Appendix 4E

Small Streamside Landslides Assessment

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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

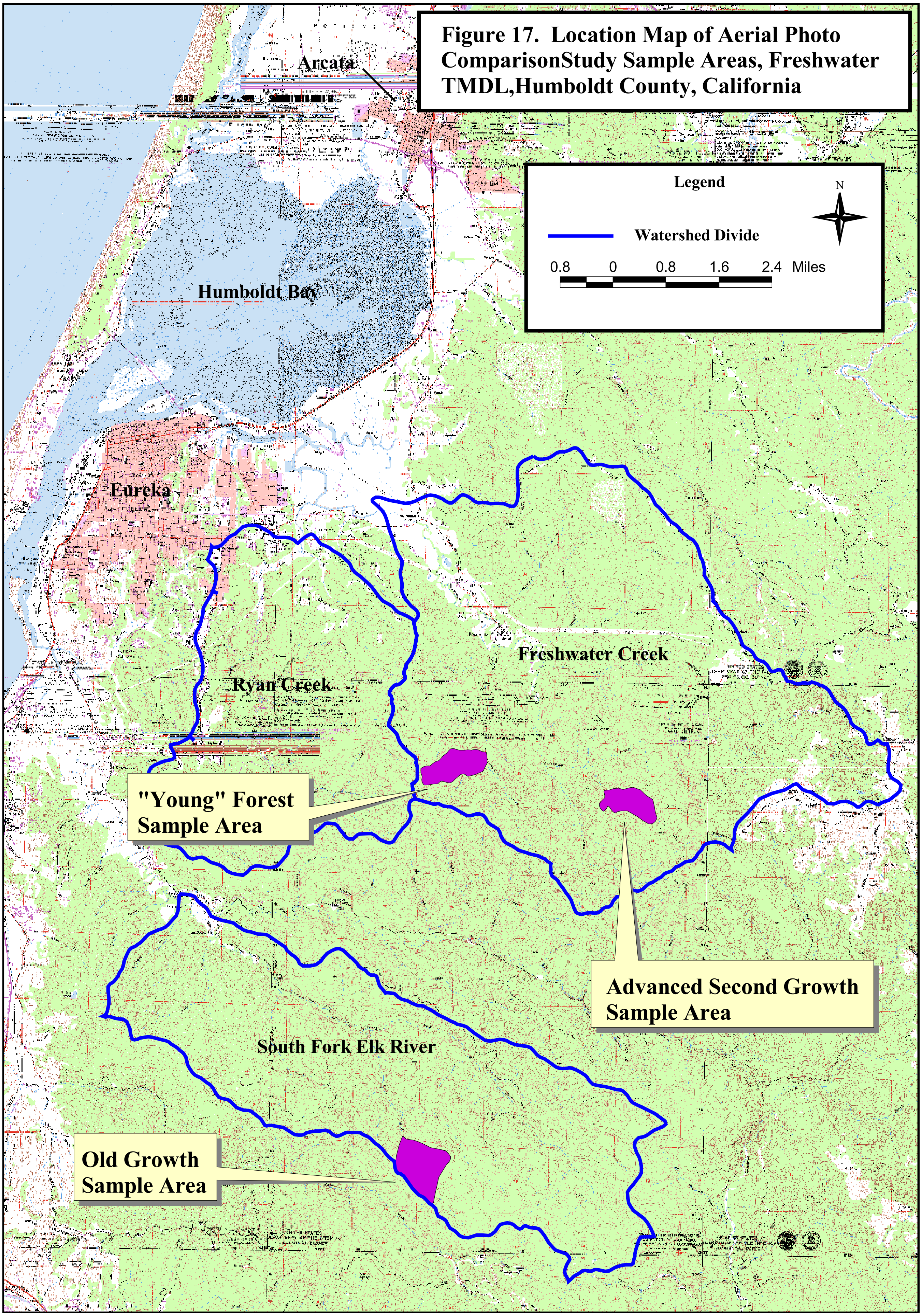
In April and May, 2006, three field crews, each consisting of a lead scientist and a field technician, conducted detailed field inventories of stream channels and related areas in three study areas or "plots" in the Freshwater Creek and Little South Fork Elk River watersheds (Figure 17). The three study 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



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

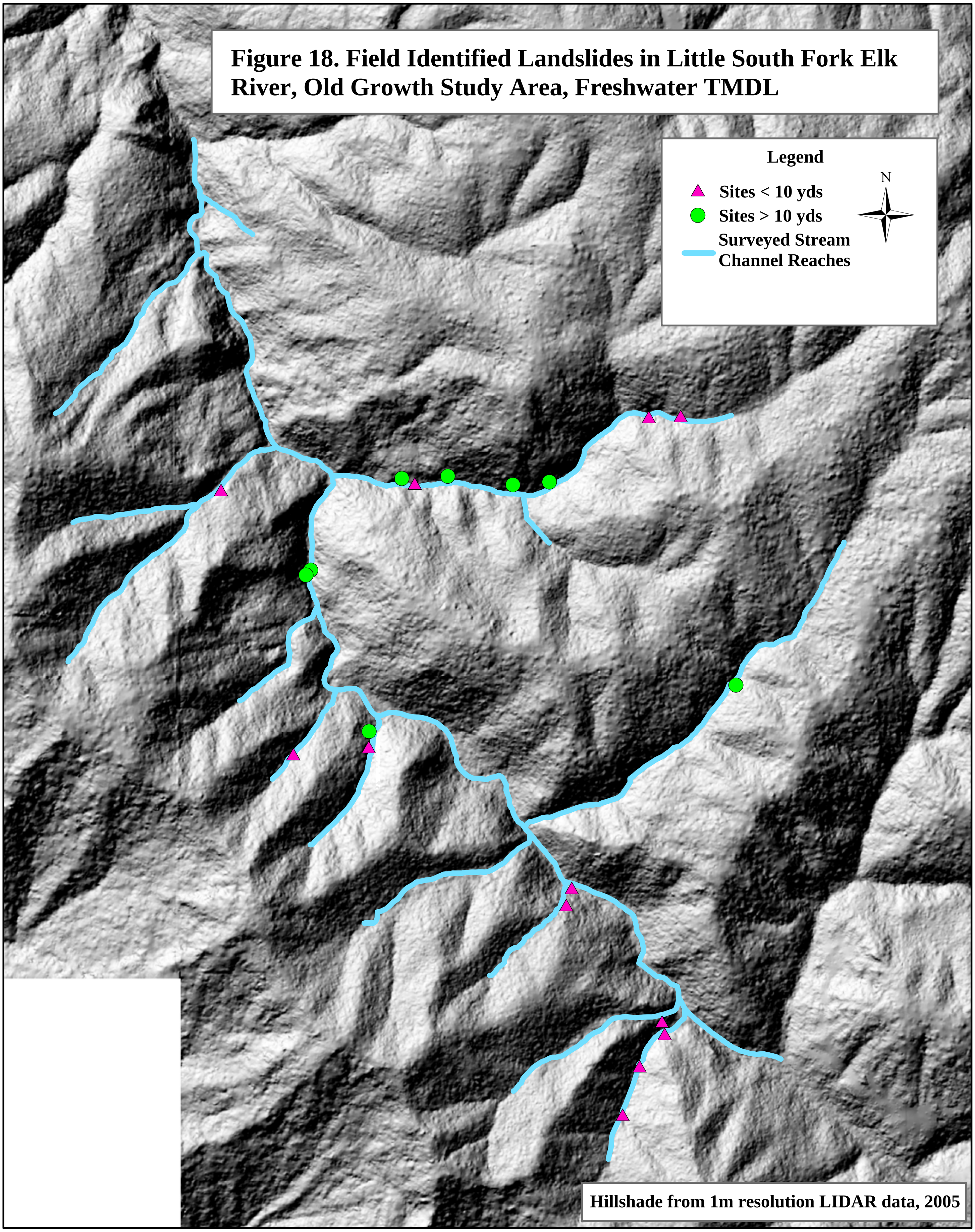


Figure 18. Field Identified Landslides in Little South Fork Elk River, Old Growth Study Area, Freshwater TMDL

Hillshade from 1m resolution LIDAR data, 2005

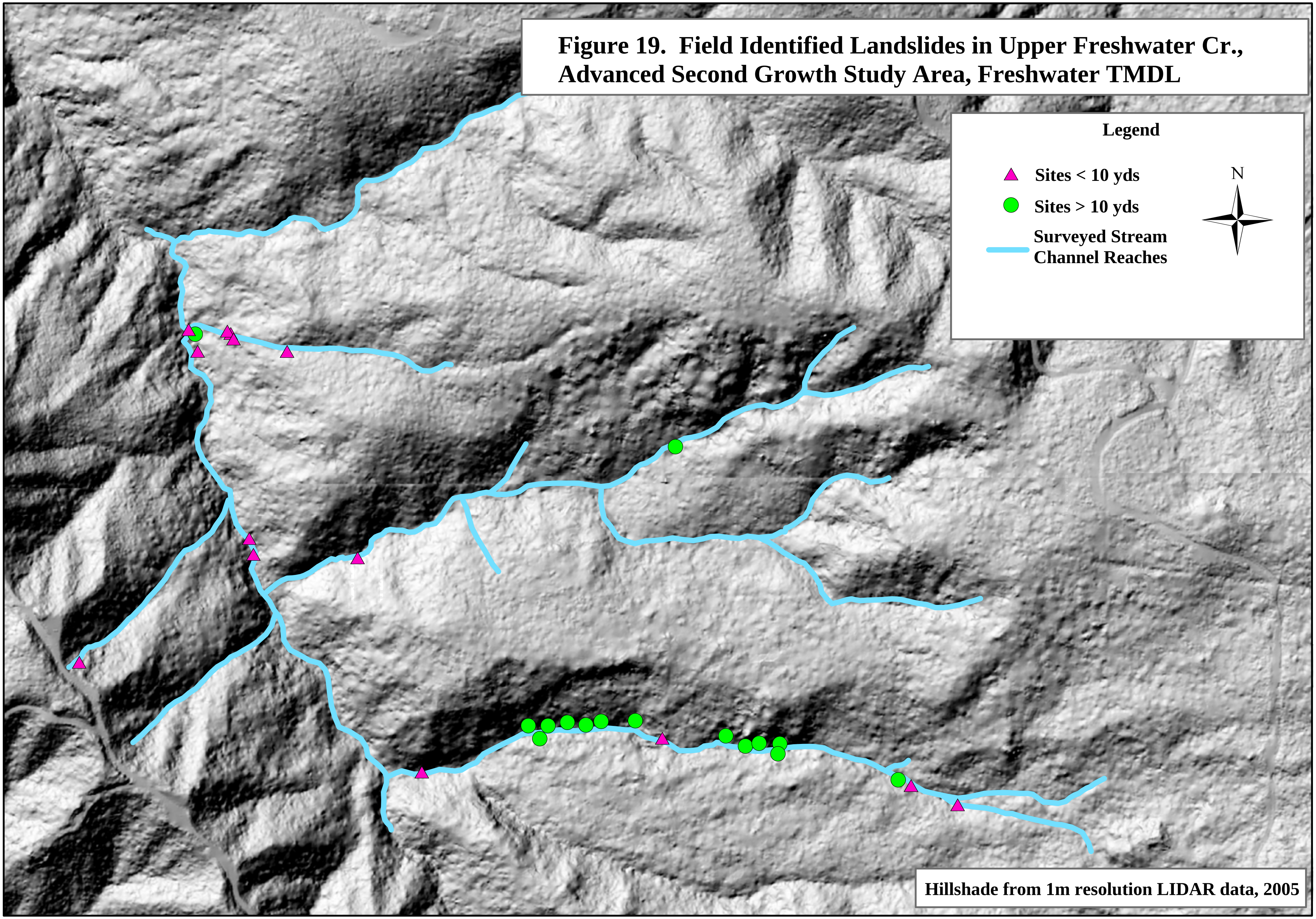
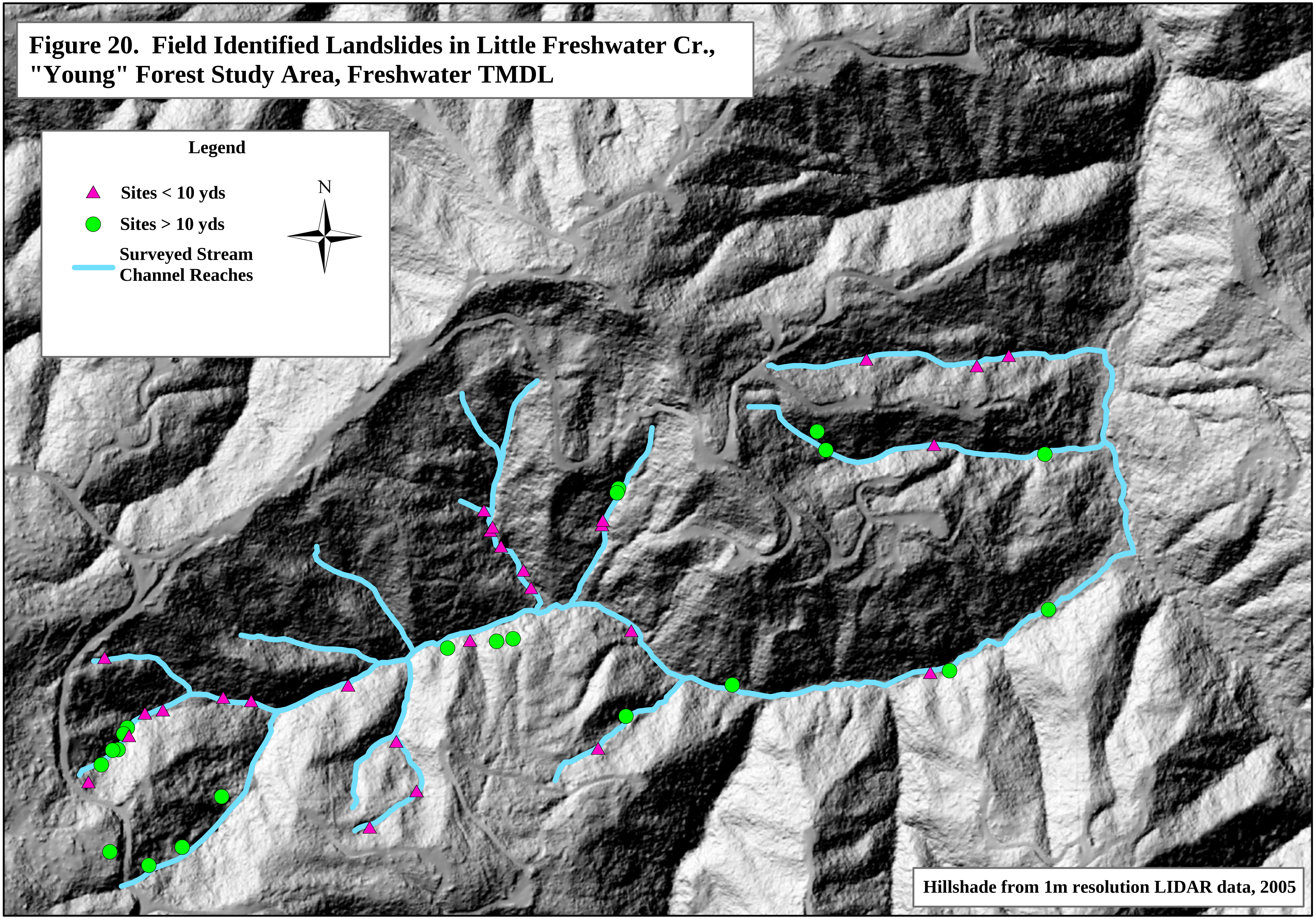


Figure 19. Field Identified Landslides in Upper Freshwater Cr., Advanced Second Growth Study Area, Freshwater TMDL

Hillshade from 1m resolution LIDAR data, 2005

Figure 20. Field Identified Landslides in Little Freshwater Cr., "Young" Forest Study Area, Freshwater TMDL

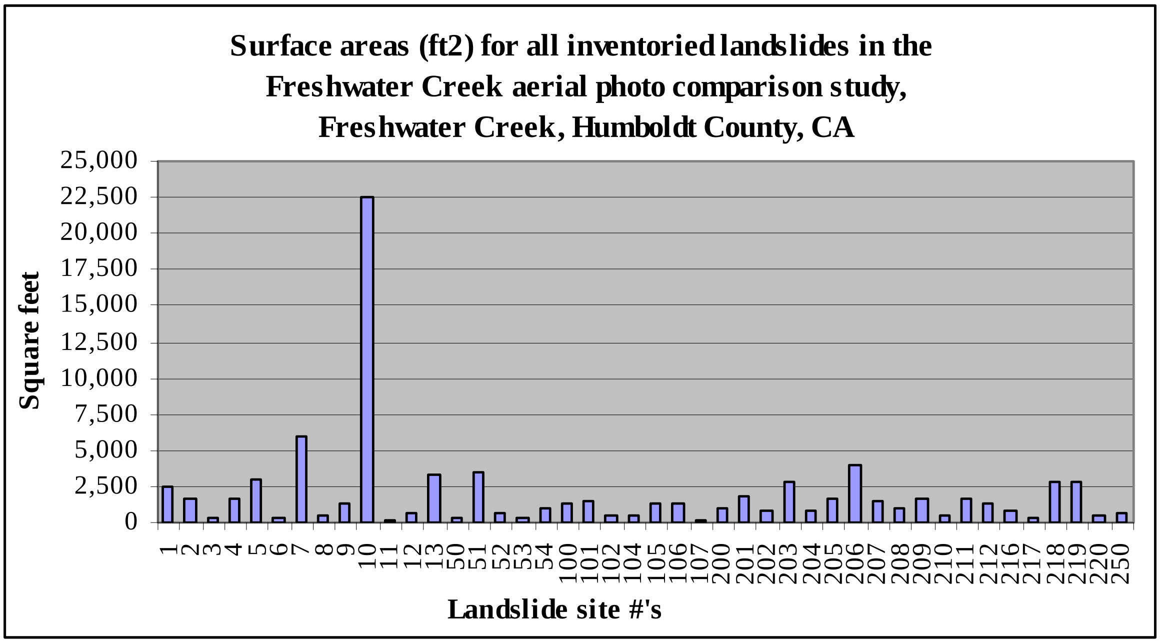


Hillshade from 1m resolution LIDAR data, 2005

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

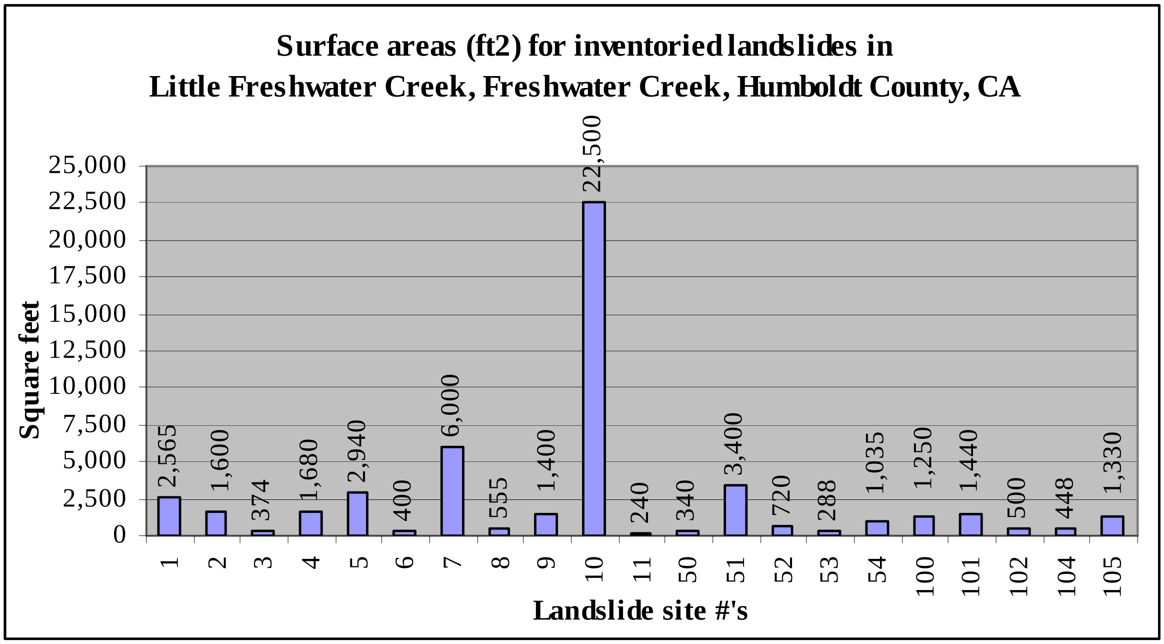
Figure 21



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.

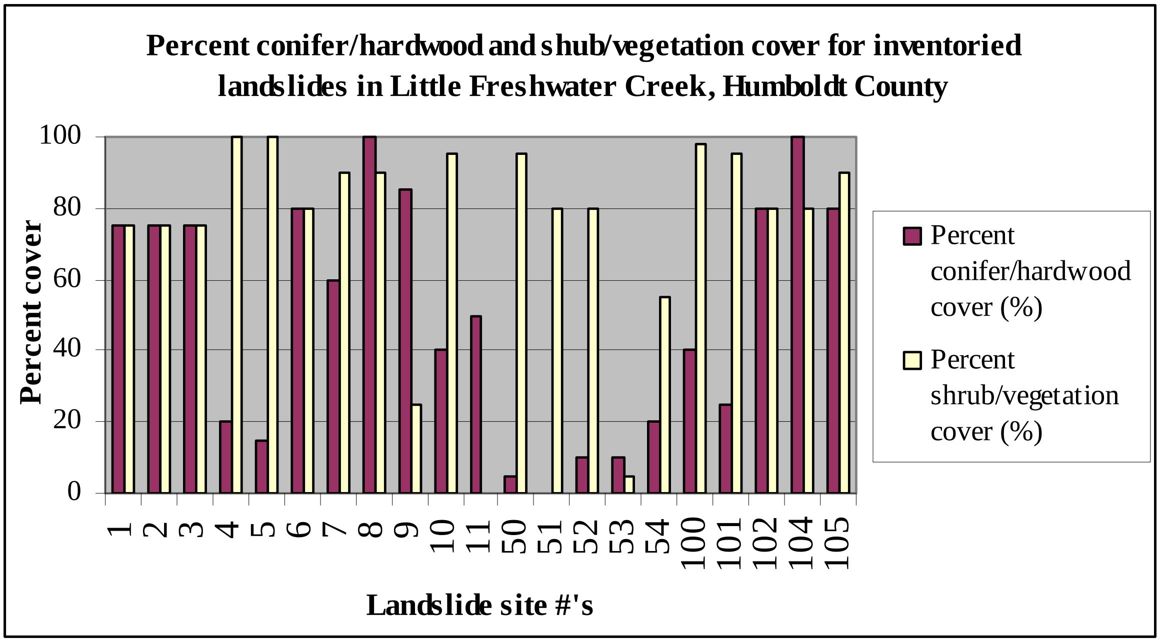
Figure 22



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