Study Area



Twenty-eight of the 102 landslides occurring within the last break-in-slope occurred on streamside slopes (non inner gorge slopes with gradients between 50 and 64%). Streamside landslides account for 12% of the total sediment delivery to streams within the TMDL study area. Inner gorge landslides accounted for 20% of the landslides occurring below the last break-in-slope, but only delivered approximately 4% (3,415 yds^3) of the total sediment delivered to streams within the TMDL study area (Table 4).

Headwall locations accounted for 12% (n=22) of the air photo identified landslides and 18% (15,397 yds^3) of the total sediment delivered to streams in the TMDL study area (Table 4). Although the frequency of landslides occurring in headwall locations is distributed evenly between Ryan Slough and Freshwater Creek, headwall landslides occurring in Ryan Slough delivered 78% (12,007 yds^3) of the sediment delivery from all headwall landslides in the TMDL study area. Similarly, landslides occurring in swale locations account for 14% (n=27) of the air photo identified landslides and 16% (13,855 yds^3) of the total sediment delivery from landslides in the TMDL study area.

Landslides by Lithologic Unit
The majority (70%) of the air photo identified landslides with sediment delivery in the Freshwater Creek TMDL study area occurred in the Wildcat Group (Table 5). These landslides were estimated to deliver 68% (59,671 yds^3) of the total sediment delivered to streams in the study area with an overall sediment delivery rate of approximately 110 tons/mi^2/yr (Table 5 and Figure 5). The Wildcat Group represents approximately 51% (29.3 mi^2) of the TMDL area. The nature of Wildcat bedrock, and the manner in which it weathers, appears to play an important role in determining the location, volume and sediment delivery of landslides occurring in the

Table 4. Landslides by Geomorphic Association, Freshwater Creek TMDL Study Area								
Geomorphic Association	**Ryan Slough**		**Freshwater Creek**		**Fay Slough**		**Total**	
	#	**Sediment Delivery (yds³)**	**#**	**Sediment Delivery (yds³)**	**#**	**Sediment Delivery (yds³)**	**#**	**Sediment Delivery (yds³)**
Inner Gorge	10	1,522	10	1,893	0	0	20	3,415
Steep Streamside Slope	42	14,756	4	1,091	0	0	46	15,847
Streamside Slope	16	4,148	12	6,580	0	0	28	10,728
Other-Streamside Slope	5	3,681	3	454	1	924	9	5,059
Break-In-Slope	2	3,655	4	4,962	0	0	6	8,617
Headwall	10	12,007	12	3,390	0	0	22	15,397
Swale	15	9,570	12	4,285	0	0	27	13,855
Stream channel	7	4,950	4	887	0	0	11	5,837
Other location	16	8,091	5	791	0	0	21	8,882
Total	**123**	**62,380**	**66**	**24,333**	**1**	**924**	**190**	**87,637**

Freshwater Creek TMDL study area. Wildcat rocks are poorly indurated (cemented) and are considered to be geologically "soft." In response to rapid regional uplift, stream channels down cut and rapidly develop relatively low gradient profiles which terminate in short, steep headwall areas (zero-order basins). Channel sideslopes along larger order streams remain steep because of the rapid channel incision. Upland slopes, where first order streams have migrated headward toward the drainage divides and interfluves, often display high drainage densities and a high frequency of steep ridge-and-swale topography. By this manner, the erosional history of the Wildcat leads to the development of preferentially susceptible failure sites including steep stream side slopes and steep headwall swales. That is, the erosional dissection of Wildcat terrain has lead to a relatively high percentage of locally steep slopes.

It is postulated that slope failures developed on steep slopes underlain by Wildcat bedrock are naturally limited in volume, primarily due to slope steepness and slope length to the nearest drainage divide, and due to the uniform weathering characteristics of the bedrock material.

Almost all 1997 failures inspected in the field had failed down to bedrock, typically at a depth of much less than seven feet. The massive, but poorly indurated Wildcat bedrock develops a weathering profile that often parallels the surficial topography. The weathered materials appear to be non-cohesive, granular and relatively porous, and the underlying unweathered Wildcat bedrock is massive and relatively impervious. As a result, precipitation infiltrates to the bedrock

Table 5. Landslides by Lithology Type, Freshwater Creek TMDL Study Area								
	Ryan Slough		Freshwater Creek		Fay Slough		Total	
Lithology	**#**	**Sediment Delivered (yds^3)**	**#**	**Sediment Delivered (yds^3)**	**#**	**Sediment Delivered (yds^3)**	**#**	**Sediment Delivered (yds^3)**
Qal	0	0	0	0	0	0	0	0
Qt	31	18,908	0	0	0	0	31	18,908
QTw	89	40,592	43	18,155	1	924	133	59,671
TKy	3	2,880	1	236	0	0	4	3,116
KJfm	0	0	22	5,942	0	0	22	5,942
KJbf	0	0	0	0	0	0	0	0
Total	**123**	**62,380**	**66**	**24,333**	**1**	**924**	**190**	**87,637**

interface and then flows along the bedrock surface. These hydrologic conditions can lead to increased pore water pressures, increased ground water levels and may provide one mechanism for lubricating potential failure surfaces.

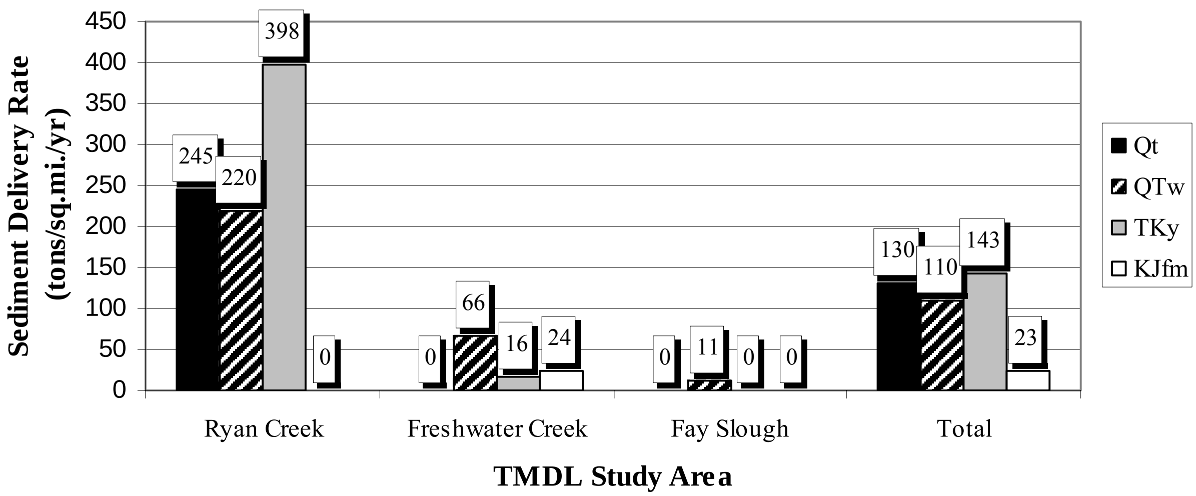
Groundwater levels and subsurface pore water pressures are known to be significant factors affecting slope stability and precipitating landslide occurrence, and it should be no different in the Freshwater Creek TMDL study area. Increased subsurface flow, increased groundwater elevation and increased seepage forces related to harvest history on steep inner gorge and stream side slopes can be expected to lead to increased risk of slope failure. Upslope harvesting may also act to increase soil water in downslope areas, including steep headwall swales, due to reduced interception and evapotransporation. Again, the impact is strongly seasonal and may have limited net effect during mid-winter high intensity, long duration storm periods when most slope failures occur.

Because of the massive nature of the bedrock, trees typically grow within the weathered mantle of soil materials but generally do not penetrate the unweathered strata. In this setting, roots probably provide arching and lateral support to the slope, but not much in the way of vertical anchoring. The Wildcat slope failures, which often exhibit planar or "sheet-like" basal slip surfaces fail to bedrock and strip both the granular weathered soil materials as well as the covering vegetation. It is unclear if loss of lateral strength from root decay or increased soil water and pore pressure are the principal causal mechanisms for increased rates of landsliding.

Approximately 16% (n=31) of the air photo identified landslides were observed on Quaternary terrace terrane. According to McLaughlin et al. (2000), Quaternary terrace deposits (Qt) are described as undifferentiated non marine Holocene and Pleistocene terrace deposits. This includes uplifted and incised Holocene fluvial terrace deposits and the late Pleistocene Hookton Formation. The Hookton Formation is underlain by the upper Wildcat Group and is predominantly located in the Ryan Slough planning watershed. Like the Wildcat Group in the TMDL study area, the Hookton Formation is composed of poorly indurated and geologically "soft" sediments (primarily non marine clay, sands and gravels). The Hookton Formation behaves like the Wildcat group in relation to depth of landsliding (landslides are typically shallow in the Hookton formation) and the topography consists of steeply incised channels caused by rapid uplift and erosional dissection. All of the observed landslides occurring in

Quaternary terrace terrain occurred in the Hookton Formation in the Ryan Slough planning watershed. The 31 landslides observed in the Hookton Formation represent 22% of the sediment delivered to streams in the TMDL study area. Quaternary terrace deposits and the Wildcat Group exhibited nearly equivalent sediment delivery rates in the Ryan Slough planning watershed (245 tons/mi^2/yr and 220 tons/mi^2/yr, respectively) (Figure 5).

Figure 5. Sediment Delivery Rate by Lithology Type, Freshwater Creek TMDL Study Area



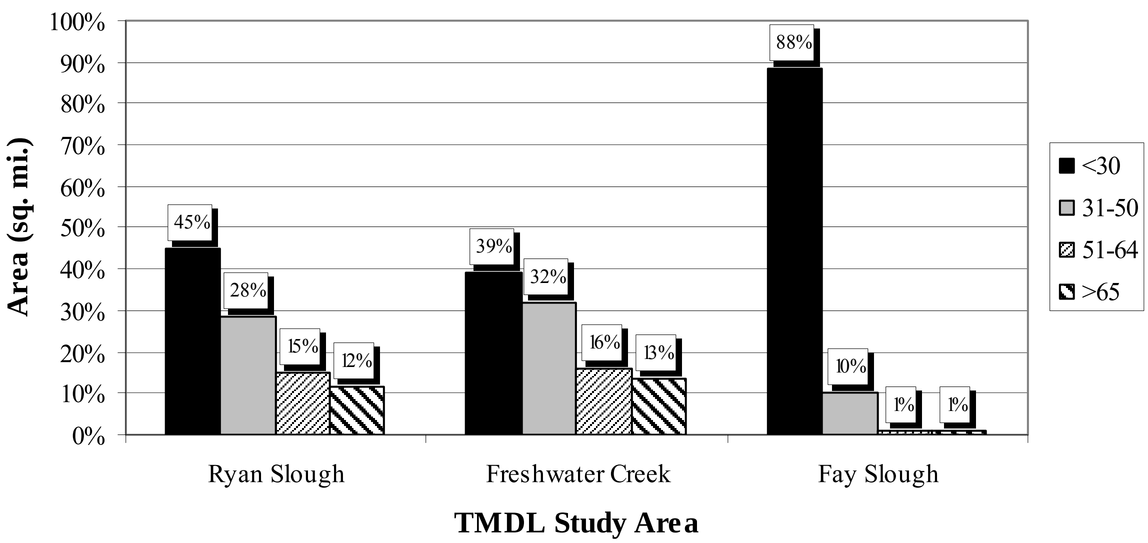
The high rates of landsliding in the Wildcat Group and Hookton Formation in the Ryan Slough planning watershed is likely due to higher stream densities. Stream densities in the Ryan Slough planning watershed are 50% higher as compared to the Freshwater Creek watershed. Approximately 95% of the Ryan Slough planning watershed is underlain by Hookton Formation and Wildcat Group lithologies (Table 1). In comparison, approximately 49% of the Freshwater Creek watershed is underlain by Wildcat Group and 41% of the watershed is underlain by the Franciscan mélange. The Franciscan mélange is more coherent and less dissected by uplift and stream incision.

The Yager terrane is typically located in the steep inner gorges underlying the Wildcat Group in the Ryan Slough and Freshwater Creek planning watersheds. Overall, the Yager terrane represents 2% of the entire TMDL study area and produced only 2% (n=4) of the landslides occurring in the study area. Although the frequency of Yager landslides is low in the TMDL study area, landslides in this terrane had the highest sediment delivery rate (approximately 143 tons/mi^2/yr). By planning watershed, the highest sediment delivery rate from landslides occurring in the Yager terrane (398 tons/mi^2/yr) occurred in Ryan Slough (Figure 5). High sediment delivery rates in the Yager terrane are likely due to a small number of large shallow debris landslides located on steeper slopes (2 of the 3 landslides on Yager bedrock originated on steep, 70-80% gradient swale locations and 1 occurred on a 60% streamside slope).

Landslides by Slope Class
To determine the frequency, magnitude and rate of landsliding by slope class, each of the Freshwater Creek TMDL planning watersheds was divided into 4 slope gradient classes (≤30%, 31-50%, 51-64%,≥65%). Slope classes for the Ryan Creek planning watershed and Freshwater Creek were derived from a LIDAR-based Digital Elevation Model at a 10 foot resolution. A 10 foot resolution is defined when converting the slope raster coverage to a slope polygon coverage by defining the output grid cell size as 10 feet for each raster. Because the LIDAR DEM does not cover the entire Fay Slough area the slope classes for that area were created from the USGS 10 meter DEM using the same resolution as the DEM. To spatially derive the area within each slope class, a polygon layer was developed for the four (4) slope classes. These areas were used to develop the landslide delivery rates, by slope class, for the TMDL study area (Table 6).

The Ryan Creek planning watershed and Freshwater Creek watershed had a similar frequency distribution between the 4 slope classes (Figure 6). Approximately 45% of the Ryan Creek planning watershed area and 39% of the Freshwater Creek watershed area are composed of slopes between 0% to 30% gradient. Approximately 30% of both the Freshwater Creek and the Ryan Creek planning watersheds are underlain by slopes between 31 and 50% in steepness. Only 12% of the Ryan Creek planning watershed and 13% of the Freshwater Creek watershed are composed of slopes greater than 65% (Figure 6). In comparison, eighty-eight (88%) percent of the Fay Slough planning watershed had slope gradients less than 30%, and 10% of the planning watershed had slope gradients between 31 and 50%. Only 2% of the slopes in the Fay Slough planning watersheds had slope gradients exceeding 50%. The majority of the Fay Slough planning watershed is composed of low gradient alluvial fan, floodplain and estuary areas.

Figure 6. Percent of Area by Slope, Freshwater TMDL Study Area

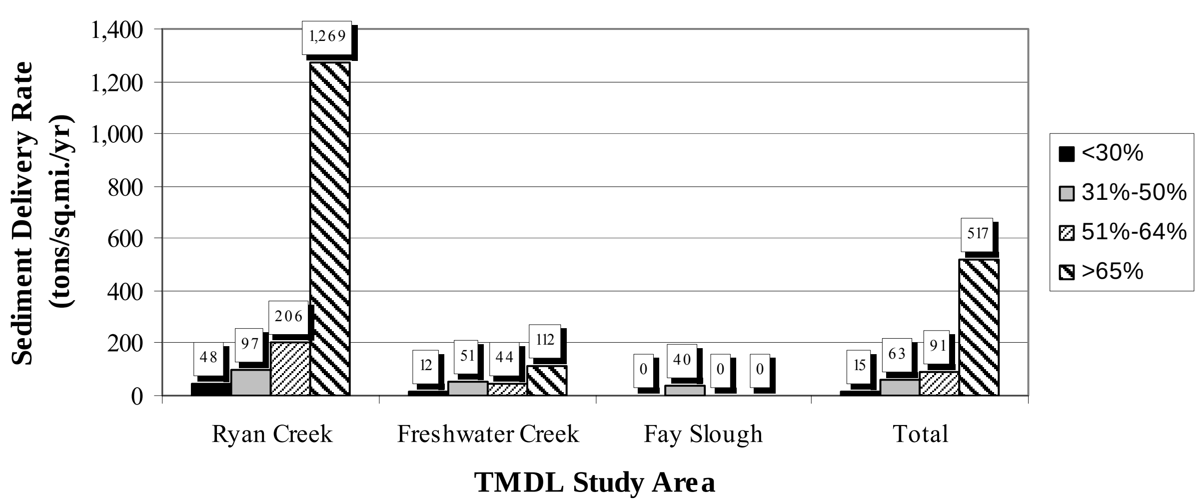


Sixty percent (n=114) of air photo landslides with sediment delivery identified in the TMDL study area were located on slopes greater than 65%. These landslides represent approximately 56% (49,062 yds^3) of the total sediment delivered to streams (Table 6) and exhibit the highest sediment delivery rate (451 $tons/mi^2/yr$) (Figure 7). Of the 114 landslides occurring on slope greater than 65%, 81 (71%) occurred in the Ryan Slough planning watershed. Landslides occurring on greater than 65% slopes in Ryan Slough alone represent 83% (40,528 yds^3) of the total sediment delivery from all slopes greater than 65% and 49% of the total sediment delivery to all streams within the entire TMDL study area. In addition, the Ryan Creek planning watershed exhibited the highest sediment delivery rate (1,269 $tons/mi^2/yr$) for landslides occurring on slopes greater than 65% slope gradient by planning watershed (Figure 7). Landslides occurring on slopes between 31% and 64% represent 37% of the landslides observed in the TMDL study area and 34% of the sediment delivered to streams (Table 6).

Table 6. Frequency and Sediment Delivery from Landslides by Slope Class, Freshwater Creek TMDL Study Area.

Slope Class	Ryan Slough		Freshwater Creek		Fay Slough		Total	
	#	Sediment Delivery (yds^3)	#	Sediment Delivery (yds^3)	#	Sediment Delivery (yds^3)	#	Sediment Delivery (yds^3)
<30	4	5,930	1	2,586	0	0	5	8,516
31-50	17	7,565	15	9,263	1	924	33	17,752
51-64	21	8,357	17	3,950	0	0	38	12,307
>65	81	40,528	33	8,534	0	0	114	49,062
Total	**123**	**62,380**	**66**	**24,333**	**1**	**924**	**190**	**87,637**

Figure 7. Sediment Delivery Rate by Slope Class, Freshwater Creek TMDL Study Area



Only 3% of the air photo identified landslides with sediment delivery occurred on slopes less than 30%. Landslides occurring on gentler slopes (<30%) represented only 10% (8,516 yds^3) of the total sediment delivered to streams in the TMDL study area (Table 6) and exhibit the lowest sediment delivery rates by sub-basin (Figure 7). Landslides occurring on gentler slopes include the 2 earthflows. Typically, earthflow topography is relatively gentle and hummocky. Earthflow sediment delivery represents 65% (5,511 yds^3) of the sediment delivery from landslides occurring on slopes <30%. Debris landslides occurring on these slopes have a lower likelihood of delivering sediment to streams because, all else equal, landslide debris travels shorter distances on gentler slopes.

The Ryan Slough planning watershed exhibited the highest frequency and sediment delivery from observed landslides occurring on Wildcat Group lithology with slopes greater than 65%. Specifically, 56% (n=66) of the observed landslides in Ryan Slough occurred on Wildcat Group lithology and slopes greater than 65%, and were estimated to deliver 52% (32,366 yds^3) of the sediment delivered to the Ryan Slough planning watershed and approximately 37% of the total sediment delivery in the entire study area (Table 7). Frequency and sediment delivery for observed landslides on Wildcat Group lithology in Freshwater Creek were nearly evenly distributed between all slope classes.

Landslides by Sediment Delivery Volume Size Class

Air photo identified landslides in the Freshwater Creek TMDL study area were analyzed by sediment delivery volume size classes within each of the three TMDL planning watersheds (Ryan Slough, Freshwater Creek and Fay Slough). The results were also compared to two air photo identified landslide sediment source studies conducted as part of: 1) the Lower Eel River TMDL sediment source study on non PALCO lands (in progress) and 2) the 2006 PALCO Upper Eel River Watershed Analysis Mass Wasting Module. Air photo identified landslides from the Lower Eel River TMDL and Upper Eel River Watershed Analysis sediment studies were selected for comparison because each study followed nearly identical air photo landslide identification and attribute methodologies, and air photo landslides were identified during the same time frame (1987 through 2003) as employed in the Freshwater Creek TMDL study.

Air photo landslides from the Freshwater Creek TMDL study were delineated according to five (5) sediment delivery volume class categories including 0-200 yds^3, 201-500 yds^3, 501-1,000 yds^3, 1,001-2,000 yds^3, and 2,001-5,000 yds^3. Overall, there is a consistent trend of decreasing frequency of landslide occurrence with increasing sediment delivery volume class (Figure 8). At the same time, there is a clear trend of increasing unit sediment delivery (yds^3/mi^2) with increasing sediment delivery volume class (Figure 9) Specifically, approximately 50% of the air photo landslides in the entire Freshwater Creek TMDL study area fell into the 0-200 yds^3 sediment delivery volume class category. Although, these landslides occur more frequently, they produced the lowest unit sediment delivery of any of the five classes (123 yds^3/mi^2) (Table 9).

Figure 8. Percent of Total Number of Landslides by Sediment Delivery Volume Class and Planning Watershed, Freshwater Creek TMDL Study Area

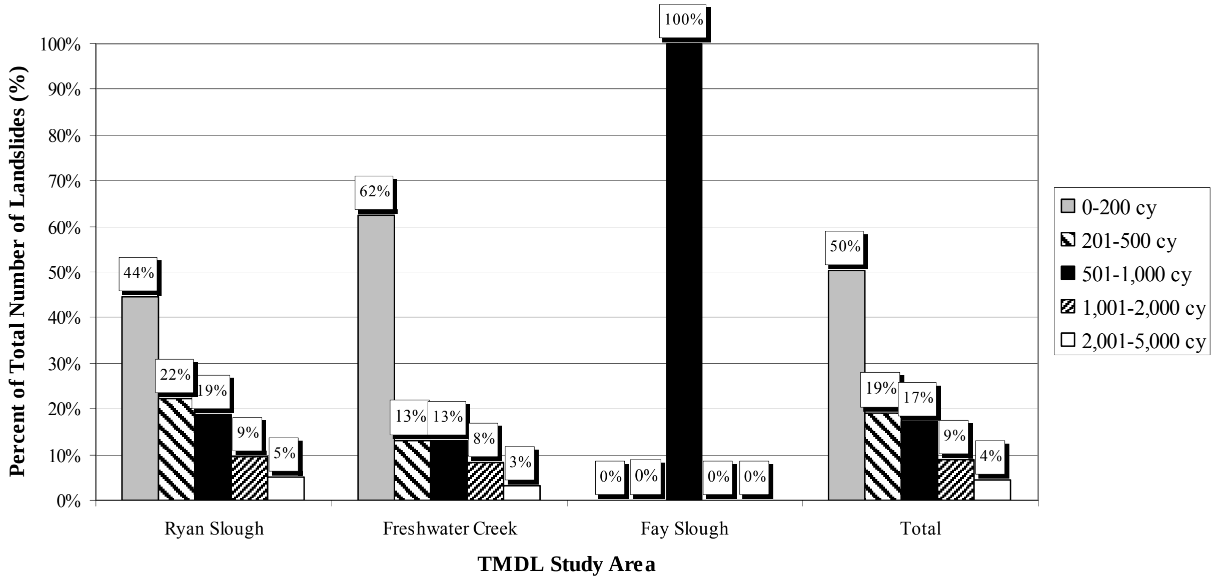
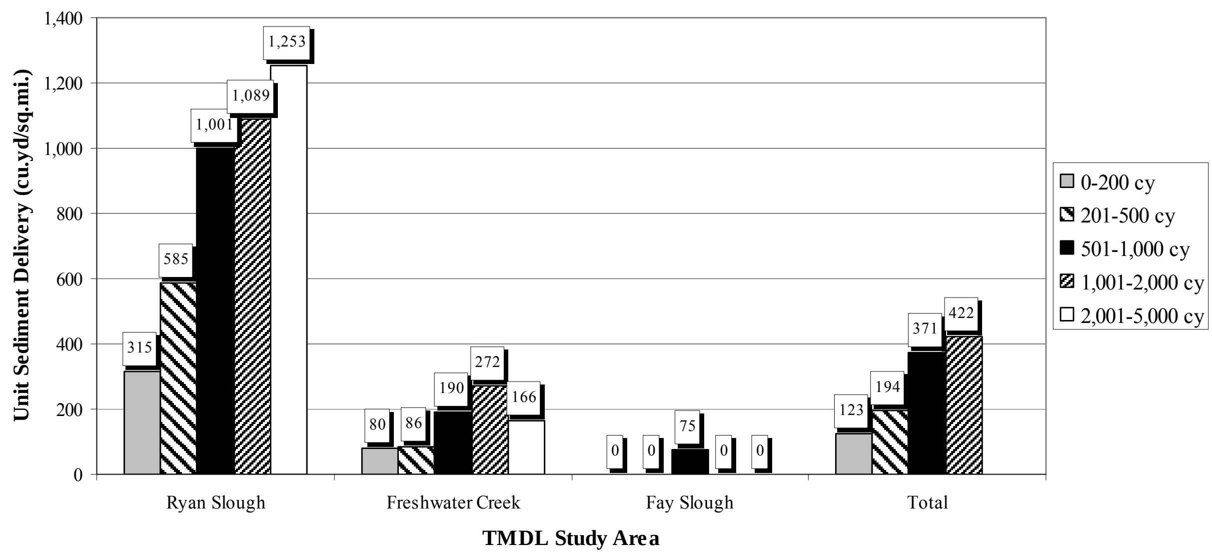


Figure 9. Unit Landslide Delivery by Sediment Delivery Volume Class and Planning Watershed, Freshwater Creek TMDL Study Area



In comparison, only 4% of the air photo landslides in the entire TMDL study area had sediment delivery volumes between 2,001 and 5,000 yds^3 (Table 8). Yet, air photo identified landslides in the 2,001 – 5,000 yds^3 volume class category exhibited the highest unit sediment delivery (422 yds^3/mi^2) in the entire TMDL study area. This suggests that small landslides occur frequently on the landscape but have less of an impact on overall sediment delivery, whereas a few large landslides deliver comparatively large volumes of sediment and therefore have the greatest affect on total sediment delivery by mass wasting processes in the Freshwater Creek TMDL study area.

The Freshwater Creek watershed exhibited the highest percent frequency (62%) of landslides in the 0-200 yds^3 volume class category, but had a low unit sediment delivery of 80 yds^3/mi^2 (Figure 8 and Figure 9). The highest unit sediment delivery (272 yds^3/mi^2) in the Freshwater Creek watershed resulted from landslides in the 1,001 -2,000 yds^3/mi^2 volume class category (Figure 9). At the same time, landslides in the 1,001 -2000 yds^3 volume class category only represent 13% of the air photo identified landslides in the Freshwater Creek watershed.

By far the highest unit sediment deliveries by delivery volume class occurred in the Ryan Slough planning watershed. Here, only 3% of the air photo identified landslides had sediment delivery volumes between 2,001 and 5,000 yds^3, yet these landslides produced the highest unit sediment delivery rates (1,253 yds^3/mi^2) for any planning watershed. Approximately 44% of the landslides identified in the Ryan Slough planning watershed had landslide delivery volumes in the 0-200 yds^3 volume class category. These landslides exhibited the lowest unit sediment delivery (315 yds^3/mi^2). Although landslides in the 0-200 yds^3 volume class category in the Ryan Slough planning watershed exhibited the lowest unit sediment delivery for that planning watershed, this unit sediment delivery is higher than that for any volume class in the nearby Freshwater Creek watershed. Clearly, mass wasting is a comparatively important process of sediment production and delivery in the Ryan Creek watershed.
The air photo landslide distribution and unit sediment delivery by sediment volume class were compared between the Freshwater Creek TMDL study area and sediment source studies conducted as part of the Lower Eel River TMDL sediment study (EPA, in progress) and the Upper Eel River Watershed Analysis (PALCO, 2006). The Lower Eel TMDL study area is approximately 201.4 mi^2 in area and includes all non-PALCO land ownership within the Lower Eel River CALWAA. The Upper Eel River Watershed Analysis Area is approximately 43.6 mi^2 in area and consists of PALCO HCP-covered lands within the Larabee Creek watershed, within eastern tributaries draining to the South Fork Eel River extending from the confluence of the main stem Eel River to Ohman Creek, and within tributaries draining to main stem Eel River extending from the confluence with the South Fork Eel River to Eel River Rock. As mentioned previously, these studies were chosen to compare against the results of Freshwater Creek because they used similar air photo analysis methodologies and the same air photo time frame (1987-2003).

Figure 10 illustrates the percent total landslide frequency for the Freshwater Creek TMDL study area, Lower Eel River TMDL study area, and the Upper Eel River Watershed Analysis Area. By far, Freshwater Creek exhibited the highest frequency of landslides with sediment delivery volumes in the 0-200 yds^3 category (Figure 10). In addition, the Freshwater Creek TMDL study area exhibited the most dramatic trend in decreasing landslide frequency with increasing landslide sediment delivery (size). The Upper Eel River Watershed Analysis Area also shows a decreasing trend in frequency of landslides with increasing sediment delivery, but much less dramatic as compared to Freshwater Creek. The frequency of landslides in the Upper Eel River Watershed Analysis Area is nearly equally distributed between the 0-200 yds^3, 201-500 yds^3 and 501-1,000 yds^3 volume classes. The Lower Eel River TMDL study area exhibited an increasing trend of landslide frequency from the 0-200 yds^3 to the 1,001-2,000 yds^3 category, with landslide frequencies evenly distributed between the 501-1,000 yds^3, 1,001-2,000 yds^3 and 2,001-5,000 yds^3 categories. In the Lower Eel River TMDL study area and the Upper Eel River Watershed Analysis area, percent landslide frequency was lowest in the 5,001-10,000 yds^3 and >10,001 yds^3 volume class categories (Figure 10).

The Freshwater Creek TMDL study area exhibited the highest unit sediment delivery (123 yds^3/mi^2) for landslides in the 0-200 yds^3 volume class category. The highest unit sediment delivery in the Freshwater Creek TMDL study area was estimated at 422 yds^3/mi^2 for landslides in the 501-1,000 yds^3 volume class category. In comparison, the highest unit sediment delivery for the Lower Eel River TMDL study area and the Upper Eel River Watershed Analysis Area was estimated at 6,730 yds^3/mi^2 and 4,678 yds^3/mi^2, respectively, for landslides in the greater than 10,000 yds^3 sediment delivery volume class category (Figure 11). These large landslides dominated sediment production and delivery from mass wasting processes in the two Eel River sediment studies.

The largest landslide observed in the Freshwater Creek TMDL study area was estimated to deliver approximately 4,389 yds^3 of sediment to the stream system and was observed in the Ryan Slough planning watershed. In comparison, the largest landslides identified in the Lower Eel River TMDL study area and the Upper Eel River Watershed Analysis area were estimated to deliver 245,400 yds^3 and 29,410 yds^3 of sediment to streams, respectively. It is apparent that the

Figure 10. Comparison of Percent of Total Number of Landslides by Sediment Delivery Volume Class and Study Area

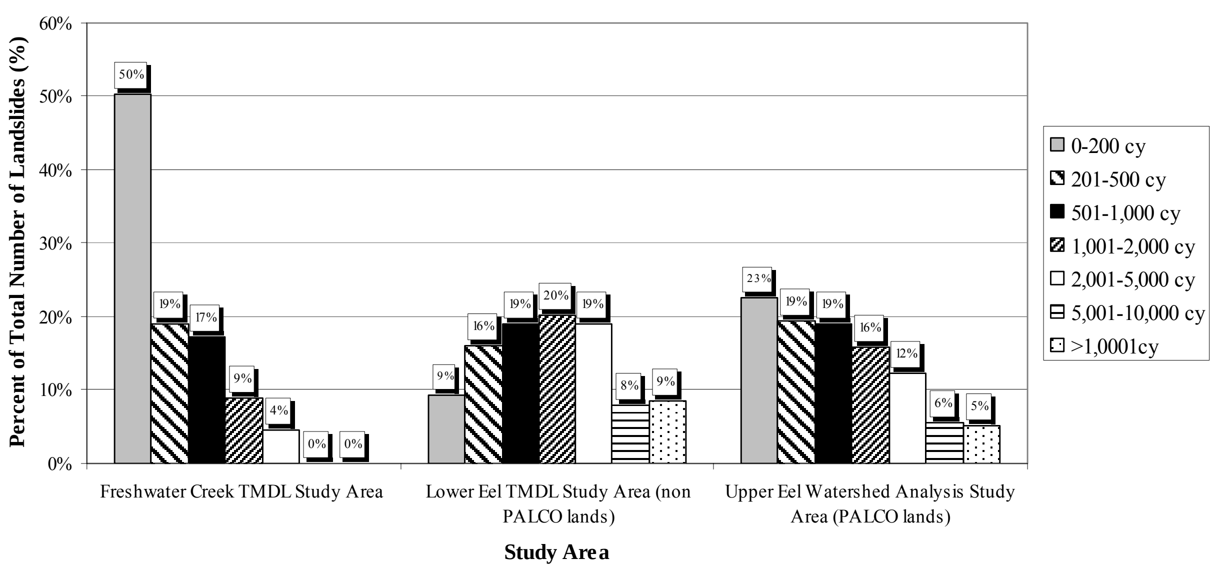
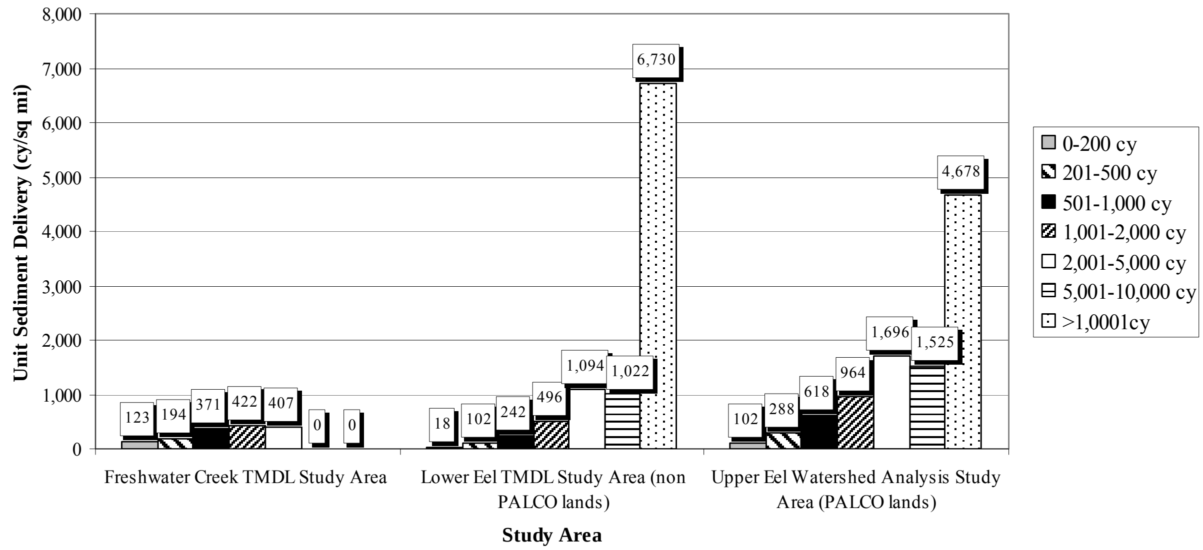


Figure 11. Comparison of Unit Sediment Delivery by Sediment Delivery Volume Class and Study Area



landslides originating in the Freshwater Creek TMDL study area have substantially smaller sediment delivery volumes as compared to the landslides observed in the Lower Eel River TMDL and Upper Eel River Watershed Analysis study areas. Landslides in the Freshwater Creek TMDL study area displayed significantly lower unit sediment delivery volumes in the majority of all sediment delivery volume classes (Figure 11). The high incidence of large landslides in the Upper Eel River watershed was a result of large natural inner gorge streamside landslides along Larabee Creek. Specifically, seventy-eight percent (78%) of the landslide sediment delivery from landslides in the >10,000 yds^3 volume class category originated from these inner gorge landslides along the confined sections of lower Larabee Creek.

Table 7. Landslide Frequency and Sediment Delivery by Slope Class and Lithology for Ryan Slough and Freshwater Creek, Freshwater Creek TMDL Study Area.

	Ryan Slough						Freshwater Creek					
	<50		51-64		>65		<50		51-64		>65	
Lithology	**#**	**Sediment Delivery (yds^3)**	**#**	**Sediment Delivery (yds^3)**	**#**	**Sediment Delivery (yds^3)**	**#**	**Sediment Delivery (yds^3)**	**#**	**Sediment Delivery (yds^3)**	**#**	**Sediment Delivery (yds^3)**
Qt	12	9,957	6	3,499	13	5,452	0	0	0	0	0	0
QTw	9	3,538	14	4,688	66	32,366	12	8,661	11	2,958	20	6,536
TKy	0	0	1	170	2	2,710	0	0	0	0	1	236
KJfm	0	0	0	0	0	0	4	3,188	6	992	12	1,762
Total	**21**	**13,495**	**21**	**8,357**	**81**	**40,528**	**16**	**11,849**	**17**	**3,950**	**33**	**8,534**

Land Use Association and Mass Wasting

Landslides identified in the air photo analysis fell into 4 categories based on land use type including road-related, timber harvest-related, skid-related, utilities, and no apparent management. To determine land use association, the air photo analyst used visual evidence at the scale of the air photos, in addition to land use history and other landform characteristics. This required that the air photo analyst be proficient (at the air photo scale and in the field) at identifying mass wasting and fluvial erosion features, understand and be able to identify land management techniques (including the relative age of harvesting), and be able to recognize geomorphic characteristics. Land use classification was not determined by land use activity and timber stand age alone. Landslides occurring on slopes with stand ages less than 15 years were not always determined to be caused by timber harvesting. For example, a landslide may be located within a recent harvest unit but be caused by stream undercutting. This landslide would be classified based on geomorphic position and geomorphic process, rather than timber harvest stand age.

To determine that a landslide should be classified as road-related it must have an initiation point or head scarp originating in the road fill, or show some concrete evidence that road-related runoff contributed to slope failure. Landslides that initiate upslope of the road, and that are caused by undercutting of the slope by road construction, are also considered road-related. However, just because a road is physically associated with a landslide does not mean the landslide was caused by the road. For example, landslides may not be considered road-related if they are very large and deep seated features caused by underlying geologic instability and the road, regardless of its location, is a relatively insignificant feature compared to the landslide mass. Professional judgment is often required at the site, or in analysis of the aerial photos, to properly assign causal relationships. Even then, landslide cause may be multivariate and the most important factor(s) may not be discernable without a detailed site evaluation. Such evaluations were beyond the scope of this study.

A landslide was classified as timber harvest-related based on a variety of air photo visual clues (i.e. fluvial erosion caused by concentrated flow from timber harvest activities, immediately adjacent harvest-related landslides with similar morphologic characteristics), bedrock lithology, geomorphic association and land use history. Without contrary evidence, a landslide was always considered harvest-related if it was located within a cable yarding corridor, regardless of the age of harvest. Landslides located on convergent hillslopes, especially in steep lower slope areas were typically classified as timber harvest related if large amounts of canopy had been removed adjacent or up-slope from the failure. Specifically, if a landslide is located in a recently harvested area (cut within the last 15 years), it was usually considered harvest-related. Landslides occurring on slopes harvested between 15 and 30 years ago may be considered harvest-related depending on whether there is visual evidence that past harvest activities influenced landslide activity (i.e. fluvial erosion – gullying). Landslides occurring on advanced second growth slopes (timber harvest age of >30 years) were usually classified as “no apparent management,” because it was judged that nearly full transpiration and root strength values had been re-attained, provided there was no visible evidence that legacy harvesting activities contribute to, or caused, slope failure. If the landslide was field-checked and skid trails, diverted streams, or other management factors were identified, then the cause is changed to reflect the on-site data.

A landslide was considered to be skid-related if it originated at a skid trail or appeared to be influenced by runoff or fluvial erosion initiated from the skid trail network. On recently harvested areas, these features could sometimes be seen on the photography. Likewise, a landslide associated with "utilities" was classified based on its location within the utility (power line) corridor, and the occurrence of roads or other management features. A landslide was classified as "no apparent management" if there was no evidence that management-related activities caused the landslide, or if the landslide was the apparent result of natural mass wasting processes.

The distribution of landslides inventoried in the Freshwater Creek TMDL study area, with respect to road association, is shown in Figure 12. Of the 190 landslides observed in the TMDL study area, 146 landslides (77% of the total number) were identified as "non road-related." The remaining 23% were classified as road-related landslides. Average landslide sediment delivery for road-related landslides (600 yds^3) was 33% larger than for the average non road-related landslide (420 yds^3). Mean sediment delivery for landslides which delivered sediment to a stream channel was estimated to be approximately 55% for road-related landslides and 60% for non road-related hillslope landslides.

Road-associated landsliding - Road-associated landslide occurrence shows peaks that correspond with storm periods and land management activities. A total of 44 road-associated landslides were identified in the aerial photo inventory (Figure 13). Approximately 57% (14,833 yds^3) of the estimated sediment delivery from road-related sites originated from 23 landslides during the 1997 air photo period (Figure 9). Increased road-related sediment delivery is likely due to very high rates of road construction during this period, coupled with the 1996/1997 storm (Figure 2).

Twelve (12) road-associated landslides were identified on the 2003 aerial photographs and were estimated to deliver 4,500 yds^3 of sediment to streams in the Freshwater TMDL study area. The road-associated landslide sediment delivery for the 2003 air photo period (4,500 yd^3) is the lowest for the entire study period, even though the road construction activities continued (road construction rate during 2003 time period = 4.3 mi/yr). The 20% decrease in road-associated sediment delivery relative to the 1997 air photo period appears at least partly attributable to HCP road construction and maintenance standards and a decrease in the rate of road construction.

Figure 12. Frequency of Landslides by Land Use Association and Time Period, Freshwater Creek TMDL Study Area

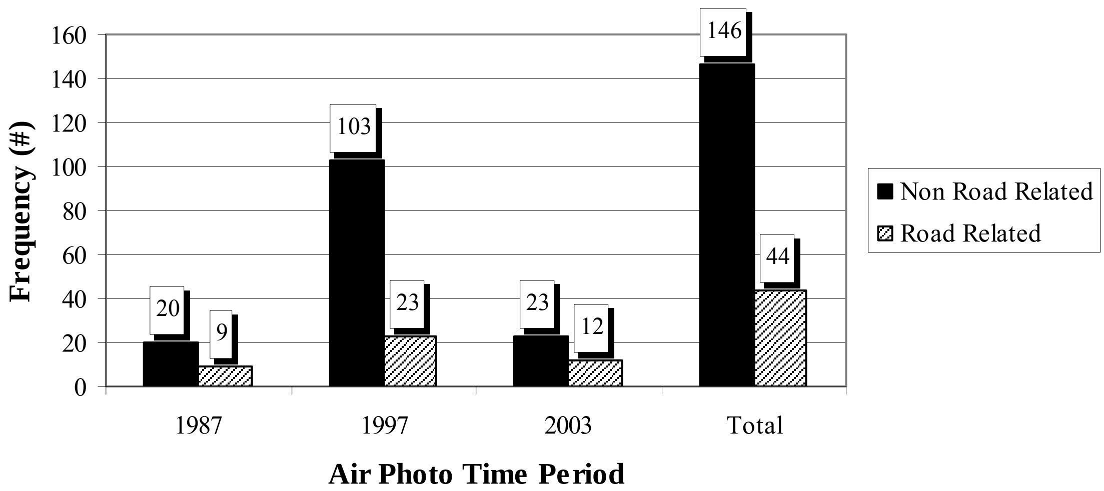
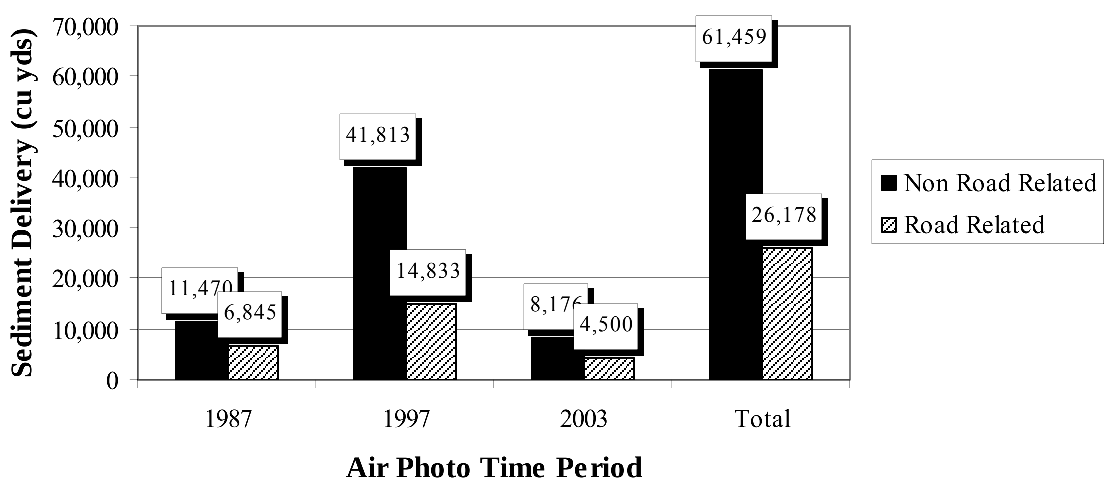


Figure 13. Landslide Sediment Delivery by Land Use Association and Time Period, Freshwater Creek TMDL Study Area



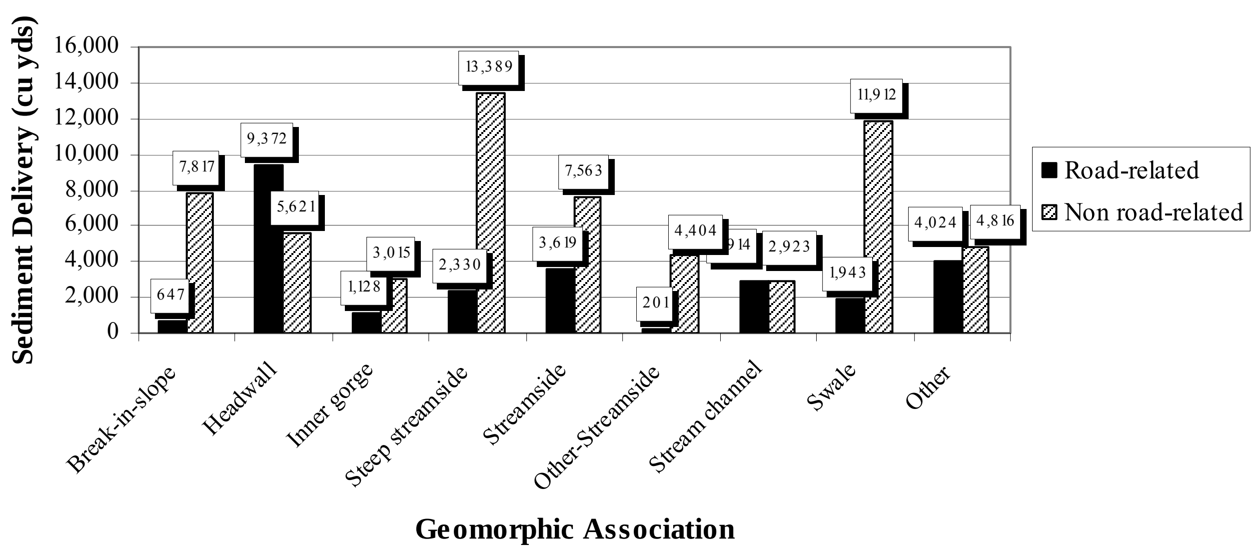
Overall, road-related landslides occurring in headwall locations delivered approximately 40% (9,372 yds^3) more sediment as compared to non road-related landslides. In comparison, non road-related landslides produced more sediment in all the other geomorphic associations (Figure 14).

Non road-associated landsliding - Regardless of the analysis time period, hillslope landslides (non road-associated) in the Freshwater Creek TMDL study area were more common than road-associated slides. During the 1997 photo period, observed non road-associated landslides were more than 4 times more common than road-associated slides (Figure 12). In 1987and 2003, hillslope debris slides again out-numbered road-associated debris slides by an overall margin of about 2.2:1 and 1.9:1, respectively.

A total of 146 non road-associated landslides were identified in the air photo analysis. Seventy-one percent (71%) of the non road-associated landslides occurred in the 1997 air photo period. These landslides delivered approximately 68% of the non road-associated sediment delivered to streams. Sediment delivered to streams from non road-associated landslides decreased significantly from the 1997 (41,813 yds^3) to 2003 (8,176 yds^3) air photo periods (Figure 13).

Similar to the decrease in road-associated landsliding, the decrease in non road-associated landsliding from the 1997 to the 2003 photo periods may be due, at least partially, to improved land management practices in the Ryan Slough and Freshwater Creek planning watersheds. Although road-related and non road-related landsliding decreased between the 1997 and 2003 time periods, timber harvesting increased by 7% in Ryan Slough and 43% in Freshwater Creek (Figure 3).

Figure 14. Landslide Sediment Delivery by Land Use Association and Geomorphic Association, Freshwater Creek TMDL Study Area



Non road-related landslides produced 71% more sediment in inner gorge and steep streamside locations as compared to road-related landslides (Figure 14). In addition, non road-related landslides delivered 92% more sediment from break-in-slope locations and 84% more sediment from swale locations, as compared to road-related landslides (Figure 14).

Non road-related landslides identified in the air photo analysis fell into 4 categories based on land use type including timber harvest-related, skid-related, utilities, and no apparent management. Thirty-one percent (31%) of the landslides observed in the entire TMDL study area were associated with timber harvest activities. Sediment delivery from timber harvest associated landslides accounts for 26% (23,116 yds^3) of the sediment delivered to streams within the TMDL study area (Table 8). The overall sediment delivery rate from timber harvest land use in the TMDL study area was estimated at 22 $tons/mi^2/yr$. The highest sediment delivery (15,912 yds^3) and highest sediment delivery rate (60 $tons/mi^2/yr$) for timber harvest associated landslides was observed in the Ryan Slough planning watershed (Table 8 and Figure 15). Overall, Ryan Slough had the highest sediment delivery rates for all land use categories including roads (Figure 11). As mentioned previously, the likely cause for high rates of landsliding in the Ryan Slough planning watershed is due to higher stream densities and very weak geologies.

For the purposes of this study, landslides classified as no apparent management are considered to be caused by natural mass wasting processes. Some observed landslides classified as having a no apparent management classification may not be solely natural/background landslides, but may be more subtly influenced by past land use activities. Land use association can be difficult to determine due to the scale of the aerial photography, the degree of vegetation obscurement, and the radial distortion of the aerial photography. In these cases, land use association can only be determined through field verification.

Table 8. Frequency and Landslide Sediment Delivery by Land Use Association, Freshwater Creek TMDL Study Area

Land Use Association	Ryan Slough		Freshwater		Slough		Total	
	#	Sediment delivery (yds^3)	#	Sediment delivery (yds^3)	#	Sediment delivery (yds^3)	#	Sediment delivery (yds^3)
Road-Related	28	19,816	16	6,362	0	0	44	26,178
Timber Harvest Related	36	15,912	22	7,204	0	0	58	23,116
Skid-Related	7	5,305	6	1,413	0	0	13	6,718
Utilities	2	3,432	0	0	0	0	2	3,432
No Apparent Management Association	50	17,915	22	9,354	1	924	73	28,193
Total	**123**	**62,380**	**66**	**24,333**	**1**	**924**	**190**	**87,637**

Thirty-eight percent (38%) of the air photo identified landslides in the TMDL study area were classified as having no apparent management association. These landslides delivered approximately 32% of the total estimated sediment delivered to streams in the TMDL study area. In addition, the landslide sediment delivery rate (26 $tons/mi^2/yr$) for landslides classified as "no apparent management" is nearly equivalent to the sediment delivery rates for road-related and timber harvest associated landslides (24 $tons/mi^2/yr$ and 22 $tons/mi^2/yr$, respectively) (Figure 15). This suggests that road construction and maintenance, and timber harvesting have equal impacts on mass wasting processes; as compared to natural mass wasting processes in the TMDL study area during the study time period (1987-2003).

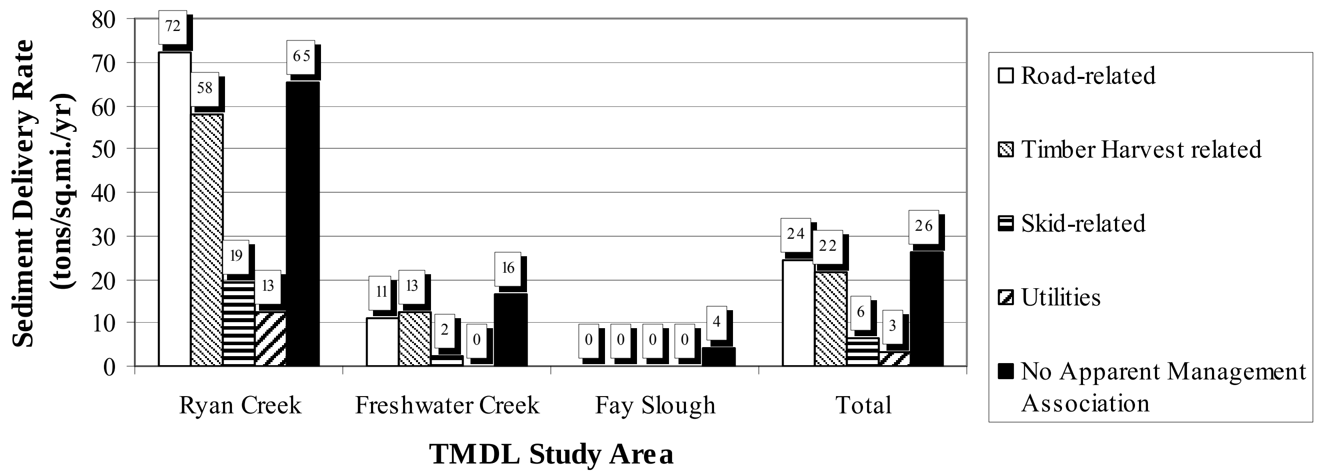


Figure 15. Sediment Delivery Rate by Land Use Association, Freshwater Creek TMDL Study Area

Mass Wasting by Sub-basin

To compare the effects of mass wasting at the sub-basin level, the Ryan Slough and Freshwater Creek planning watersheds were broken down into key sub-basins based on the subwatershed boundaries of major tributaries and main stem reaches. Both the Ryan Slough and Freshwater Creek planning watersheds were broken down into 8 sub-basins (Map 5). The Freshwater Creek watershed sub-basin breakdown was based on the delineation outlined in the Palco Freshwater Creek Watershed Analysis.

Ryan Slough

Overall, the Ryan Creek planning watershed exhibited the highest sediment delivery (228 tyons/mi^2/yr) rate as compare to Freshwater Creek (38 tons/mi^2/yr) and Fay Slough.
Eight sub-basins were delineated in the Ryan Slough planning watershed according to major tributary watershed and main stem reach boundaries (Map 5). Sub-basin area ranges from 0.5 mi^2 for Bob Hill Gulch to 2.94 mi^2 for the Ryan Creek - Main sub-basin (Table 9). Bob Hill Gulch, Guptil Gulch, and Henderson Gulch were delineated based on named blue lined streams on the USGS 1:24,000 topographic quadrangles (Field Landing, Eureka, McWhinney Creek, Arcata South). The Ryan Creek - East, Ryan Creek - West, Unnamed Tributary A, and Un-named Tributary B sub-basins were delineated by Pacific Watershed Associates based on watershed boundaries of un-named major tributaries. The Ryan Creek – Main sub-basin was defined by the main stem reach of Ryan Creek and adjacent interfluves or minor tributaries to the main stem.
The highest landslide frequency (n=37), sediment delivery volume (20,452 yds^3) and sediment delivery rate (400 tons/mi^2/yr) from air photo identified shallow landslides in the Ryan Slough planning watershed was observed in the Ryan Creek - East tributary (Table 9). The Ryan Creek

Table 9. Frequency, Sediment Delivery and Sediment Delivery Rates by Sub-basin, Ryan Slough Planning Watershed, Freshwater Creek TMDL Study Area.

Sub-basin	Area (mi^2)	Frequency (#)	Sediment Delivery (yds^3)	Sediment Delivery Rate ($tons/mi^2/yr$)	Area Managed by Green Diamond (mi^2)	% Area Managed by Green Diamond
Bob Hill Gulch	0.50	2	1,075	116	0.34	68%
Guptil Gulch	1.88	16	7,091	203	1.37	73%
Henderson Gulch	0.89	17	2,986	181	0.55	62%
Ryan Creek - East	2.75	37	20,452	400	2.71	99%
Ryan Creek - West	2.81	21	15,180	291	2.47	88%
Ryan Creek - Main	2.94	13	8,704	159	2.39	81%
Un-named Tributary A	1.17	6	4,315	199	1.17	100%
Un-named Tributary B	1.80	11	2,577	77	0.56	31%
Total	**14.74**	**123**	**62,380**	**228**	**11.56**	**78%**

– East tributary represents approximately 19% of the Ryan Slough planning watershed area and is predominantly underlain by the geologically weak Wildcat Group lithology. Nearly all (99%) of the Ryan Creek – East tributary is managed by the Green Diamond Resource Company for timber harvesting.

The lowest sediment delivery rate (77 $tons/mi^2/yr$) was observed in the Un-named Tributary B sub-basin. This tributary is also primarily underlain by Wildcat lithology. Approximately 31% of the sub-basin is managed by the Green Diamond Resource Company. Green Diamond land ownership is located in the upper reaches of this sub-basin. The remaining 69% of the sub-basin is composed of rural subdivisions, City Garbage Company lands, and the Humboldt Waste Management Authority Cummings Road Landfill. It is likely that the low sediment delivery rate is due to low percentage of land managed for timber harvesting.

Sediment delivery rates in the remaining sub-basins range from 116 $tons/mi^2/yr$ in the Bob Hill Gulch sub-basin to 291 $tons/mi^2/yr$ in the Ryan Creek – West tributary. The majority of the sub-basin area in these locations is managed for timber harvesting by the Green Diamond Resource Company.

<u>Freshwater Creek</u>

Similar to the Ryan Slough planning watershed, the majority (78%) of the Freshwater Creek planning watershed is managed for timber harvesting by the Pacific Lumber Company. The Freshwater Creek watershed was delineated into eight sub-basins. The sub-basin breakdown was developed for the Palco Freshwater Creek Watershed Analysis conducted in 2000. Sub-basin area within Freshwater Creek ranges from 0.6 mi^2 in the School Forest sub-basin to 9.99 mi^2 in the Upper Freshwater Creek sub-basin (Table 10).

Table 10. Frequency, Sediment Delivery and Sediment Delivery Rates by Sub-basin, Freshwater Creek Planning Watershed, Freshwater Creek TMDL Study Area.

Sub-basin	Area (mi^2)	Frequency (#)	Sediment Delivery (yds^3)	Sediment Delivery Rate ($tons/mi^2/yr$)	Area Managed by PALCO (mi^2)	% Area Managed by PALCO
Cloney Gulch	4.68	3	319	4	4.1	88%
Graham Gulch	2.54	6	4,747	101	2.24	88%
Little Freshwater Creek	4.68	24	10,416	120	4.66	100%
Main Stem Freshwater	3.09	14	2,618	46	0.85	28%
McCready Gulch	2.01	4	622	17	1.74	87%
School Forest	0.6	4	183	16	0.5	83%
South Fork Freshwater	3.15	3	2,240	38	3.14	100%
Upper Freshwater	9.99	8	3,188	17	6.84	68%
Total	**30.74**	**66**	**24,333**	**43**	**24.07**	**78%**

The highest landslide frequency (n=24), sediment delivery volume (10,416 yds^3) and sediment delivery rate (120 $tons/mi^2/yr$) were observed in the Little Freshwater Creek sub-basin (Table 10). The Little Freshwater sub-basin represents 15% of the Freshwater Creek planning watershed area and is completely owned and managed by the Pacific Lumber Company. The majority of the Little Freshwater sub-basin is underlain by Wildcat Group lithology and is directly adjacent to the eastern boundary of the Ryan Slough planning watershed (Map 5).

The second highest sediment delivery volume (4,747 yds^3) and sediment delivery rate (101 $tons/mi^2/yr$) were observed in the Graham Gulch sub-basin. Approximately 55% of the sediment delivery was a result of one earthflow delivering 2,586 yds^3 to Graham Gulch. The high sediment delivery rate is due to a small number of large debris landslides.

The estimated sediment delivery rates from the remaining sub-basins range between 4 $tons/mi^2/yr$ in the Cloney Gulch sub-basin to 46 $tons/mi^2/yr$ in the Main Stem Freshwater sub-basin. Overall the sediment delivery rate for Freshwater (38 $tons/mi^2/yr$) was significantly lower (83%) than the overall sediment delivery rate in the Ryan Slough planning watershed (228 $tons/mi^2/yr$) (Table 10).

2. Field Verification of Air Photo Identified Landslides

In order to field verify air photo identified landslide attributes for landslides identified in the Freshwater Creek TMDL study, 30% of the landslides identified in the Ryan Slough planning watershed were field verified by PWA staff in May 2006. Methods for field verification are described above in Section III A-2: Methods for Field Verification of Air Photo Identified Landslides. Existing field verification data collected for 1997 landslides identified as part of the 1999 PALCO Freshwater Creek Sediment Source Investigation were used to develop landslide depths for the 2003 air photo landslides identified by PALCO from their comprehensive landslide forensics study. The one air photo identified landslide in Fay Slough was not field verified due to landowner access.

Ryan Slough

Thirty-five (35) air photo identified landslides from the 1997 and 2003 air photo time periods in the Ryan Slough planning watershed were field verified for accuracy of landslide attributes collected as part of the air photo analysis (Table 11). Landslides chosen for field verification were selected based on volume of sediment delivered, landslide types, geology, and accessibility. Of the 35 field verified sites, three (9%) were determined not to be sites according to the study plan objectives and assumptions. In the field, these three sites proved to be a road turnout, a landslide with no sediment delivery, and a bank erosion site. Although two of the three sites identified as not sites were past erosion sites, they did not qualify for inclusion in the study due to erosion type (analysis of bank erosion was not included in the study) and lack of sediment delivery (only landslides with sediment delivery are included in the study).

Table 11 lists the field verified and air photo derived measurement data for the 35 field verified landslides. The data comparison shows that site by site measurements have a great deal of variability, but the overall total sediment deliveries from the field verified data and the air photo measured data are comparable.

Variability is the most apparent in the depth, length and sediment delivery % estimate. This variation is to be expected from these two variables. The air photo derived depth estimates are based on statistical analysis of the field verified landslide attributes. Several analyses were conducted to determine a relationship between landslide dimensions, area and depth. Statistical analysis showed no relationship between landslide area, length, width, and/or depth. A strong statistical relationship was noted between landslide volume and area suggesting that overall landslide depth was consistent regardless of landslide area. An average depth of 3.5 feet was determined for air photo landslides by computing the average landslide depth for all field verified landslides.

There was significant variability between air photo measured landslide length and field verified landslide length. Variability in field measured and air photo estimated length is due to the difficulty in determining where the length of the landslide void ends and where landslide deposition begins at the scale of the historic aerial photography. In addition, significant variability can be observed between the field verified sediment delivery % and the air photo derived sediment delivery %. This variability is to be expected since the ability to estimate landslide delivery from the air photos is very problematic. The scale of the aerial photography makes it difficult to confidently determine the percent of sediment that has delivered to streams.

Although variability is high between field verified and air photo derived data on a site by site comparison with respect to width, length and sediment delivery percentage, the estimates of overall sediment delivered to streams from field verified and air photo derived measurements are very comparable. From the data comparison, this analysis suggests that air photo derived sediment delivery was over estimated by approximately 25%.

Table 11. Field Verified Landslides in the Ryan Slough Planning Watershed, Freshwater Creek TMDL Study										
Field Verified Site No.	**Length (ft)**		**Width (ft)**		**Depth (ft)**		**Sediment Delivery % (%)**		**Sediment Delivered (yds3)**	
	Field	**A.P.**	**Field**	**A.P.**	**Field**	**A.P.**	**Field**	**A.P.**	**Field**	**A.P.**
17	90	94	45	40	5	3.5	30	75	214	365
20	450	509	60	48	3	3.5	85	100	2,550	3167
26	60	44	32	18	2	3.5	70	60	99	62
30	75	55	27	18	2.5	3.5	35	30	66	38
34	98	77	51	48	1.5	3.5	20	25	56	120
37	76	63	63	48	4	3.5	60	70	425	274
38	350	188	40	48	1	3.5	80	10	484	117
42	45	57	75	12	2	3.5	0	90	0	80
43	43	27	35	24	3.5	3.5	35	75	68	63
48	222	292	57	72	4	3.5	30	70	604	1908
49	119	92	73	72	11	3.5	85	80	3008	687
50	195	185	23	24	3	3.5	95	100	424	576
52	210	75	73	60	8	3.5	3	90	135	525
53	130	228	115	96	5	3.5	10	25	289	709
56	45	140	100	144	4	3.5	35	80	234	2090
58	270	337	55	72	5	3.5	55	80	1522	2516
60	600	374	20	24	0.5	3.5	100	100	2222	1164
64	67	59	43	36	2	3.5	80	90	170	248
65	NAS	61	NAS	60	NAS	3.5	NAS	90	NAS	427
77	93	88	39	36	2.5	3.5	35	25	118	103
78	59	100	80	36	3	3.5	60	25	315	117
84	350	351	70	72	5	3.5	60	80	2758	2621
86	85	123	60	72	1	3.5	40	40	86	459
87	125	117	45	48	2	3.5	50	10	208	73
88	150	65	80	72	2	3.5	75	100	667	607
91	495	314	26	24	2	3.5	80	10	686	98
97	100	81	45	48	4	3.5	85	80	567	403
98	220	234	70	120	3	3.5	40	90	504	3276
99	85	123	47	48	2.5	3.5	20	20	74	153
102	125	97	40	24	1.5	3.5	75	80	208	242
106	80	68	43	36	2	3.5	45	25	115	79
107	200	403	450	240	4	8	21	20	2925	5732
111	15	31	10	48	2	3.5	75	70	9	135
114	NAS	40	NAS	40	NAS	3.5	NAS	90	NAS	186
115	102	88	55	50	3.5	3.5	80	90	562	513
Total									**22,372**	**29,933**

In addition to verifying the air photo landslide dimensional and delivery data, the field inventory checked other air photo landslide attributes such as geomorphic association, slope % and causal mechanisms. As stated previously, 2 of the 35 field verified landslide sites were determined to be not sites. No landslide attributes were collected for non sites and therefore are not included in the field verification and air photo identified landslide comparison. Seventeen of the 32 field verified landslides (53%) had different field determined geomorphic associations from the air photo derived data and 8 (21%) had significantly different (>20%) landslide hillslope gradients. The high disparity between air photo estimated geomorphic association and field verified landslide geomorphic association is due to the difficulty in determining a watershed scale geomorphic association in the field.

The field verification study collected attributes pertaining to landslide causal mechanisms. Field verified landslide causal mechanisms were broken down into 4 main categories: 1) harvest-related, 2) road-related, 3) skid-related and 4) no apparent management. No apparent management refers to those instances where landslides are located in open slopes areas where no evidence of earthwork, skid, road or other management-related cause could be attributed to the field verified landslide. Table 12 outlines the differences between the landslide causal mechanisms determined during the landslide field verification and the air photo derived landslide management association.

Table 12. Field Verified Landslide Causal Mechanism and Air Photo Identified Land Use Association, Ryan Slough Planning Watershed, Freshwater Creek TMDL Study

Field Verified Landslide Cause	**Total**	**Air Photo Identified Land Use Association (#)**				
		Timber Harvest	**Road-related**	**Skid**	**Utilities**	**No apparent management**
Harvest	9	6	0	0	0	3
Road-related	13	1	9	0	0	3
Skid	5	0	1	1	0	3
Utilities/Power Line	2	0	0	0	2	0
No apparent management	4	2	0	0	0	2
Total	**33**	**9**	**10**	**1**	**2**	**11**

The discrepancies observed between the air photo identified and field verified landslide attributes for slope gradient (%), geomorphic association, and land use association can be attributed to a variety of potential sources. By far, the most common cause for errors associated with air photo identified landslide attribute data collection stem from proximal but incorrect placement of landslides during the transfer of landslides to the LIDAR base map.

Landslide location - Grossly incorrect placement (>20 feet away from correct location) will result in incorrect classification of most of the landslide attributes collected as part of the TMDL air photo analysis (excluding landslide dimensions and sediment delivery, which are measured or estimated from the air photos and do not rely on a transfer process). Even minor offset by less than 20 feet can result in errors in the resultant set of air photo-derived landslide attributes. If landslides are not directly mapped on the LIDAR imagery, or precisely located using GPS technology, then great care must be taken in the transference and mapping of landslides in order to prevent minor to gross placement errors. This can be achieved by checking air photo measured landslide dimensions with transferred polygon dimensions on the base map or GIS, and using contours and LIDAR imagery to increase the confidence of landslide placement.

Although no gross placement errors were noted with the air photo identified landslides in the Freshwater Creek TMDL study, it is likely that some minor offset error occurred. Such offset is to be anticipated and cannot be easily prevented, due to human error and the interpretation of probable location using small scale photos and even smaller scale topographic maps during the transference of air photo identified landslides. In addition, landslides in the Freshwater Creek TMDL study area are typically shallow and smaller in area as compared to landslides observed in other nearby watersheds. Small, shallow landslides are difficult to detect on the LIDAR imagery due to subtle topographic relief and therefore make accurate transference problematic.

Slope gradients - Approximately 25% of the field-verified landslides had slope gradients that differed by more than 20% gradient from the comparable slope gradient derived during the air photo analysis. The possible causes of the slope gradient discrepancies between the two methodologies include slightly incorrect mapping of landslide location, the use of different slope gradient measurement locations, variability of slope gradient between the top to the bottom of the landslide void on both the right and left marginal hillslopes adjacent to the slide surface, and the use of the finely pixilated LIDAR imagery in the determination of average slope gradient.

Normally, in most regional or watershed-wide landslide studies, landslide slope gradients are determined from small scale USGS topographic maps and/or associated DEMs. Slope gradients for air photo identified landslides in most of the Freshwater Creek TMDL study area were determined from high quality LIDAR imagery with a 1 meter resolution. Although the high resolution is excellent for providing a detailed representation of the watershed study area, it can be problematic because of the high variance of slope gradients over relatively small areas. Slope gradients were determined by developing a slope map from the LIDAR DEM using ARCMAP at a 1 meter horizontal resolution.

Each 1 meter pixel in the LIDAR slope coverage was attributed with a slope gradient. To determine slope gradient at a landslide feature, several slope gradient pixel measurements need to be averaged on the adjacent slopes around the landslide erosional void. At a 1 meter pixel resolution, slope gradients were found to vary, depending on location, from 10% slope to 100% slope gradient within in a distance of 100 feet. This suggests highly irregular topography or error in the LIDAR imagery. The high variation of slope gradient between nearby pixels (slope areas) can influence the correct estimation of slope gradient for the feature. In anticipation of this, and because the exact location of landslide initiation is generally not known, slope gradients over the area in question would require the averaging of a relatively large number of pixel values. The number of pixels to be averaged for an accurate value of average slope gradient could be statistically derived and will be dependent on the variance of the pixel slope values.

Determining average slope gradient from the LIDAR one-meter pixels may not be the most accurate way of collecting slope gradients for air photo identified landslides without sampling and averaging a large number of pixels adjacent to the landslide erosional void. As an alternate methodology, it may be more prudent to calculate the average slope gradient over the hillslope in question using the LIDAR DEM values to generate elevation values at two locations and then and the formula for "rise over run" to calculate average hillslope gradient. At a minimum, these two methodologies should be compared in their ability to provide useful and accurate slope values.

In the field, landslide slope gradient was estimated using a clinometer and measured downslope at the mid-point on either the left or right side of the erosional void. After reviewing the LIDAR slope data on either side of mapped erosional voids, it became apparent that average slope gradient varied from the right side and the left side of the landslide feature. In some cases, the average air photo estimated slope gradients from the LIDAR were correct on one side of the feature and the field measured slope gradient was correct according to the LIDAR on the other side of the landslide feature.

Discrepancies between air photo LIDAR-verified and field estimated slope gradients may also stem from different slope gradient measurement locations. It is unlikely that slope gradients for field verified and air photo identified landslides were measured at exactly the same location and over the same slope distance. Different slope gradient measurement locations and different slope length measurements may result in different slope gradient values. These potential differences can be minimized by employing a strict protocol for the location and length of slope gradient measurements.

<u>Geomorphic associations</u> - Fifty-three percent (n=17) of the field verified landslides had different geomorphic associations as compared to the geomorphic associations derived from air photo analysis. Error in determining geomorphic association can occur both in the field and at the air photo scale. Geomorphic association attributes include inner gorge slopes, steep streamside slopes, streamside slopes, break-in-slope, headwall, swale, stream channel, and "other" miscellaneous slope locations.

Steep streamside slopes and streamside slopes are designated by slope gradient extending downslope from the last major slope-break leading to a stream. Steep streamside slopes have slope gradients greater than 65%, whereas streamside slopes have slope gradients between 50 and 64%. "Other" slope locations include low gradient (<50% slope gradient) hillslopes either higher upslope or directly leading to a stream, and steeper slopes (>50% slope gradient) above the last major break-in-slope leading to a stream.

In some instances, field verified landslides were correctly located at the last major slope leading to a stream, but had slightly different slope gradients which categorized them into a geomorphic association than that derived from air photo analysis. For example, an air photo identified landslide had a geomorphic association of "steep streamside slope" with a slope gradient of 70%, but field verification of the landslide resulted in a measured slope gradient of 50%. The 50% slope gradient placed the landslide in a "streamside slope" geomorphic association; hence the differing geomorphic classification. Without LIDAR, this type of classification difference is likely to be common. Even a few degrees difference between the field- and LIDAR-derived slope gradient can result in a differing geomorphic classification.

In many cases, discrepancies between field verified and air photo derived geomorphic associations resulted from field analyst judgment. Defining geomorphic association is a professional judgment call in the field, as one or more geomorphic associations may exist at a single site. In addition, because of limited visibility it is often difficult to have larger hillslope-scale view of the landslide when evaluating the landslide site. For example, it can be difficult to determine whether one is at the last major break-in-slope leading to a stream, without climbing down the slope all the way to the stream channel. Extensive field time would have to be allocated to provide this type of assurance.

In the field, identification of geomorphic association is "professional" call and the resultant choice can differ between analysts. This professional classification can differ, whether at the field scale or in the analysis of aerial photos. In addition, determining if the slide is located at a break-in-slope or in a headwall can be problematic when standing at the landslide location. According to the data, differences between field-derived and air photo-derived geomorphic association resulted from incorrectly determining slope location above or below the last major break-in-slope. In most cases, we believe the air photo-derived geomorphic associations were more likely to be correct than the field-verified geomorphic associations. When verifying the air photo classifications, it is important that field crews know the classification developed by the air photo analyst, and then to either verify or reject the classification based on field evidence.

The high resolution Freshwater Creek TMDL LIDAR imagery provided an excellent tool for determining and verifying geomorphic association. The 1 meter resolution resulted in clearly defined topography, with well defined breaks-in-slope. At the watershed and hillslope scale, it was relatively easy to accurately determine geomorphic association, using the definitions developed for each geomorphic location. In the future, the estimation of geomorphic association should be done as a GIS exercise using digital elevation models and air photos, rather than in the field or solely using air photos. If field crews are used to check this classification, they should either verify the air-photo classification, or describe data that discounts that classification. High resolution LIDAR, if available, should be used to provide the proper classification.

Land use - Forty-one percent of the field verified landslides had different attributes for land use association compared to land use attributes derived from air photo analysis. Three of the field verified landslides with land use attribute discrepancies were classified as harvest-related in the field and had a "no apparent management" classification on the air photos. Similarly, two of the field verified landslides were attributed as "no apparent management", but were classified as "harvest-related" during the air photo analysis. It is difficult to determine in the field, or at the scale of the air photos, whether or not a landslide was caused by timber harvesting activities, unless there is clear visual evidence. Many harvest-related landslides are caused by reduced root strength, and this is nearly impossible to determine in the field and definitely not possible at the scale of the air photos. It is usually defined by the process of elimination, rather than by direct evidence.

Regardless of expertise and professional judgment, it may be too difficult to accurately determine the difference between harvest-related landslides and landslides with no apparent management, unless there is a clear cause (such as earthworks, stream diversion or slope drainage). One method that can be used to standardize the land use classification of landslides is to employ a systematic approach that classifies land use management causes based on timber harvest stand age, silviculture method and yarding method. For example, the Upper Eel River

Watershed Analysis used a systematic method that assumed that all landslides occurring on 1) tractor clear cut, cable clear cut and cable partial cut slopes less than 30 years old were harvest-related, 2) tractor partial cut slopes less than 15 years old were harvest-related, 3) tractor partial cut slopes >15 years old and tractor clearcut, cable clear cut and cable partial cut slopes greater than 30 years old were classified as "no apparent management". Although this strict classification methodology may not be truly accurate for all landslides (i.e. not all landslides occurring on slopes harvested less than 15 years previously are necessarily harvest-related), but it does provide a repeatable methodology for classifying mass wasting "caused" by timber harvest.

Six of the 13 field-verified landslides with land use attribute discrepancies were classified as road- or skid-related in the field, but were classified as "no apparent management" during the air photo analysis. When reviewing the field verified landslides on the LIDAR imagery with an overlay of the road construction history, it was apparent that these road-related landslides occurred on legacy roads (legacy roads are not currently maintained and were built more than 20 years ago). These roads were not visible on the 1987, 1997 and 2003 air photos and were barely detectable on the LIDAR imagery. Because the roads were obscured by dense vegetation, they were given a "no apparent management" classification during the air photo analysis. The landslides may have been attributed correctly on the air photos had a comprehensive road construction history been developed for the TMDL study area. Typically, the majority of the legacy roads in the Freshwater Creek and nearby watersheds were built by the 1966 air photo time period and these are not visible on the air photos of more recent years.

Finally, three of the of the 13 field-verified landslides with land use attribute discrepancies were classified as skid-related in the field, but were classified as "no apparent management" during the air photo analysis. Because the majority of the tractor harvesting occurred in the 1970's and earlier (pre-Forest Practice Rules), these areas were obscured by dense vegetation and the landslides were given a "no apparent management" classification. The "skid-related" land use association can only be applied when skid trails are visible on the air photos and the landslide feature is clearly associated with a skid trail. If the analysis does not employ older photography (i.e., it is limited to the most recent photos), these skid trails are not likely to be visible and the land use associations are likely to be misclassified.

Freshwater Creek

No air photo identified landslides observed in Freshwater Creek were field verified in May 2006 as part of the Freshwater Creek TMDL sediment source study. A sample of landslides identified on the 1997 air photos were field verified in 2000 as part of PALCO's Freshwater Creek Watershed Analysis. Thirty-five landslides were observed in Freshwater Creek on the 1997 air photos. Of the thirty-five 1997 air photo identified landslides, 12 (34%) were field verified for landslide type, dimensions, sediment delivery, geomorphic association and adjacent land use association (Table 13).

The field verification of 1997 air photo identified landslides in Freshwater Creek showed a disparity between air photo identified landslide sediment delivery and field verified landslide sediment delivery. Air photo identified landslide sediment delivery was underestimated by approximately 55% (3,987 yds^3) (Table 13). The disparity between field and air photo sediment

Table 13. Field Verified Landslides in the Freshwater Creek watershed, Freshwater Creek/Ryan Creek TMDL Project Area[1]

Field Verified Site No.	Length (ft)		Width (ft)		Depth (ft)		Sediment Delivery % (%)		Sediment Delivered (yds^3)	
	Field	A.P.	Field	A.P.	Field	A.P.	Field	A.P.	Field	A.P.
609	130	140	58	42	2	2.8	25	40	140	244
613	140	98	58	42	2	2.2	30	15	180	85
623	100	71	20	21	2.5	1.7	35	15	65	14
626	105	118	83	42	4	2.4	95	65	1,227	888
628	50	50	35	21	1	1.6	25	15	16	9
651	150	103	75	63	7	3	80	40	2,333	288
652	90	47	30	42	2.5	2	20	40	50	58
656	90	60	100	80	3	2.4	40	15	400	64
660	85	100	70	42	2	2.3	35	40	154	143
665	50	75	100	21	2	1.7	100	40	370	256
678	60	49	22	21	3	1.6	5	65	7	40
681	230	165	90	63	6	3.5	50	65	2,300	1,166
Total	--	--	--	--	--	--	--	--	**7,242**	**3,255**

[1] Landslide dimensions (length, width, depth) refer to the landslide erosional void. The dimensions do not include torrent track dimensions. Landslide sediment delivery includes sediment delivery from erosional void and associated torrent track sediment delivery.

delivery results from high variation of landslide length, width and sediment delivery. As mentioned previously, the likely cause of the variability between the air photo identified landslide and field verified landslide dimensions, sediment delivery % and sediment delivery volume is from the difficulty in the accurate measurement of landslide dimensions at the scale of the air photos and landslide obstruction by vegetation cover.

Table 14 outlines the 12 landslides field verified as part of the 1999 PALCO Freshwater Creek Sediment Source Investigation. Approximately 25% (n=3) of the field verified landslide land use associations differ from the air photo identified landslide attributes. Specifically, three air photo identified landslides were associated with timber harvesting. During field inspection, the three landslides were attributed to skid trails and not to the adjacent timber harvest land use. Skid trail association can be difficult to determine at the scale of historic aerial photography.

Table 14. Field Verified Landslide Causal Mechanism and Air Photo Identified Land Use Association, Freshwater Creek Watershed, Freshwater Creek TMDL Study				
Field Verified Land Use Association	**Total**	**Air Photo Identified Land Use Association (#)**		
		Timber Harvest	**Skid**	**No apparent management**
Harvest	7	7	0	0
Skid	4	3	1	0
No apparent management	1	0	0	1
Total	**12**	**10**	**1**	**1**

IV. Air Photo Identified Landslide and Field Inventoried Landslide Comparison Study

A. Introduction

Landslides are one of the most important components of the sediment budget of North Coast stream systems. The Freshwater Creek watershed and TMDL study area is no exception (PWA, 1999). Sediment budget studies and sediment source analyses conducted in steep forested watersheds of the North Coast typically involve the analysis of historic sets of stereo vertical aerial photographs to identify the largest and most significant sediment sources, including shallow landslides, deep seated landslides, channel migration, and (to a lesser extent) smaller scale bank erosion and hillslope gullying features.

The Freshwater TMDL sediment analysis requires an understanding and quantification of both natural and anthropogenic sources of sediment delivery to the streams of the study area. It also requires an accounting of the possible sources of sediment that are known to exist, but have not otherwise been accounted for or quantified because of limitations inherent in study design, measurement techniques, or watershed terrain. For example, the processes of bank erosion and hillslope gullying are only locally suitable for analysis using air photos because the forest cover masks or obscures these smaller scale erosion features. Instead, these erosion processes are often quantified in sample plot studies, traverses, or channel reach studies in which representative areas or channel lengths are inventoried and the measured results are extrapolated to the remaining comparable unsampled areas of the watershed.

Even under the most favorable conditions, air photo analysis is an inexact and imperfect method for landslide identification and the quantification of sediment delivery from mass wasting in a forested landscape (Pyles and Froehlich, 1987; Robison, et al., 1999; Brardinoni, et al., 2002). Air photo analysis will successfully provide an order-of-magnitude estimate of the location, frequency and magnitude of shallow mass wasting (Reid and Dunne, 1996). However, limitations associated with the air photos (photo quality, sun angle, scale, etc) and site conditions (slope gradient, stand type and age, stand height, canopy cover, rate of revegetation, etc) combine to reduce the potential accuracy of the overall landslide identification process.

Shallow debris slides, the most common type of historic mass wasting feature in the Freshwater Creek study area, are difficult to accurately quantify by classic remote sensing, even with large scale aerial photographs. Shallow landslides are often visible on air photos if the photography is taken less than 10 years and preferably less than 5 years, after the landsliding event. Older landslide scars in the cool and wet coastal climate of Freshwater Creek quickly revegetate and become invisible to even the most highly trained analyst. For this reason, photo sets of at least one flight per decade, preferably taken shortly after regional or local landslide-triggering storm events, are required to adequately portray the location and character of shallow landsliding in a watershed.

In spite of employing the best and most careful analytical methods to identify shallow landslide contributions in the watershed an unknown number of landslides are missed. Tall stands of conifers and thick understory vegetation, combined with steep streamside slopes, make the identification of small landslides difficult and imprecise over certain parts of the Freshwater Creek study area. Some portion of the missing or unidentified landslides also contributes to watershed sediment production and delivery, and this is likely to affect the potential accuracy of the sediment source analysis and future TMDL allocations.

To understand just how many landslides were missed and not identified in the earlier air photo analysis, and to quantify their potential contribution to watershed-wide sediment production and delivery, we conducted detailed field inventories of three “randomly” selected watershed areas or plots. The results of this under-canopy assessment will be used to inform the TMDL analysis of the potential magnitude of small scale landsliding in the watershed, and to quantify its influence on basin-wide sediment production and delivery.

B. Previous Studies

Air photo interpretation of landslides has long been the staple analytical method for analyzing watershed sediment production and delivery from mass wasting processes. It is the method of choice for determining landslide frequency, the effects of forest management practices on mass wasting in various terrain types, and for sediment source analyses and sediment budget studies. For example, the widespread use of aerial photography in forest management has led to many studies that concluded that forest clearing dramatically accelerates rates of landsliding over rates in undisturbed forest (Sidle et al., 1985). However, the method itself, and the results it sometimes produces, has recently come under some criticism for its localized inability to detect small landslides beneath forest canopies due to photographic angles, photographic quality, and the obscuring effect of tall trees and other site conditions (Montgomery, et al., 2000).

The debate has been whether or not it is appropriate to use aerial photo analysis to compare landslide frequencies and sediment delivery in recently harvested areas with those areas containing mature forest stands. A limited number of studies have focused on this topic, and all provide some measure of the potential bias that reliance on aerial photo interpretation is likely to bring to such studies. Wolfe and Williams (1987) analyzed historic aerial photography and digital terrain slope maps to study landsliding rates on slopes ranging from pristine to highly disturbed. They found that forest management increased landslide rates in all managed terrains.

This sparked a debate about whether or not the data showed the management effects on landsliding, or if it simply revealed a bias caused by the inability of analysts to accurately identify landslides beneath undisturbed forest canopies (Pyles and Froehlich, 1987). Inner gorges and slopes over 80% are the most landslide prone zones and most sensitive to forest management; but these are also the areas when landslides are most difficult to identify using air photo interpretation.

More recent air photo studies and theoretical evaluations have shown air photo interpretation to be biased due to the inability to identify small landslides under forest canopy (Pyles and Froehlich, 1987); Robison et al., 1999; Brardinoni, et al., 2002; Rogers and Doyle, 2003). In general, these reports indicate that to various degrees aerial photo surveys under-estimate the number of landslides under a forest canopy. "Not visible" landslides can represent up to 85% of the total number of failures and account for 30% of the landslide volume (Brardinoni, et al. 2002). In their study, they found that the percentages also display high sub-basin variability with rates of sediment production varying by one order of magnitude in nearby sub-basins. Lidar imagery helps compensate for the inability of air-photo based methods to see through the forest canopy. However, LIDAR is not considered sufficient to map small (<100 m^3) debris flows that are the most common landslide types in steep forested areas (Haugerud, et al., 2003).

Creating sediment budgets for watersheds requires the use of air photo interpretation to identify sediment sources. Reid and Dunne (1996) assert that most landslides are visible on aerial photos, while also conceding that the frequency of smaller slides that cannot be seen should be estimated. This estimation procedure is not defined, and most landslide studies assume that the small "invisible" landslides are of low or negligible importance to the overall picture of sediment production and delivery. Brardinoni, et al. (2002), in a landslide study in British Columbia, determined that the "unseen" slides account for one-third of landslide sediment delivery over last 30 years in their study area, and that 59 - 85% of slides were not visible. These landslides produced an additional 5% to 30% sediment delivery over that documented by air photo analysis alone. Robison et al. (1999) reported that from 41% to 53% of the sediment generated by a single large storm event went undetermined by solely using air photo analysis of landslides in two heavily forested watershed areas of coastal Oregon.

In heavily forested slopes landslide visibility is complexly controlled by landslide size, air photo geometry, height and density of forest canopy, and the direction and amount of slope gradient (Bucknam et al., 2001)(Figure 16). Pyles and Froehlich (1987) theoretically determined that in the center of a photo the landslide would need to be 30m on a side (0.1 ha) to be visible. At the edge of a photo, a slide on an 80% slope facing away would need to be 100m on a side (1.0 ha) to be equally visible. They showed that without knowledge of the true density of landslides in heavily forested areas, landslides cannot be used to draw inferences about the impact of forest clearing on landslide occurrence. Tree height was found to be important in blocking views of the forest floor, but canopies of >50 year old forests were found to have essentially the same effect as old growth forests on restricting landslide visibility (Brardinoni, et al., 2002). Yet even with the best of ground surface conditions, the air photo analysis method still has inherent limitations for landslide detection, recognition and identification simply due to photo scale and image contrast (Ouattara., et al., 2004).

Figure 16. Ranking factors affecting landslide visibility on aerial photographs

LANDSLIDE VISIBILITY

Importance (least - most)			
	Land use:	Old Growth/	Recently Harvested
	Gully relation:	Sidewall / gully channel	Open slope / headwall
	Slope gradient:	Steep	Gentle
	Valley width:	Narrow	Wide
	Slope position:	Lower portion	Upper portion
	Stream connection:	Connected	Not connected

from Brardinoni, et al., 2002

Robison et al. (1999), in a study comparing landslide frequencies derived from analysis of aerial photos at three different scales compared to field inventories of the same areas, found air photo analysis to result in a biased and incomplete assessment. This bias and significant underestimate of landslide frequency and sediment delivery was found to be true for all forest age classes. In their eight study plots, they found that the majority (72-98 percent) of shallow landslides were not visible on aerial photos of any scale (1:6000, 1:12,000 or 1:24000). The "missed" landslides were found to represent from 41% to 53% of the total landslide-related sediment delivery volumes. Landslide identification was most problematic and inaccurate in areas of mature or semi-mature forest stands. For example, although 50% of the slides could be identified in recently harvested areas, only 5% of the shallow landslides in mature stands (>100 years old) were identified by air photo analysis. As a result of the air photo comparison studies in the Oregon Coast Range, Robison (2003) recommends a de-emphasis of the use of air photos in landslide detection in areas of heavy forest cover.

The larger the photo scale, the more slides can be identified (Robison, et al., 1999). For this reason, a minimum size criterion is sometimes used to eliminate or reduce the bias of landslide detection in studies whore purpose is to compare landslide rates on harvested and unharvested slopes. In Robison's investigation, landslides less than 210 ft^2 were not detected on 1:6000 scale photos. Most landslides less than 5000 ft^2 were not identified on air photos. Based on extensive ground surveys, Robison, et al. (1999) found that about 50% of slides in young growth stands were visible on 1:6000 scale aerial photos, and this detection level dropped to less than 5% in mature and old growth areas. This is not considered surprising in that the reported Oregon Coast Range landslide sizes are smaller than any of the air photo thresholds reported as being used in the literature (Brardinoni, et al., 2002). The two shortcomings of the Oregon study were: 1) only landslides that impacted stream channels were measured (and most of these occurred in the more heavily vegetated riparian zones), and 2) the study focused on the most heavily impacted areas (thereby generating results that are not easily extrapolated).

In addition to underestimating landslide occurrence and sediment delivery volumes for all stand classes, Robison et al., (1999) showed how air photo analysis can significantly magnify landslide density and erosion volume per unit area for recently harvested areas relative to older forested areas (FPAC, 2000). In 35 studies employing either air photo interpretation (n=10), ground surveys (n=6), or both (n=19), air photo analyses indicated that clearcut harvesting increased landslide frequencies by 15-fold over rates in areas of mature forest, whereas the comparable increase in landsliding derived from ground-based inventories alone was only 3-fold. Thus, air photo analysis was found to overestimate the frequency of landslides in clearcut areas compared to mature forest stands by a factor of five (5). However, the discrepancy between air photo inventories and field inventories may have little management implication, due the higher number of hidden slides in old growth areas (Brardinoni, et al., 2002). They found that the management effects of the undetected small landslides beneath the forest canopy did not significantly change attribution or percent attribution.

Although landslide frequency data is altered by the inability to adequately capture slides beneath a forest canopy, landslide volumetric relationship may not be as significantly affected. Brardinoni and Church (2004) used magnitude-frequency analysis to quantify erosion caused by landslides and debris flows in British Columbia. They employed air photo analysis and ground surveys to show that departure from the power law distribution customarily observed for small magnitude landslides is an artifact of sampling deficiencies. However, the total distribution is not sensitive to the frequency of small slides and total erosion remains adequately represented in air-photo-derived data.

Ground-based observations and surveys offer the most reliable conclusions regarding landslide rates and sediment delivery from mass wasting processes; yet they are too expensive and labor-intensive to be widely employed. Although ground-based observations and surveys are more accurate in documenting landslide rates, air photo interpretation affords the opportunity to cover much large portions of the landscape. A sampling strategy employing ground-based inventories in combination with air photo analyses across various geologic and topographic terrains within a study area might provide a mechanism for extrapolating field-based results or defining the probable error associated with broader scale photo-based landslide inventories (FPAC, 2000). The effectiveness of air photo interpretation in delineating small landslide features in a forest landscape is highly variable (Brardinoni, et al., 2002). Certain watershed characteristics and vegetative conditions may dictate when and where supplementary ground-based inventories or sampling will be needed to more accurately determine landslide frequencies and rates of sediment production and delivery from mass wasting processes (Brardinoni, et al., 2002).

C. Purpose of Landslide Comparison Study

A comparison study of air photo identified landslides versus field identified landslides in Freshwater Creek watershed was conducted to: 1) determine the accuracy of air photo analyses for landslides in three vegetation types (young forest, mature second growth and old growth) and

2) develop a correction factor to be applied to the air photo landslide assessments for the remainder of the watershed areas in the Freshwater Creek TMDL study area.

The comparison study and analysis was performed to address the accuracy of air photo identification of landslides that deliver sediment to streams. Specifically, we compared the numbers of air photo-identified landslides from the watershed-wide air photo inventory to field identified landslides in selected sample areas delineated by the following stand ages: 1) old growth, 2) advanced or mature second growth, and 3) "young" forest. Advanced or mature second growth is defined as conifer stands greater than 30 years old (1947/1954, 1966, 1974 air photo time periods). "Young" forest is defined as those stands that are less than 30 years old (post-1975, or those landslides shown on 1987, 1997, and 2003 air photos). Because old growth forest stands do not exist in Freshwater Creek, uncut stands in the Little South Fork Elk River were also investigated. The comparison study, with one study area or "plot" in each forest age class, was designed to determine what percentage of landslides are "missed" during an air photo analysis and how this affects the total volume of sediment delivered to Freshwater Creek.

D. Field Methods

In April and May, 2006, three field crews, each consisting of a lead scientist and a field technician, conducted detailed field inventories of stream channels and related areas in three study areas or "plots" in the Freshwater Creek and Little South Fork Elk River watersheds (Figure 17). The three study plots and associated channel inventory reaches were selected based primarily on forest stand age (<30 yrs, >30 yrs, and uncut old growth). Within these potential study areas, sample sub-watershed study areas and channel reaches were selected for the field inventory. A total of 10.1 miles of stream channel was inventoried for debris slides in the three sample plots (Table 15).

Table 15. Three Landslide Study Areas, Aerial Photo and Field landslide Comparison Study, Freshwater Creek TMDL, Humboldt County, California.

Forest type	Old growth (unmanaged)	Advanced Second Growth (ASG)	Recently Harvested	Total
Location of Sample Plots (Watershed)	South Fork Elk River	Upper Freshwater Creek	Little Freshwater Creek	
Length of Channel Inventoried (feet)	19,008'	16,896'	17,424'	53,328'

The project geologists identified channel reaches in the field and developed access points for the inventory crews. Plot areas consisted of small sub-watersheds. Each channel reach and tributary reach in a sample plot was stationed starting at the top of the channel or at a tributary channel confluence within the study area. Measuring tapes were pulled through the center line of the

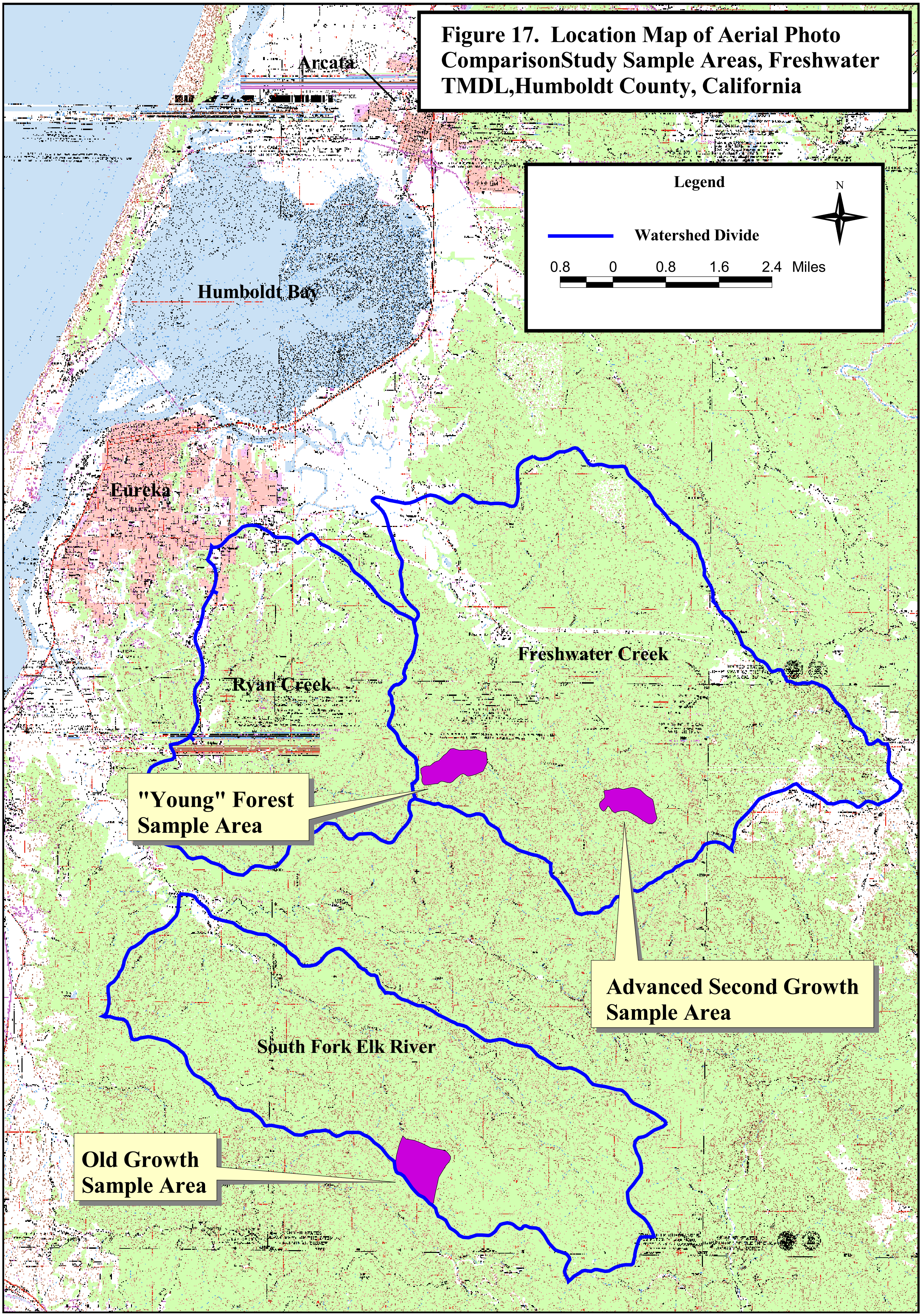


Figure 17. Location Map of Aerial Photo ComparisonStudy Sample Areas, Freshwater TMDL,Humboldt County, California
Arcata
Legend
N
Watershed Divide
0.8 0 0.8 1.6 2.4 Miles
Humboldt Bay
Eureka
Freshwater Creek
Ryan Creek
"Young" Forest Sample Area
Advanced Second Growth Sample Area
South Fork Elk River
Old Growth Sample Area

channel and stationing flags were hung at 100 or 200 foot intervals, depending on the observed landslide frequency and inter-station visibility within the channel.

As the channels were stationed, geologists inventoried left and right channel banks and sideslopes for evidence of past or present instability. If any landslide features were identified, field personnel hiked and investigated the entire slide surface, including the crown and lateral scarps, to characterize slide morphology, to determine slide age, and to identify the most likely primary and secondary causes of mass wasting. The location of each landslide was plotted on LIDAR imagery and recorded according to the stationing along the channel. Geomorphic features and landslides were mapped on mylar overlays on 1" = 100' scale LIDAR base maps with 20 ft contours. Geomorphic features, including channel grades, boulder cascades, tributary junctions, sideslope swales, rock outcrops and log jams, were also mapped.

A data form was prepared for each landslide "site" identified in the field inventory, and a variety of site variables (feature type, slope gradient, estimated canopy closure, slide age, cause, etc) were recorded. Only delivering landslides were inventoried. Landslides were further broken down into two categories: those less than 10 cubic yards in volume and those larger than 10 cubic yards. The smaller slides (<10 yds^3) were mapped and tabulated, but data forms were prepared only for those that were over 10 yds^3 in volume. Landslide dimensions were measured using cloth tapes and recorded on the data form. Multiple widths, depths, and an average length dimension were taken to develop average dimensions. Sediment delivery was quantitatively determined by measuring void dimensions and on-site deposits, and then independently generated by ocular estimation.

Determination of landslide cause was sometimes difficult and required professional judgment. The most obvious contributing cause to slope failure (the primary cause) was listed on the data form. Only one primary and one secondary cause could be selected for the database. Landslide were classified as active, active-suspended, and inactive (dormant). Landslide activity indicators were only collected for active slides. Landslides were age-dated using geomorphic and vegetative site conditions (scarp morphology, slide scar revegetation, leaning trees, sapling growth whorls, soil bareness, type of cover (herbaceous versus trees), etc.) and placed in one of three age categories (1975–1987; 1988–1997; 1998–2003). Landslide in these time periods would be subject to potential identification on air photos from 1987, 1997 and 2003. Landslides pre-dating 1975 and post-dating 2003 were mapped but not inventoried on data forms. A sketch was prepared and photographs taken for many inventoried sites to aid in interpretation and location. Data collected on the data form was then entered in a relational database and sites were mapped in GIS. The database was then cleaned before being analyzed.

E. Results

Over 53,300 feet (10.1 miles) of stream channel, covering over 106,600 feet (20.2 miles) of stream bank and streamside hillslope, was inventoried for the field portion of the landslide comparison study (Table 16). This included 3.6 miles of channel in uncut old growth redwood stands in the little South Fork Elk River (Figure 18), 3.2 miles of channel in advanced second growth forest areas of upper Freshwater Creek (Figure 19), and 3.3 miles of channel in recently harvested areas of Little Freshwater Creek, a tributary to Freshwater Creek (Figure 20; Table 16).

A total of 53 small landslides, each displaying less than 10 cubic yards of past sediment delivery, were mapped in the 10.1 miles of inventoried stream channel in the three study plots. The small slides averaged about 70 ft^2 in surface area. Assuming an average delivery volume of 5 yds^3, the total sediment delivery from the small landslides was 265 cubic yards or approximately 5 cubic yards per 1000 feet of channel (Table 16). Channels in recently harvested areas showed the highest frequency of small landslides (1.5 slides/1000 feet) and the greatest unit sediment delivery (7.75 yds^3/1000 feet). Data forms were not prepared for these small features.

A total of 44 "larger" landslides were also inventoried within the 10.1 miles of sampled stream channel in the three study areas (Figures 18-20). Data forms and attribute information were collected for each of these landslides. Assuming an average landslide depth of three feet, the typical streamside debris slide averaged 1,270 ft^2 in surface area, or 35 feet on a side. These are still small slides that are not likely to be observed on air photos even in good conditions. The largest landslide, an earthflow, measured 150' x 150' (22,500 ft^2) and was found in the "young" growth sample area of Little Freshwater Creek.

The 44 inventoried landslides in the field study plots delivered a total of 6,100 yds^3 of sediment of streams (Table 16). These included 2 earthflows and 2 translation landslides. The remaining 40 mass wasting features were classified as debris landslides. Only six of the 44 landslides were classified as currently active; 15 were judged to be totally inactive.

By far the greatest number of inventoried landslides (48%) and total measured landslide sediment delivery (77%) originated from recently harvested areas in the "young" growth forest stands of Little Freshwater Creek (Table 2). The largest (150' x 150' = 22,500 ft^2) and deepest (5 ft deep) slide was from Little Freshwater the sample area. It delivered 417 yds^3 of sediment to Little Freshwater Creek. The slide was a small earthflow on the outside bend of the channel. It was characterized by leaning trees and other evidence of continued and perhaps long term instability, but not extensive areas of bare mineral soil. It was assigned a primary cause of "unstable geology."

Inventoried landslides in the unmanaged old growth study area in the Little South Fork Elk River watershed (Figure 18) accounted for 9% of the inventoried landslides and less than 6% of the measured sediment delivery from the three plots over the 28 year time period from 1975 – 2003 (Table 16). Only seven of the landslides delivered more than 100 yds^3 of sediment during the analysis period (1975-2003). Twenty-two of the slides delivered 30 yds^3 or less and all but seven of the inventoried landslides had depths of three feet or less. The maximum document landslide depth was five feet. The second deepest landslide (4.5 ft deep; 112 yd^3) was from the Upper Freshwater advanced second growth (ASG) plot.

All the landslides in the three study plots were small, and it was not surprising that they did not show up on 1:12,000 scale aerial photos of the plots. Landslide areas ranged from 150 ft^2 to 22,500 ft^2 feet (Figure 21). Only eight landslides were larger than 2000 ft^2 (45' x 45'), and none

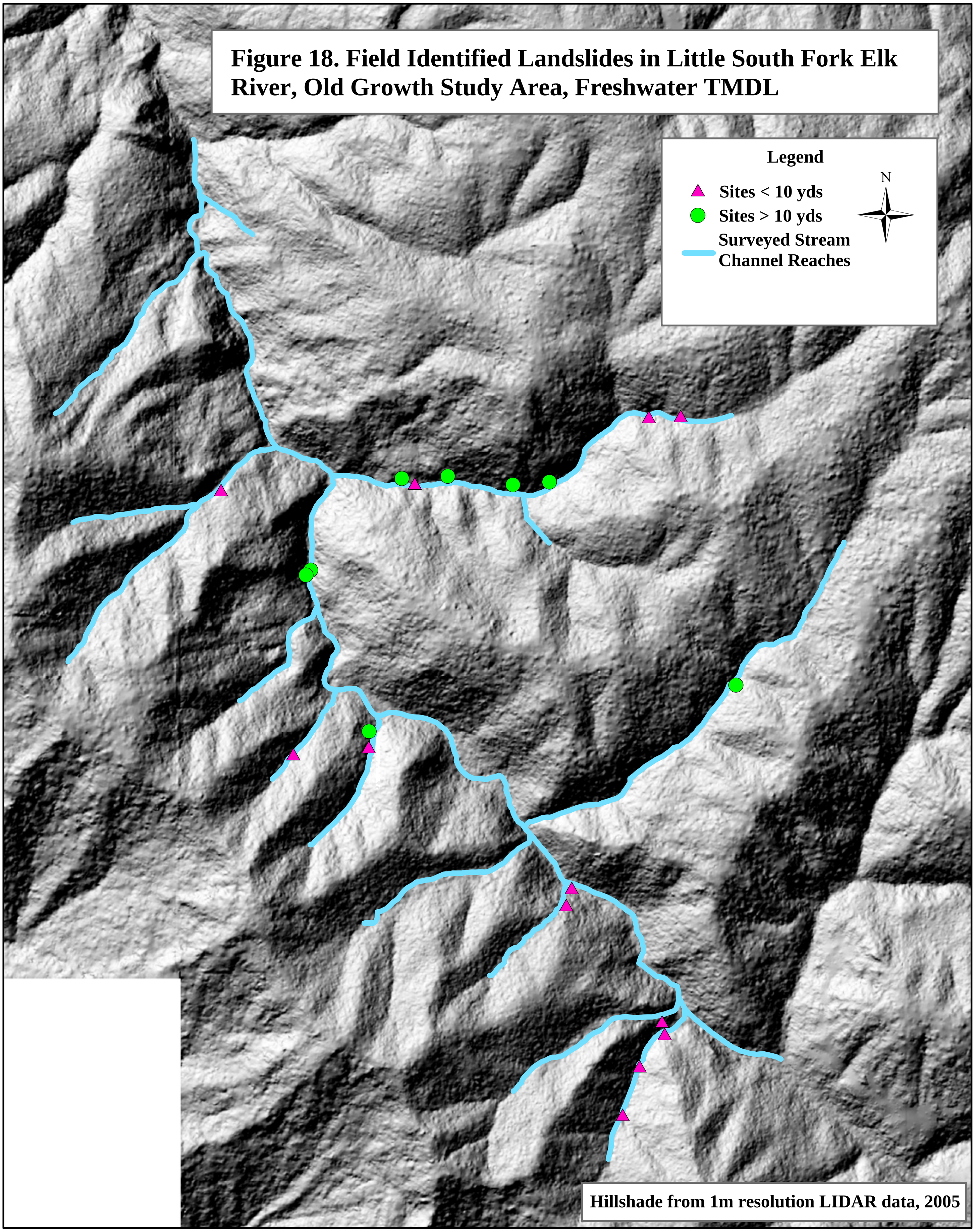
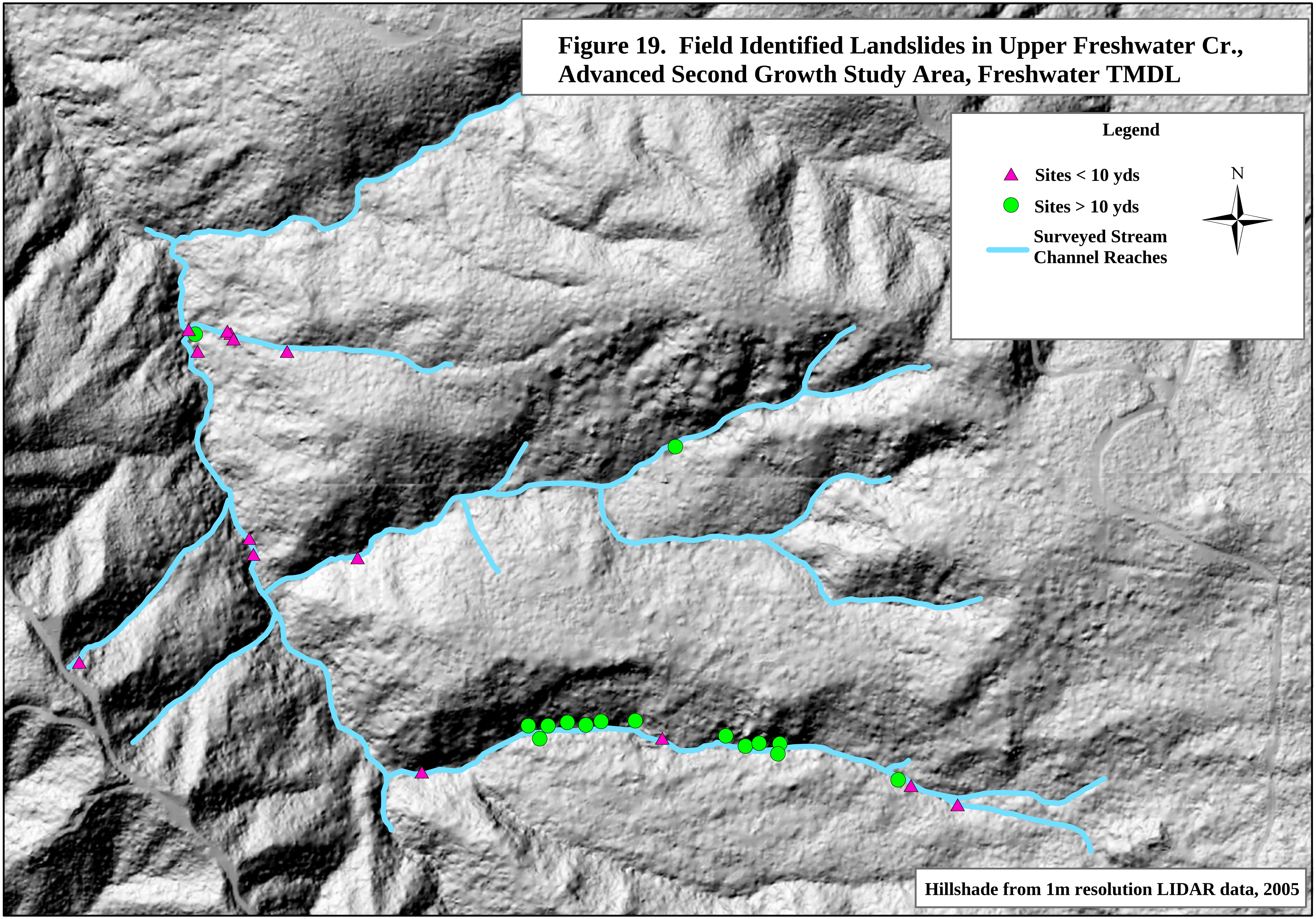


Figure 18. Field Identified Landslides in Little South Fork Elk River, Old Growth Study Area, Freshwater TMDL
Legend
Sites < 10 yds
Sites > 10 yds
Surveyed Stream Channel Reaches
N
Hillshade from 1m resolution LIDAR data, 2005

Figure 19. Field Identified Landslides in Upper Freshwater Cr., Advanced Second Growth Study Area, Freshwater TMDL



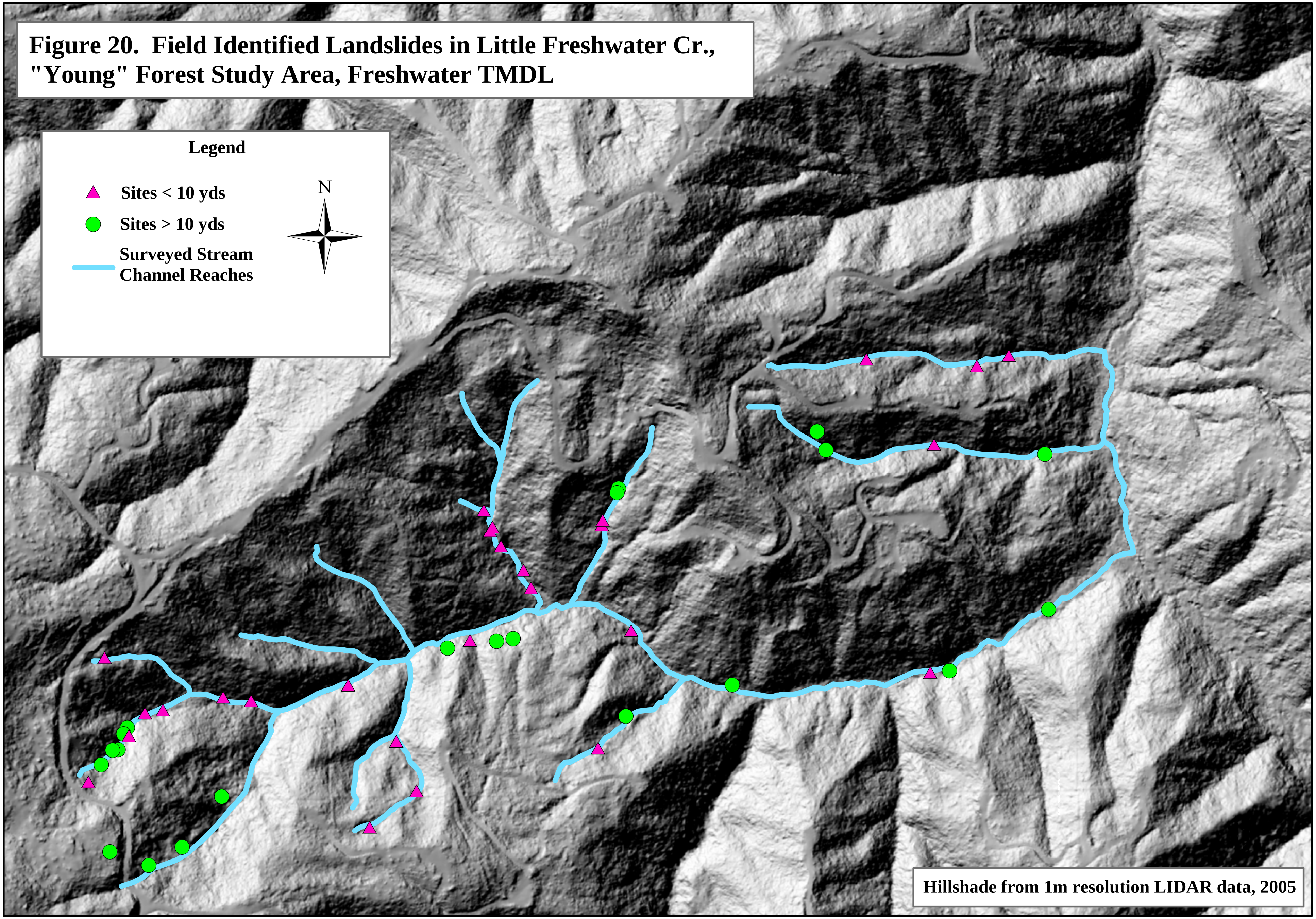
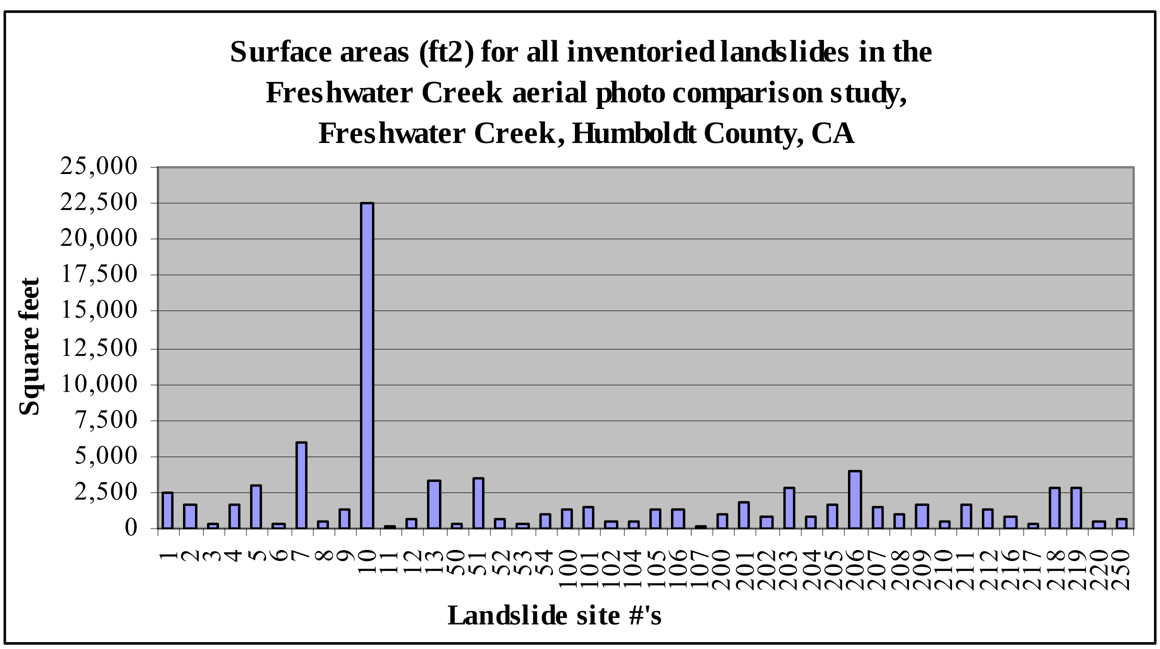


Figure 20. Field Identified Landslides in Little Freshwater Cr.,
"Young" Forest Study Area, Freshwater TMDL
Legend
Sites < 10 yds
Sites > 10 yds
Surveyed Stream Channel Reaches
N
Hillshade from 1m resolution LIDAR data, 2005

Table 16. Forest Types, Landslides, and Sediment Delivery for the Freshwater Creek TMDL Aerial Photo / Field Inventory Landslide Comparison Study, Humboldt County, California.

Forest type	**Unmanaged Old Growth**	**Recently Harvested Areas**	**Advanced Second Growth**	---
Watershed	South Fork Elk River	Little Freshwater Creek	Upper Freshwater Creek	Total
Length of inventoried stream channel	19,008' (3.6 miles)	17,424' (3.3 miles)	16,896' (3.2 miles)	53,328 (10.1 mi)
No. of small (<10 cubic yard) landslides	12	27	14	53
Sediment delivered from small landslides (yds^3)	60	135	70	265
No. of >10 cubic yard landslide sites	8	21	15	44
Sediment delivered from > 10 yd^3 landslide sites (yds^3)	352	4,791	1,056	6,199
Landslides identified in air photo analysis of same watershed area	0	0	0	0
Sediment delivered from air photo-identified landslides (yds^3)	0	0	0	0

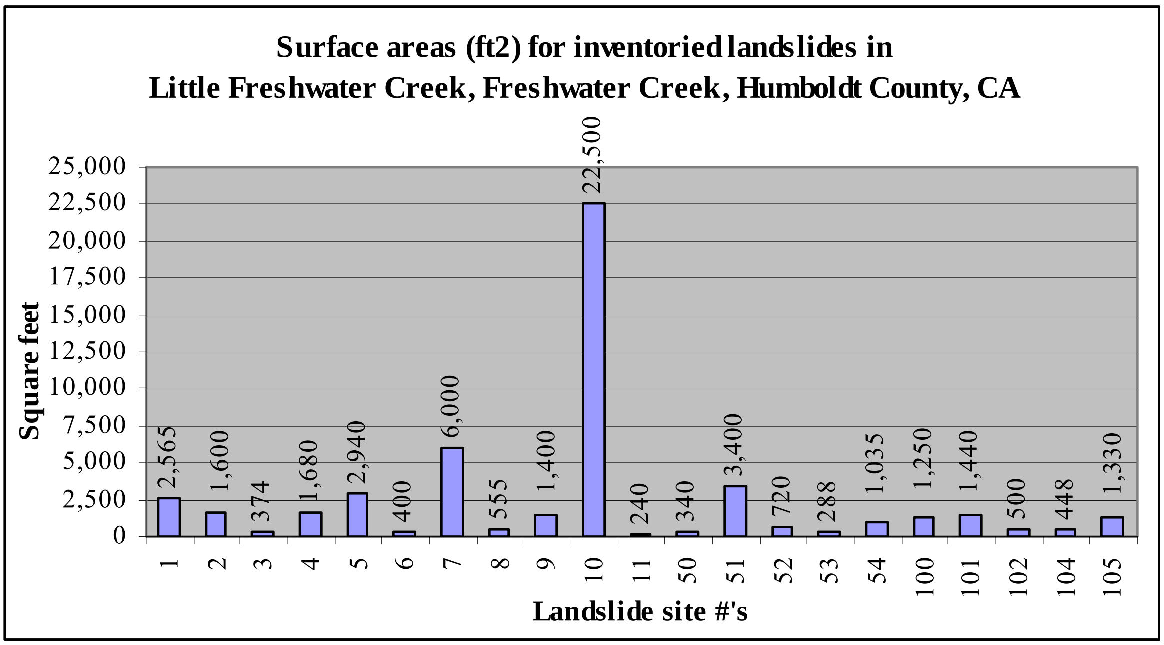
Figure 21



of these showed up on aerial photos. The largest landslide (150' x 150') was an earthflow with minimal surface disturbance. The second largest slide was 6000 ft^2 in surface area (60' x 100') and was classified as a translational landslide, also with minimal exposure of bare mineral soil. Of the eight landslides exceeding 2000 ft^2 in surface area, five occurred in the young growth plot; the two largest were deep seated slides with minimal exposure of bare mineral soil and the remaining three were classified as debris landslides.

Due to the young overstory and understory vegetation, landslides inventoried in the Little Freshwater Creek study area were judged to be the most likely to be seen in air photo analysis of the three study sites. However, none were identified. This is likely the combined result of rapid revegetation, small landslide size (Figure 22) and steep streamside slopes.

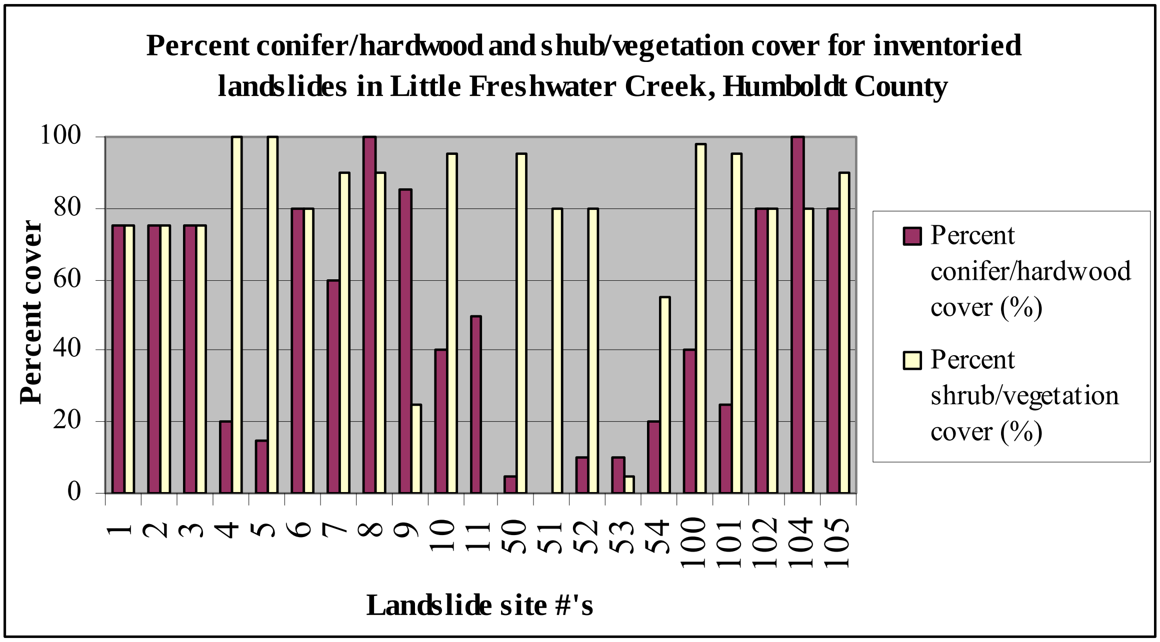
Figure 22



All the debris slides occurred on relatively steep streamside slopes and this is another factor that can mask their visibility on aerial photos (Pyles and Froehlich, 1987; Brardinoni, et al., 2002). Debris slides occurred on slopes gradients ranging from 40 to 115%, and averaging 72%. These narrow, steep valleys serve to reduce the exposure of the landslide to overhead photography, especially if the flight line and resultant photo centers are taken at a low angle to the slide surface. Twenty-nine of the failures have mid-feature slope gradient exceeding 60%. In contrast, earthflow and translational slides typically displayed slope gradients in the 40% to 55% range, but because of their extensive canopy and ground cover, they were also masked from aerial photographic identification.

Table 17 summarizes some of the attribute data that was collected for the inventoried landslides in each of the three study plots. In addition to the small size of the inventoried landslides, overstory conifer cover on the inventoried landslide sites is likely one of the leading reasons that the landslides were not identifiable on aerial photos. For example, even landslides in the recently harvested plot in Little Freshwater Creek exhibited 50% mean overstory cover and 74% mean understory cover when the survey was undertaken in 2006 (Table 17; Figure 23). Estimated conifer cover in the unmanaged old growth plot was estimated to be only 40% higher than that at slide sites in the recently harvested plots. It is likely that even in the recently harvested areas riparian leave strips and buffers that are now left to provide shade and protect slope stability are also functioning to mask the small landslide sites from more accurate air-photo landslide identification.

Figure 23



The identified causes of the landslides in the three study plots were varied and dispersed among a variety of factors (Table 17). Direct and clear management associations were only occasionally present at the landslide site. "Unstable geologic materials" was the most common primary cause identified in the field, accounting for 16 of the primary landslide causes. Although seven landslides were classified as having some apparent connection to management, it was difficult to make clear and unambiguous management associations at the landslide site. Similarly, because of the lack of direct field evidence, we were not able to identify the relative importance of upstream hydrologic changes that may have occurred from off-site timber harvesting and road building, if any. Significant increases in peak flows for some storm flows may contribute to the seven sites where undercutting (bank erosion) was identified as the primary causal mechanism.

Landslide causes and attribute data have also been expressed according to the photo period (Table 18). Only 20% of the identified landslides were attributed to the earliest photo period (1975-1987). This may be at least partially the result of revegetation and natural obscuring of older slide surfaces. Once identified on the ground, the age classification was actually relatively straightforward using more mature vegetation on the landslide scars. In practice, it was more difficult to differentiate the relative age classes of landslides in the two most recent photo periods (1988-1997 and 1998-2003), largely because both age classes had developed a slid ground cover,

Table 17. Forest types and site attribute data, Freshwater Creek TMDL Aerial Photo / Field Identified Landslide Comparison Study, Humboldt County, California

Harvest type	**Unmanaged (Old Growth)**	**Recently Harvested**	**Advanced Second Growth**	Total
Watershed	South Fork Elk River	Little Freshwater Creek	Upper Freshwater Creek	
Number of sites	8	21	15	44
Dates of survey	May 1 to May 3, 2006	April 18 to April 25, 2006	April 24 to April 26, 2006	April 18 to May 3, 2006
Percent conifer cover	40-95	0-100	30-99	---
Percent shrub cover	60-95	0-100	15-100	---
Mean % conifer cover (overstory)	69	50	58	---
Mean % shrub cover (understory)	83	74	72	---
Landslide Types	8 DS	18 DS 2 EF 1 TDL	14 DS 1 TDL	40 DS 2 EF 2 TDL
Slide age	4 1975 -1987 2 1988-1997 2 1998-2003	2 1975 –1987 11 1988-1997 8 1998-2003	3 1975 –1987 9 1988-1997 3 1998-2003	9 1975 -1987 22 1988-1997 13 1998-2003
Field Observed Geology	2 Wildcat 6 Yager	21 Wildcat	12 Wildcat 2 Yager 1 unknown	35 Wildcat 8 Yager 1 unknown
Primary cause	3 natural flow deflection 3 undercutting 2 unstable geology	3 diverted flow on hillslope 2 harvest 1 management flow deflection 2 undercutting 12 unstable geology	1 emergent ground water 1 natural flow deflection 2 unstable geology 11 undercutting	
Secondary cause	1 none 1 harvest 1 undercutting 3 natural flow deflection 2 unstable geology	5 none 1 emergent ground water 2 harvest 1 natural flow deflection 4 undercutting 8 unstable geology	1 none 1 other 1 diverted flow on hillslope 3 management flow deflection 3 natural flow deflection 2 undercutting 4 unstable geology	
Activity	6 active-suspended 0 active 2 inactive	9 active-suspended 2 active 10 inactive	8 active-suspended 4 active 3 inactive	23 active-suspended 6 active 15 inactive

Table 18. Inventoried Landslides By Age Class, Freshwater Creek TMDL Aerial Photo / Field Comparison Study, Humboldt County, California

Age Class	**(1) 1975-1987**	**(2) 1988-1997**	**(3) 1998-2003**	Total
Sites	9	22	13	44
Geology	4 Wildcat 5 Yager	22 Wildcat	9 Wildcat 4 Yager 1 unknown	35 Wildcat 4 Yager 1 unknown
Activity	5 active suspended 0 active 4 inactive	10 active suspended 2 active 10 inactive	8 active suspended 4 active 1 inactive	23 active suspended 6 active 15 inactive
Primary Cause	1 harvest 1 natural flow deflection 6 undercutting 1 unstable geology	1 diverted flow on hillslope 1 emergent ground water 1 natural flow deflection 8 undercutting 11 unstable geology	2 diverted flow on hillslope 2 harvest 1 management flow deflection 2 natural flow deflection 2 undercutting 4 unstable geology	
Secondary cause	1 management flow deflection 3 natural flow deflection 1 undercutting 4 unstable geology	6 none 1 emergent groundwater 2 harvest 2 management flow deflection 2 natural flow deflection 1 other 2 undercutting 6 unstable geology	1 none 1 diverted flow on hillslope 1 harvest 2 natural flow deflection 4 undercutting 4 unstable geology	

but there was often not a clear difference between in the character of the woody vegetation that had established.

Most landslides occurred in the 1988-1997 photo period (Table 18), and this was likely the result and expression of the importance of the 1997 storm and flood event. However, the 2003 storm event has also been described as a significant and potentially landslide-producing storm for both Elk River and Freshwater Creek, yet air photo analyses by the Pacific Lumber Company indicate that basin response (landsliding observed during post-storm air photo analysis) was not as significant as in 1997 (Pacific Lumber Company, 2004).

F. Discussion and Conclusions

The landslide detection and identification comparison study was conducted to determine the accuracy of air photo analyses for landslides in three vegetation types (young forest, mature second growth and old growth) and to develop a possible correction factor to be applied to the air photo landslide assessments for the remainder of the unsampled watershed areas in the Freshwater Creek TMDL study area. The comparison study, with one study area or “plot” in each of three forest stand classes, was designed to determine what percentage of landslides are “missed” during an air photo analysis and how this affects the total volume of sediment delivered to Freshwater Creek.

There is a relatively clear relationship between the three forest age classes and the landslide sediment production and delivery that has been generated in each stand type (Table 19). In a previous sediment source investigation in the Freshwater Creek watershed (PWA, 1999), 16.8 miles of Class 1 stream channels were walked and inventoried for small streamside debris slides that had not been identified from air photo analyses. That study documented a unit sediment yield from small sub-canopy landslides of 147 yds/1000 feet of Class 1 stream channel. The 1999 inventory was conducted in channel along mature second growth stands and recently harvested slopes (there are no old growth forest stands in the Freshwater Creek watershed). The average sediment production for channel located in young growth and advanced second growth forest stands in the current study is a comparable 169 yds^3/1000 ft) of channel.

Although the relationship of increasing sediment delivery with younger harvest ages (Table 19) is suggestive of the role of recent management in small landslide occurrence, it could also be related to the decreasing ability of trained observers to correctly detect and identify small landslides that have become increasingly vegetated over time. Although sample size isinsufficient for drawing definitive conclusions, the findings do suggest answers to some of the broad questions posed above (e.g., how much sediment production is missed by not identifying

Table 19. Sediment delivery from landslides not visible on air photos, Freshwater Creek TMDL Aerial Photo / Field Identified Landslide Comparison Study, Humboldt County, California

Forest Age Class	Unit sediment delivery from small (<10 yd^3) landslides (yds^3/1000 feet of channel)	Unit delivery from landslides larger than 10 yd^3 (yds^3/1000 feet of channel)	Total unit sediment delivery (yds^3/1000 feet of channel)
Old Growth	3.2	18.5	21.7
Advanced Second Growth (>30 yrs old)	4.1	53.1	57.2
“Young” Growth (<30 yrs old)	7.7	274.0	281.7

the small landslides). Again, the sample size (three plots and 20 miles of stream bank and channel sideslope) is probably insufficient to make widespread extrapolations elsewhere or even to other sub-watershed in the Freshwater and Elk River drainages without additional analyses. For example, research elsewhere shows that sample variability for these types of studies can be large and that findings in one location may not be easily extended to nearby sub-watersheds in the same watershed (Brardinoni, et al., 2002).

Landslides that were not identified in the Freshwater TMDL air-photo based landslide inventory were expected to be small; air photo resolution using 1:12,000 scale photos should reveal slides and bare areas down to 400 ft^2 under ideal conditions of visibility. While the unidentified slides were relatively small, the study revealed that landslides in the 500 to 2000 ft^2 size class, and even in the 2000 to 3000 ft^2 size range, were not identified, either due to rapid revegetation, canopy cover, local topography or other factors. These relatively small, undetected slides may be numerous but without the ground-based survey their density on the ground, and their importance to basin-wide sediment production, would not be known. Other researchers have found small landslides to be potentially important in watershed sediment studies (Brardinoni, et al., 2002; Robison, et al., 1999).

The "random" sampling strategy employed to pick the streams and inventory areas in the three forest age classes unintentionally resulted in the absence of air-photo inventoried landslides in the study areas. This was not unanticipated, as landslide densities in the Freshwater Creek watershed during these three photoperiods (1987, 1997, and 2003) are not particularly high. This result conveys both benefits and limitations to project findings. First, all landslides encountered in the field could be clearly classified as "invisible" to the previous air photo analysis. Our photo analyst even returned to the original photo set to confirm that these relatively small field-identified landslides could not be seen on the photos, even though their exact location was known from the field study. At the same time, the lack of larger, more visible landslides does not allow us to evaluate the minimum visible landslide size class that can be reliably and consistently identified in each of the forest age classes, nor to quantitative differences in the accuracy with which landslides can be identified under various aged forest stands.

Creating sediment budgets for watersheds requires the use of air photo interpretation to identify all significant sediment sources. The undetected small landslides that were mapped in the field inventory ultimately affect the frequency distribution of the overall landslide population. Shallow debris slides, the most common type of historic mass wasting feature in the Freshwater Creek study area, are difficult to accurately quantify by classic remote sensing, even with large scale aerial photographs. Even under the most favorable conditions, air photo analysis is an inexact and imperfect method for landslide identification and the quantification of sediment delivery from mass wasting in a forested landscape (Pyles and Froehlich, 1987; Robison, et al., 1999; Brardinoni, et al., 2002). Some landslides, together with their contribution to basin-wide sediment production and delivery, will always be missed. Most landslide studies assume that the small "invisible" landslides are of low or negligible importance to the overall picture of sediment production and delivery. Some portion of the missing or unidentified landslides contributes to watershed sediment production and delivery, and this is likely to affect the potential accuracy of the sediment source analysis and future TMDL allocations.

Ground-based observations and surveys offer the most reliable methods for identifying small landslides that cannot be reliably identified by air photo analysis. Tall stands of conifers and thick understory vegetation, combined with steep streamside slopes, prevented the identification of small landslides up to about 2500 ft^2 in size. All the landslides in the three study plots were small, and it was not surprising that they did not show up on 1:12,000 scale aerial photos of the plots. By far the greatest number of inventoried landslides (48%) and total measured landslide sediment delivery (77%) originated from recently harvested areas in the "young" growth forest stands of Little Freshwater Creek. In contrast, inventoried landslides in the unmanaged old growth study area in the Little South Fork Elk River watershed accounted for only 9% of the inventoried landslides and less than 6% of the measured sediment delivery from the three plots over the 28 year time period from 1975 – 2003. The implied relationship between the age of harvesting and landslide frequency is interesting and intuitive, but may be a relic of the small sample size.

All the inventoried debris slides occurred on relatively steep streamside slopes and this is another factor that can mask their visibility on aerial photos. Conifer cover in the unmanaged old growth plot was estimated to be only 40% higher than that at slide sites in the recently harvested plots. It is likely that even in the recently harvested areas riparian leave strips and buffers that are now left to provide shade and protect slope stability are also functioning to mask any small landslides that do occur from more accurate air-photo landslide identification.

Finally, the identified causes of the landslides in the three study plots were varied and dispersed among a variety of factors, most of which could not directly tied to a management activity. Direct and clear management associations were only occasionally present at the small landslides sites. Because of this, the increased landslide sediment production and delivery associated with the unidentified landslides will likely add to or increase the background or natural sediment delivery component of watershed wide sediment production and discharge. Management causes are often difficult to identify through direct observation in the field. For this reason, a more thorough analysis of landslide causal mechanisms for small debris slides would be needed to provide a clearer breakdown of management associations and the allocation of landslide volumes to either natural or anthropogenic causes.

V. Road Surface Erosion Analysis

To develop an estimate of road surface erosion for the Freshwater Creek TMDL study area, SEDMODL2 was applied to roads identified as part of the air photo analysis in the Ryan Sough and Fay Slough planning watersheds. In addition, road surface erosion estimates generated by SEDMODL as part of the Freshwater Creek Watershed Analysis (PALCO, 2000) were reviewed and combined with the road surface erosion estimates for the Ryan Slough and Fay Slough planning watersheds so as to produce a total estimate of road surface erosion for the entire Freshwater Creek TMDL study area.

A. Methods

SEDMODL2, is a GIS-based model developed by NCASI (2002) to determine the portions of roads that directly and indirectly drain to streams. By employing a series of assumptions, the model provides an average annual sediment input (tons/yr) from road reaches that deliver road runoff and fine sediment to streams. To run, the model required a comprehensive GIS road layer that included all the pertinent roads within the Freshwater Creek TMDL study area. The SEDMODL2 model was only applied to roads within the Ryan Slough and Fay Slough planning watersheds. Estimates of road surface erosion from Freshwater Creek were derived from existing SEDMODL data from the previously completed Freshwater Creek Watershed Analysis (PALCO, 2000).

A comprehensive road layer was developed for the Ryan Slough and Fay Slough planning watersheds using the CDF FRAP 1:24,000 roads layer supplemented by air photo analysis. The FRAP road layer was used as the base transportation layer that was then modified to correct road position and to add additional roads not present on the FRAP roads layer. All roads were age-dated according to first appearance on the historic aerial photography (1987, 1997, and 2003).

In addition to roads, other GIS data requirements for the SEDMODL2 included topography generated from available DEM layers, hydrology, study area boundary, precipitation data, geology, and soils (soils depth and bulk density). For the purposes of generating road surface erosion estimates for the Ryan Slough and Fay Slough planning watersheds, SEDMODL2 was run on a sub-basin scale for the Ryan Slough planning watershed and for the entire Fay Slough planning watershed. Topography and hydrography GIS layers for the Ryan Slough planning watershed were developed from the LIDAR DEM. Because the LIDAR DEM was not complete for the entire Fay Slough planning watershed, topography and hydrology layers were developed from the USGS 10 meter DEM. Precipitation data used in the SEDMODL2 analysis of roads within the Ryan Slough and Fay Slough planning watersheds was derived from PRISM data for California compiled by Oregon State University.

Geology GIS layers for the TMDL study area were developed from the Geology of the Cape Mendocino, Eureka, Garberville, and Southwestern Part of the Hayfork 30 x 60 Minute Quadrangles and Adjacent Offshore Area, Northern California (McLaughlin et al., 2003). Geologic units were attributed according to SEDMODL2 geologic erosion factors. SEDMODL2 erosion factors range between 1 and 5 based on erodibility. Factor 1 represents lithified Quaternary, Tertiary, Mesozoic, Paleozoic and Precambrian rocks. Geologic factor 5 applies to unlithified sands and silts. Table 20 outlines the geologic factors applied to lithologic units found in the Freshwater Creek TMDL study area.

Table 20. SEDMODL Geologic Factor by Lithologic Unit, Freshwater Creek TMDL Study Area

Lithologic Unit	SEDMODL Geologic Factor
Qal (alluvium)	3
Qt (terrace deposits and Hookton Formation	3
QTw (Wildcat Group)	1
TKy (Yager Formation)	1
KJfm (Franciscan mélange)	1

The required SEDMODL factors for soils include soil depth and soil bulk density. A soil depth of 5 feet was estimated for the Ryan Slough and Fay Slough planning watersheds based on average soil depth data employed in the Freshwater Creek Watershed Analysis (PALCO, 2000). In addition, an average soil bulk density of 1.4 gm/cc was used in the SEDMODL2 analysis.

Road surface and traffic factors are required for SEDMODL calculation of road surface erosion. Due to the limited time period available to conduct the SEDMODL analysis and the limited project budget, roads in the Ryan Slough and Fay Slough were not field verified culvert drainage locations or for the specific road erosion factors necessary to optimize model output. As a result, the SEDMODL2 documentation model, and the SEDMODL analysis conducted as part of the Freshwater Creek Watershed Analysis were reviewed to develop average road erosion factors for the Ryan Slough and Fay Slough planning watersheds. Table 21 outlines the road erosion factors used in the SEDMODL2 model runs in the Ryan Slough and Fay Slough planning watersheds.

Table 21. SEDMODL Road Erosion and Traffic Factors, Freshwater Creek TMDL Study Area

Traffic Use	Traffic Factor	Tread Surfacing Factor	Road Surface Type	Road Width (ft)	Cutslope Cover (%)	Cutslope Height (ft)	Maximum Sediment Delivery Road Distance (ft)	Average Road Slope Gradient (%)[1]	Road Age Factor
County Road	50	0.03	Paved	35	70	2.5	1,000	10/2	1
Primary Road	10	0.2	Gravel	25	70	10	1,000	10	1
Secondary Road	2	1	Native	18	70	10	1,000	10	1

[1] Average road gradient was assumed to be 10% for all roads within the Ryan Slough planning watershed and 2% in the Fay Slough planning watershed.

The SEDMODL program estimates road surface erosion using the following equations:

1. Total Sediment Delivered from each Road Segment (tons/yr) = Tread + Cutslope

2. Tread = Geologic Erosion Rate x Tread Surfacing Factor x Traffic Factor x Segment Length x Road Width x Road Slope Factor x Precipitation Factor x Delivery Factor

3. Cutslope = Geologic Erosion Rate x Cutslope Cover Factor x Segment Length x Cutslope Height x Delivery Factor

B. Results

Table 22 outlines the results for the SEDMODL2 analysis of the Ryan Slough and Fay Slough planning watersheds, and the SEDMODL analysis conducted in Freshwater Creek as part of the 2000 Freshwater Creek Watershed Analysis, by sub-basin. Approximately 166,392 yds^3 of sediment is estimated to have been delivered to streams from road surface erosion as calculated by SEDMODL (Table 22). Approximately 80% (132,340 yds^3) of the sediment delivery from road surface erosion occurred in the Freshwater Creek watershed. In addition, Freshwater Creek exhibited the highest road surface erosion sediment delivery rate (276 tons/mi^2/yr) and the lowest road density (7.6 mi/mi^2).

Table 22. Surface Erosion Estimates Generated by SEDMODL, Freshwater Creek TMDL Study Area.

Sub-basin	Sub-basin Area (mi^2)	Total Road Mileage (mi)	Road Density (mi/mi^2)	Road Surface Erosion (tons/yr)	Road Surface Erosion Rate (tons/mi^2/yr)	Total Road Surface Erosion (1987-2003) (yds^3)	Total Road Surface Erosion (1987-2003) (tons)
Ryan Slough	14.74	128	8.7	1,486	101	25,877	36,228
Freshwater Creek	30.73	234	7.6	8,470	276	132,340	185,275
Fay Slough	12.38	109	8.8	456	37	8,175	11,445
Total	**57.85**	**471**	**8.1**	**10,412**	**180**	**166,392**	**232,949**

Road densities in the Ryan Slough and Fay Slough planning watersheds were 14% higher than those in Freshwater Creek. The high road densities are a reflection of the higher concentration of county, urban and rural residential roads in the Ryan Slough and Fay Slough planning watersheds. The Fay Slough planning watershed had the lowest road surface erosion sediment delivery (8,175 yds^3) and the lowest sediment delivery rate (37 tons/mi^2/yr) due to the high percentage of low gradient county roads and urban paved roads. Although 78% of the Ryan Slough planning watershed is managed by the Green Diamond Resource Company, the road surface erosion rate was nearly 64% lower than the road surface erosion rate in Freshwater Creek.

C. Conclusions

Road surface erosion is a highly important component of the sediment budget of each of the three planning watersheds, but especially for Ryan Creek and Freshwater Creek. Sediment delivery from road surface erosion processes, traveling and discharging through hydrologically connected road reaches, may annually contribute more sediment to the stream system than mass wasting across the entire TMDL study area (Tables 9, 10 and 22).

The high road densities and low yield rates from roads in Ryan Creek are the result of paved residential and public road systems. It is likely that the unpaved logging roads and driveways in the Ryan Creek planning watershed erode and deliver fine sediment to streams at a rate at least comparable to Freshwater Creek. Highly erodible Hookton Formation sediment occur more commonly in Ryan Creek and unsurfaced roads through this terrain would be expected to generate comparably high rates of erosion and sediment delivery.

The high rate of fine sediment flux from roads in the Freshwater Creek planning watershed (Table 22) is likely the result of the high percentage of unsurfaced roads in the analysis area, and the high erosion rate that is applied by the model. Because actual road connectivity in Freshwater Creek is likely considerably lower than the default parameters applied in SEDMODL, because of a number of years of road storm-proofing activities, sediment delivery rates are probably less than depicted in Table 22. Actual surveyed connectivity lengths and cutbank measurements would significantly refine the delivery estimate for all three planning watersheds considerably.

VI. References

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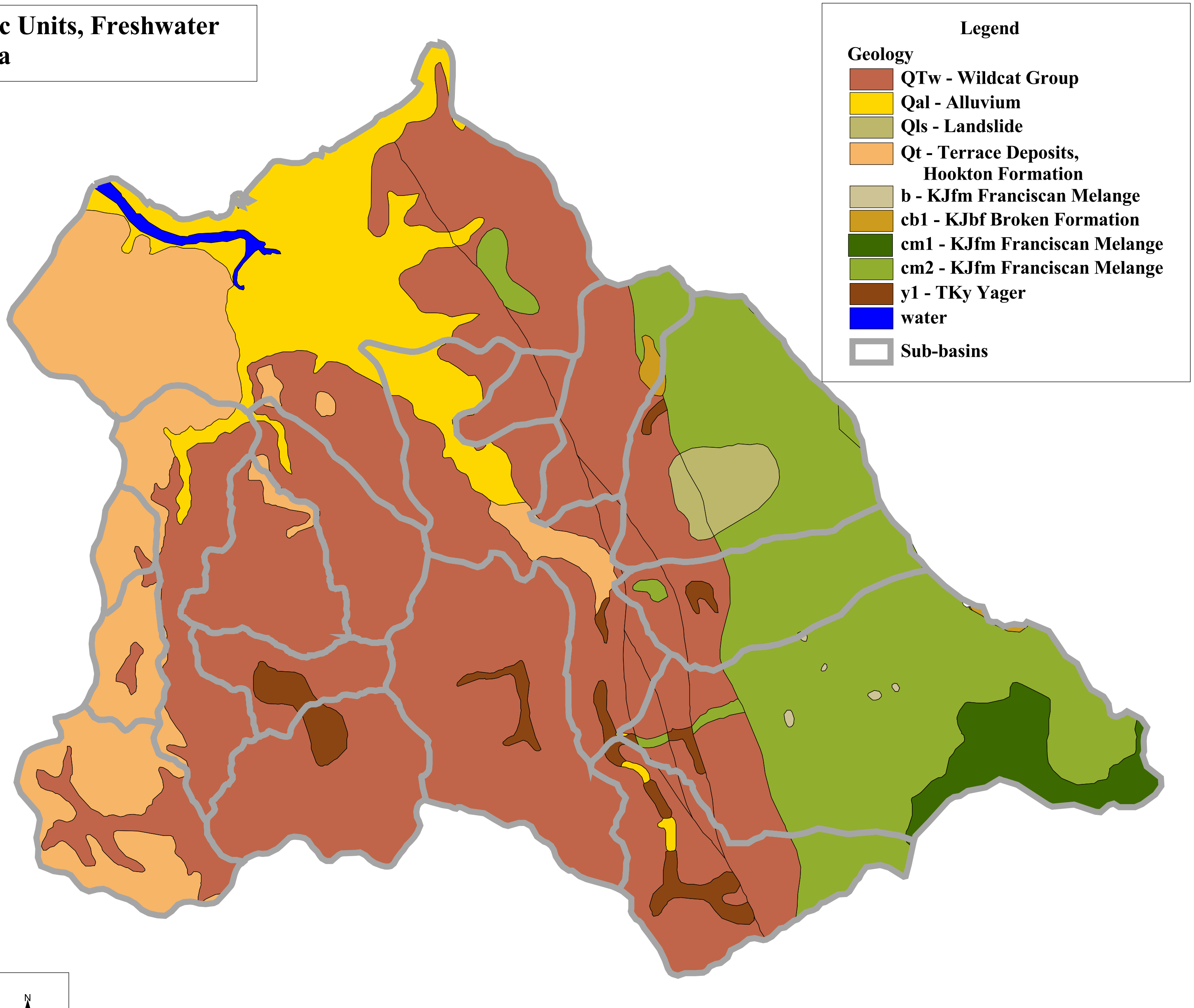
Map 1. Map of Lithologic Units, Freshwater Creek TMDL Study Area



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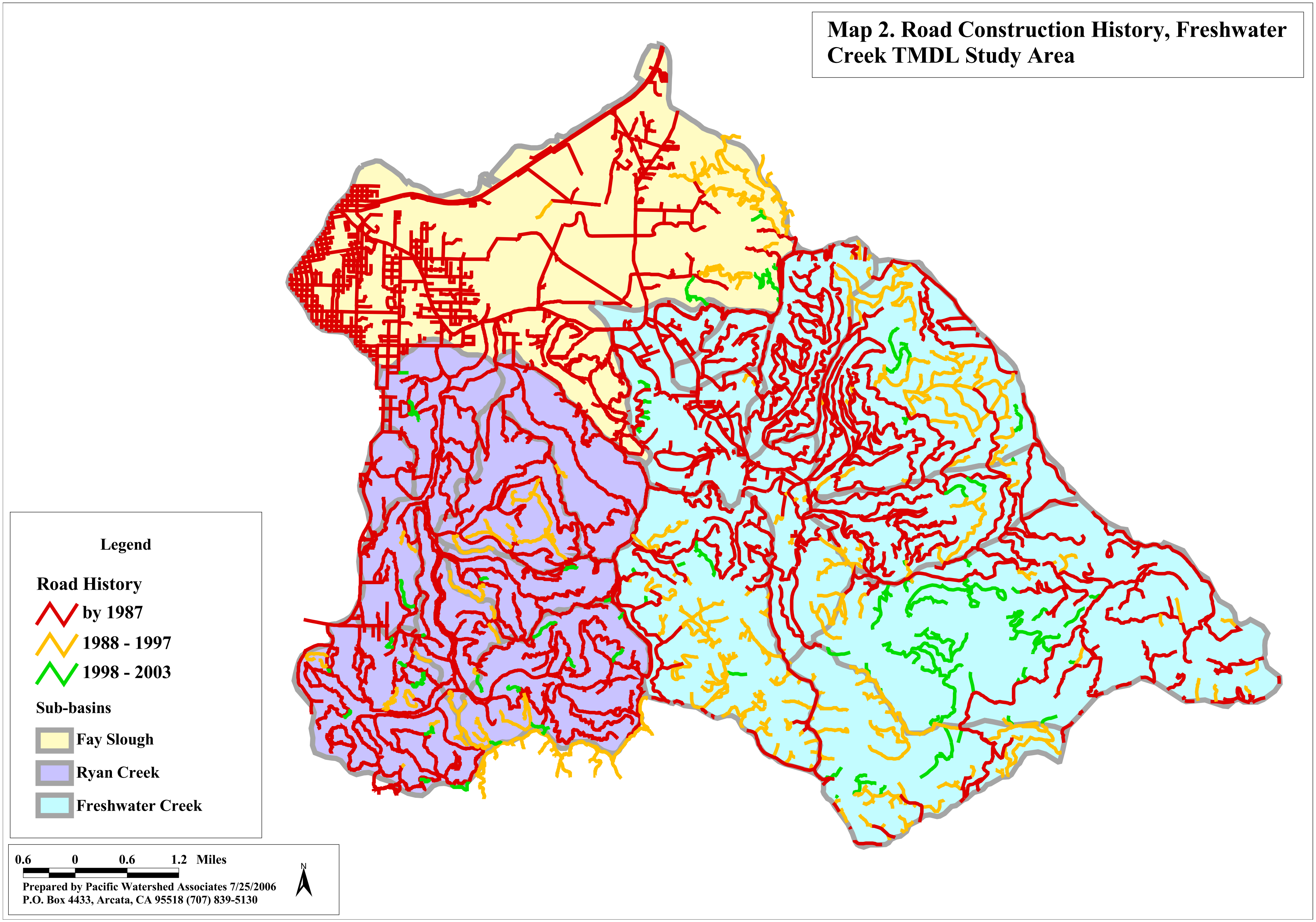
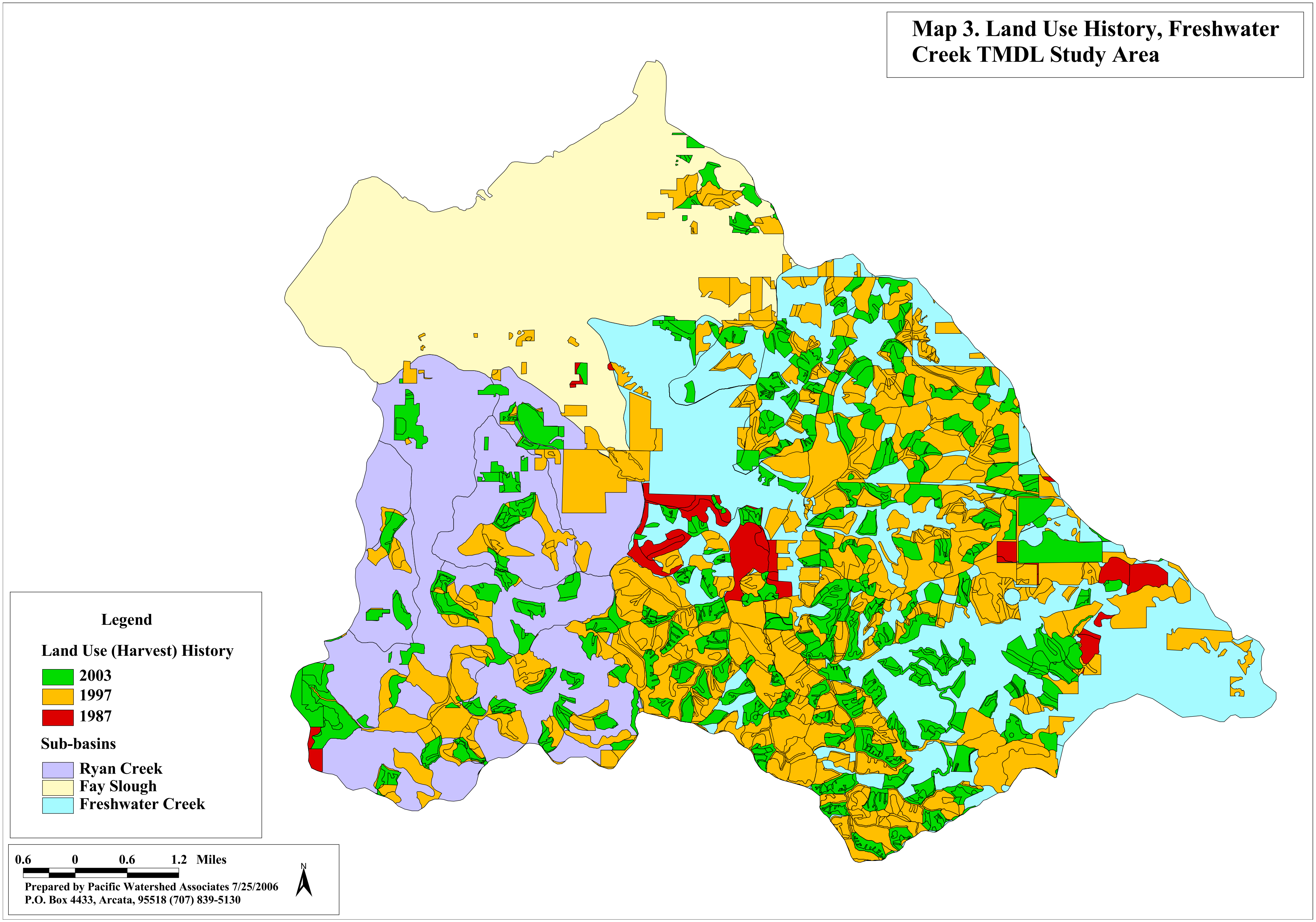
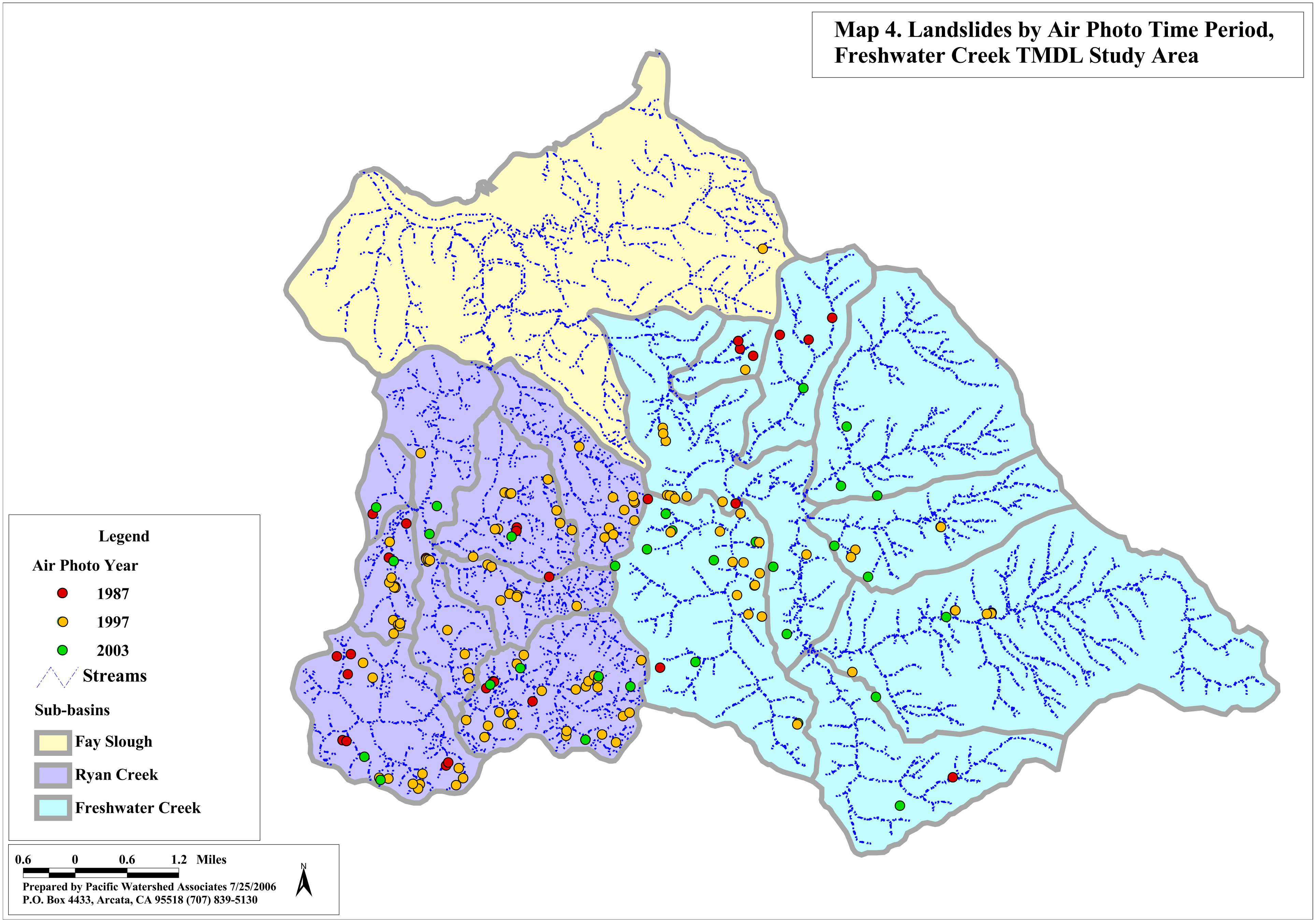
Map 2. Road Construction History, Freshwater Creek TMDL Study Area





Map 3. Land Use History, Freshwater Creek TMDL Study Area

Map 4. Landslides by Air Photo Time Period, Freshwater Creek TMDL Study Area



Map 5. Sub-basin Delineation, Ryan Slough, Fay Slough, and Freshwater Creek Planning Watersheds