Appendix F1. Assessment of Long-term Landslide Sediment Delivery under Existing and Proposed Plan Conditions

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F1.1 INTRODUCTION

The following chapter outlines the methodology, assumptions, limitations, and results of a modeling exercise designed to estimate approximate long-term landslide delivery rates from the road and skid trail network and from hillslopes to watercourses in several pilot watersheds within the Plan Area. The modeling is also intended to estimate long-term sediment delivery under various silviculture options.

The purpose of this exercise was to evaluate the potential impacts of forest practices on landslide-related sediment delivery and to assist in evaluating the most effective and efficient slope stability measures. Such evaluations are the focus of Appendix F3, which takes the models and results developed in this chapter and applies them to the Plan Area to develop property-wide sediment delivery estimates.

A general discussion of landslide types and processes is summarized in Appendix B. A general discussion of the potential impact management activities can have on these processes is summarized in Section 5.

Estimates of landslide delivery rates are based primarily on landslide data collected from the historical set of aerial photographs. Historical rates of landslide delivery from grading activities (i.e., roads, skid trails, landings, etc.) and from hillslopes were estimated separately. A simple model was developed to estimate management-related landslide delivery rates in harvest areas that are attributable to silvicultural treatment. Landslide rates for the pilot watersheds were applied to the remainder of the Plan Area based on professional experience.

A mechanistic modeling approach was considered. However, due to the inherent variability in many of the input parameters that can affect slope stability, the difficulty in obtaining the precise data required for any mechanistic model, temporal and spatial variability of the parameters, and limitations in the slope stability models, Green Diamond does not believe that accurate results could be obtained from such a model.

The information provided in this appendix is specific to sediment production and delivery from shallow and deep-seated landslides associated with roads and silvicultural treatment. Sediment production and delivery from other processes, such as surface erosion, channel bank erosion, or erosion of watercourse crossings are not addressed in this appendix, although the potential for such sediment causing effects is addressed elsewhere in the Plan.

F1.1.1 Approach

Total sediment delivery from landslides is the sum of natural landslide sediment and management induced landslide-related sediment. Management induced landslide related sediment includes sediment derived from cut slopes and fill slopes of roads (including skid trails and landings) and from harvest units (as influenced by silvicultural treatment). This relationship is illustrated by the following equation:

Equation 1: $\mathbf{SED_{tot} = SED_{background} + (SED_{road} + SED_{harvest})}$

Landslide delivery volumes were estimated based on empirical evidence that related management activities to increased erosion rates. These models are based largely on the results of preliminary mass wasting assessments (MWAs) conducted on several pilot watersheds within Green Diamond property. The impact of harvesting on sediment delivery was estimated from landslide inventory data collected throughout north coastal California and Oregon published scientific literature, and complemented by professional judgment where data were lacking.

Average long-term sediment delivery volumes from shallow and deep-seated landslides were estimated for both current management practices and those under the proposed Plan measures for three pilot watersheds: Salmon Creek, Little River, and Hunter Creek. Sediment delivery from deep-seated landslides was also estimated in the Upper Mad River pilot watershed.

F1.1.2 Limitations

It should be recognized that estimating landslide rates across all of Green Diamond ownership property with its diverse terrain and types of landsliding is a complicated process. Sediment delivery rates are temporal and spatially variable. The sediment delivery volumes presented here are long-term averages using empirically determined associations between sediment delivery and land management. The model is based on best available data.

Short-term sediment delivery rates may be higher or lower than the average presented here due to land-use and metrological events. Sediment delivery will be higher than average following major events and lower during relatively dry periods. Moreover, the post harvest impact immediately after harvesting is expected to be higher than average, diminishing as vegetation becomes reestablished. Sediment delivery is also not spatially characterized by the models presented herein. Local differences in geology, terrain, land use, and climate may result in locally different rates of sediment delivery to watercourses.

Ranges in model parameters have been provided in an attempt to evaluate ranges in sediment delivery due to uncertainties in estimates or measurements of the parameters. These ranges were useful in the Monte Carlo simulation exercise reported in Appendix F3.

The sediment delivery volumes presented here are intended as a means for evaluating the relative effects of different management scenarios on landslide sediment delivery to develop a physically based approach to prescription development. The results from this modeling effort are considered approximate and are not intended as detailed sediment budget of each watershed.

F1.2 MODEL DESCRIPTION

The following sections provide a detailed description of the data and analytical methods used to determine sediment delivery volumes for both shallow and deep-seated landslides. The impact of harvesting on shallow landslide processes was considered separately from the impact of harvesting on deep-seated landslides because of the difference in landslide processes and the availability and quality of existing data. Each of the following sections also includes a description of the limitations and assumptions used in the development of the model, and the limitations that should be understood during the application of the model output.

F1.2.1 Shallow Landslides

Shallow landslides are characterized by debris slides, debris flows, channel bank failures and small to large hillslope failures. These landslides are typically rainfall-activated, relatively fast-moving, shallow (less than 10 feet deep), and generally incorporate only the overlying surficial mantle of soil, colluvium, and weathered bedrock (see Appendix B).

F1.2.1.1 Methods

Average long-term sediment delivery from shallow landslides was calculated from preliminary landslide sediment delivery data collected in the MWAs of five pilot watersheds: Salmon Creek, Ryan Creek, Little River, Hunter Creek, and Tectah Creek. Sediment delivery from road-related landslides was estimated directly from the aerial photograph-based landslide inventory. Sediment delivery from hillslope landslides was estimated by applying a simple model that relates the relative impact of different harvest scenarios to landslide rates. The landslide inventories for Ryan Creek and Tectah Creek are incomplete at present; therefore, only the results from shallow, road-related failures in these areas were used as a supplement to the analysis.

F1.2.1.2 Total Sediment Delivery

Historical rates of sediment delivery from shallow landslide processes operating in each of the five pilot watersheds were estimated from an analysis of the historical set of aerial photographs (Table F1-1). Landslides were mapped from the historical set of aerial photographs and, with the exception of Ryan Creek and Tectah Creek, their location entered into the geographic information system (GIS) database for further analysis. The age of the slide was reported as the year of the photograph the slide was first observed. The input of landslide data from Ryan Creek and Tectah Creek into the GIS is pending.

Table F1-1. Landslide inventory photo record.

Pilot Watershed	Acreage	Photo Years
Salmon Creek[a]	7,889	1997, 1991, 1978, 1958, 1954
Ryan Creek	7,590	1997, 1990, 1984, 1978, 1966
Little River	28,755	1997, 1987, 1978, 1966, 1948
Hunter Creek	10,126	1997, 1984, 1972, 1958
Tectah Creek[b]	12,675	1997

Notes
a: 1958 photos used where 1954 photos were unavailable
b: Landslide inventory for earlier years incomplete at present

Pertinent data associated with each landslide were recorded into a database for further analysis. This included landslide type, estimated size (ft^2), estimated depth (ft), sediment delivery ratio (%), slope form (convergent, divergent, planar) and location (headwall swale, inner gorge, midslope), any association with graded areas (road, skid trail, landing, railroad tracks, etc.), and level of harvest (clearcut, partial cut, forested, grassland).

Limited field verification of mapped landslides was undertaken in all pilot MWA areas except Ryan Creek. Additional fieldwork in all watersheds is pending. Sediment delivery from each of the pilot watersheds is summarized in Tables F1-2 and F1-3.

In Tables F1-2 and F1-3, the road category is the sum of landslide sediment derived from all graded areas including roads, skid trails, landings, railroad tracks, etc. It is assumed that any landslide that initiates at, or adjacent to, a graded area is a result of that grading. The Non-Road category is the sum of all landslide-derived sediment that is not associated with grading. The % Historical Road category is the percentage of the total sediment for the period of the air photo record that is road-related (including all graded areas), whereas the % 1997 Road category is the percentage of 1997 sediment that is road-related. The % Historical Road can be higher or lower than the % 1997 Road depending on road construction history. The % 1997 Road is considered a better estimate of the current relative impact of roads on shallow landslide sediment delivery.

Table F1-2. Shallow landslide sediment delivery volumes.

Watershed	Acres	Years of Record	Landslide Delivery (cy)			% Historical Road[1]	% 1997 Road
			Total	Road[1]	Non-Road		
Salmon Creek	7,889	58	156,732	41,650	115,082	26%	17%
Ryan Creek	7,590	46	27,903	9,240	18,663	33%	56%
Little River	28,755	64	139,457	28,491	110,966	20%	40%
Hunter Creek	10,126	54	494,523	306,751	187,772	62%	39%
Tectah Creek	12,675	n/a	104,121	550	84,982	n/a	18%

1 Road includes all graded areas including roads, landings, skid trails, railroad tracks and other graded areas.

Table F1-3. Long-term shallow landslide delivery rates.

Watershed	Cy/ac/yr			T/mi^2/yr[b]		
	Total	Road[c]	Non-Road	Total	Road[c]	Non-Road
Salmon Creek	0.34	0.09	0.25	295	80	217
Ryan Creek	0.08	0.03	0.05	69	22	46
Little River	0.08	0.02	0.06	65	13	52
Hunter Creek	0.90	0.57	0.34	781	485	297
Techtah Creek[a]	--	--	--	--	--	--

Notes
a: Pre-1997 landslide data unavailable at present
b: Assumes a unit weight of soil of 100 pcf.
c: Road includes all graded areas including roads, landings, skid trails, railroad tracks and other graded areas.

F1.2.1.2.1 Confidence of Landslide Volume Estimates

The accuracy of identifying and characterizing landslides in aerial photographs is variable and depends, in part, on the size of the slide, thickness of the vegetative cover, and timing and quality of the photographs. Large landslides, or landslides mapped in recently harvested areas or through thin canopy, are identified with relatively high accuracy. However, small streamside failures, which are often numerous, are difficult to identify because of thick riparian canopy. Therefore, aerial photo analysis will only allow for a partial identification of the total number of landslides in the Plan Area. As a result, the number of slides inventoried for use in landslide delivery should be considered a minimum representation of the actual number of slides that are present in the area. To illustrate this point, the Oregon Department of Forestry's (ODF) evaluation of storm impacts and landslides for 1996 (Robison et al. 1999) revealed that air photo inventories may underestimate sediment production from landslides by as much as 50 percent. The error is greatest in mature forests with thick canopy and less apparent in recently harvested areas.

Field verification of air photo measurements was conducted in Hunter Creek and to a lesser extent in Salmon Creek, Little River, and Tectah Creek. Where field verification is complete, air photo estimates of sediment production are generally within 30 percent of field measurements. This relatively high level of accuracy may be partly explained by data indicating that small slides, potentially undetected in the aerial photograph record, do not deliver large volumes of sediment to streams and are not a large component of the total sediment budget. This leads to the conclusion that the majority of sediment is probably delivered by large slides that have a high likelihood of detection in the air photo record. It should be noted, however, that Green Diamond has accounted for uncertainty in landslide sediment delivery rates in its modeling efforts. Appendix F3 contains a description of four assumption variables that address such uncertainties: Delivery From Road-Related Landslides, Little River Sediment Multiplier, Hunter Creek Sediment Multiplier, and Salmon Creek Sediment Multiplier.

Table F1-4 summarizes the expected range of shallow landslide sediment delivery volumes relative to measured aerial photograph volumes. The range is based on limited field reconnaissance and verification of slides in Salmon Creek, Little River and Hunter Creek, and professional judgment. The range in landslide delivery volumes incorporates uncertainties in slide identification and volume estimates. The higher range in Salmon Creek and Little River compared to Hunter Creek is a result of the expected higher incidence of small stream bank failures that were apparent during field reconnaissance of the watershed but may not be apparent in the air photos.

Table F1-4. Assumed range in landslide delivery volumes relative to air photo estimates.

Watershed	***Lower Bound***	***Most Likely***	***Upper Bound***
Salmon Creek	80%	100%	150%
Ryan Creek	80%	100%	150%
Little River	80%	100%	150%
Hunter Creek	70%	100%	130%
Tectah Creek	--	--	--

F1.2.1.3 Road -Related Landslide Sediment

Landslide delivery volumes from road-related landslides were calculated directly from the air photo inventory. Failures were identified as road, landing, skid trail or “other” related landslides. “Other” related landslides included failures originating from railroad fill and building pads. It was assumed that any landslide on or adjacent to one of these road features occurred as a result of the construction of that feature. Cutbank failures were not inventoried unless they overtopped the road and delivered sediment directly to a watercourse.

The classification of failures related to grading activities is relatively straightforward in harvested areas or areas with thin canopy. Some small roads may have been classified as skid trails; likewise, some large skid trails may have been classified as roads. Identification of roads or skid trails in areas of thick canopy is speculative at times and therefore it is possible that some failures in these areas may have been misclassified. Landslide delivery volumes from roads are summarized in Tables F1-2 and F1-3.

F1.2.1.4 Harvest-Related Landslide Sediment

Harvesting can potentially impact landslide rates through reduced root reinforcement and changes in the hydrologic regime (See Section 5). Determining the contribution of sediment from harvest areas is a much more difficult endeavor than estimating sediment contribution from roads. Unlike roads, the simple existence of a slide within in a harvest unit is insufficient to make a causal link between that particular slide and the harvesting activity. This is because natural landslides may occur within harvest units therefore determining the casual mechanism of failure of any given in unit slide often requires in-depth field review. Although many studies have addressed the impact of roads on sediment production, there are few comparable studies in the region that have quantitatively evaluated the impact of harvesting (i.e., tree removal alone) on sediment production and delivery rates, and those studies that have been completed give widely varying results.

With respect to sediment delivery, the relative impact of timber harvesting on landsliding is probably best evaluated using an empirical approach that compares landslide delivery rates from harvested areas to forested ground. Unfortunately, few studies of this kind have been conducted in northern California.

The difficulty in evaluating the impact of harvesting is further compounded by the fact that different harvest methods are expected to have different implications for slope stability. For example, a selection harvest is not expected to have the same impact on slope stability as clearcutting. Similar problems exist with differences in terrain and geology. For example, the reduction of root strength in cohesionless soils is expected to have a greater impact on shallow landsliding than harvests in soils with relatively high cohesion. Further, it is possible that some harvests may have impacts on slope stability offsite. For example, it has been hypothesized that in some areas, extensive upslope harvesting may have an impact on downslope areas through alterations in the hillslope hydrology (see Section 5).

In this study, the harvest contribution of non-road-related, shallow, landslide-derived sediment was estimated using a relatively simple empirical model that applies a regional average ratio between harvest-related sediment (timber removal alone) and natural "background" sediment [herein referred to as *"harvest ratio"* (HR)] to the non-road-related component of shallow landslide sediment measured in each pilot watershed (see Equation 3).

The average clearcut HR was estimated from published and unpublished studies, including total maximum daily load (TMDL) studies, Pacific Lumber Company (PALCO) sediment source assessments, the ODF study, and from preliminary results from Green Diamond's Hunter Creek pilot MWA (these studies will be discussed in detail later in this appendix). HRs for other silvicultural prescriptions are not reported. Therefore, adjustments to the clearcut HR were required to account for differences in silvicultural prescriptions and expected differences in mass wasting rates as a result of inherent sensitivity of the hillside as delineated by the mass wasting prescription zones (MWPZs).

Green Diamond has assumed that sediment delivery from harvest areas can be reasonably estimated based on the following equation:

Equation 2: $\mathbf{SED_{harv} = SED_{nonroad} / (HR_{clearcut} * N_{partcut\,(y)} * N_{terrain})}$,

where SED_{harv} is the rate of sediment delivery resulting from timber removal alone, $SED_{nonroad}$ is the rate of non-road-related sediment delivery measured from the historical set of aerial photographs, $HR_{clearcut}$ is the clearcut harvest ratio, $N_{partcut\,(y)}$ is a factor to account for different silvicultural techniques (y) other than clearcutting, and $N_{terrain}$ is a factor to account for terrain differences.

The model assumes that the rate of harvesting has remained relatively constant over time. In addition, the model assumes a direct spatial link between harvesting and slope failure. In other words, the analysis assumes that vegetation retention has only a local effect on slope stability. Any offsite impact of harvesting (such as changes in downslope hillslope hydrology from upslope harvesting, or increased stream flow from upstream harvesting) is assumed to be negligible and was not modeled.

While Green Diamond recognizes that upslope harvesting may have an impact on downslope harvest areas, there is little data at present to model this process. Nonetheless, Green Diamond believes the model provides a reasonable and simple method to evaluate the relative impact of different silvicultural methods. As more data are collected and the understanding of the impact of harvesting increases, the model can be revised.

F1.2.1.5 Harvest Ratio

HR is defined as the ratio between the average long-term rate of sediment delivery (cy/acre/yr) derived from harvest blocks (includes harvest-derived sediment and background sediment) compared to uncut or advanced second growth forested ground (background sediment):

Equation 3: $\mathbf{HR(n) = (SED_{harvest}(n) + SED_{background})/SED_{background}}$,

where n is the type of silviculture applied, $\mathbf{SED_{background}}$ is the measured volume of sediment generated from undisturbed or advanced second growth forests, $\mathbf{(SED_{harvest}(n) + SED_{background})}$ is the measured volume of sediment generated from failures originating in harvest blocks, and $\mathbf{SED_{harvest}}$ is the volume of extra sediment above background that is generated as a result of harvesting. This value cannot be directly measured because it is generally not possible to distinguish between individual natural and harvest-caused landslides within harvest blocks.

The model assumes that the impact of harvesting is uniform and constant across the landscape. It is likely, however, that HRs are quite variable, depending on terrain, geology, hydrology and vegetation type. Moreover, the period during which a slope is most prone to shallow instability is a function of the magnitude of the hydrologic event and the decay time to a critical root cohesion value low enough to allow for landsliding, and the duration of time spent below the critical root strength (SWS 1999; Ziemer and Swanston 1977). With the amount of data available at present, however, it is not possible to tailor the HR to individual watersheds or sub-watersheds.

As a first approximation, a regional long-term average clearcut HR ($HR_{clearcut}$) was estimated based on published and unpublished reports. HRs for other silvicultural strategies are not presented in the literature. Therefore for the purpose of this model, the clearcut HR was then modified to account for other silvicultural prescriptions (e.g., 85 percent overstory retention, selection, hardwood retentions, etc.) based on what data was available, review of deterministic models and professional judgment.

F1.2.1.5.1 Clearcut Harvest Ratio

An average clearcut harvest ratio was estimated from a review of published and unpublished landslide inventories, including TMDL studies, the ODF study on the impacts of 1995 and 1996 storms (Robison et al. 1999), PALCO Sediment Source Investigations (PWA 1998a, 1998b, 1999a, 1999b), PALCO Freshwater Creek Watershed Analysis (PALCO 2001a), and Green Diamond's preliminary Mass Wasting Assessment for Hunter Creek. The results of these studies are summarized in Table F1-5. Results from the other pilot watersheds are pending.

Based on the foregoing, the historical average **long-term** increase in sediment delivery from clearcut areas ranges between 1.25 and 4.0 times background (most likely equal to 2.0). The results from Freshwater and Hunter Creek were weighted more heavily than the other studies because these were the most rigorous in evaluating the impact of clearcut harvesting, and because they are more representative of geologic and terrain conditions on Green Diamond lands. In addition, each of these cases includes periods of record in which extensive clearcut harvesting occurred a few years prior to intense triggering storms.

It is important to note the clearcut harvest ratio likely presents a 'worst' case scenario for a long term average given that the ratio is based on data originating from areas recently subjected to very intensive land use dominated by the effects of recent large storm events (i.e., Hunter Creek and Freshwater Creek). Recent work by Schmidt et al. (in press) on root cohesion and susceptibility to shallow landsliding found that 100-year-old industrial forests had lower root strength and inferred higher landslide rates in comparison to natural forests. However, these results should be viewed with caution since the lower root strength in the 100-year-old industrial forests is attributed to forestry practices a century ago that did not include replanting of conifer, therefore allowing the site to regenerate with hardwood. Conceptual modeling by Schmidt et al. (in press) suggests that if the site is replanted with conifer immediately following harvesting root cohesion values can return to pre-harvest levels within 16 years.

It is important to note that the HR used for modeling is intended to be a long-term average over the 50-year period of the harvest. Short-term impacts may be higher or lower depending on the occurrence of triggering hydrologic events and the rate of vegetation regrowth.

F1.2.1.5.2 Partial Cut Harvest Ratios

Because partial cutting retains understory vegetation and leaves a substantial live root mass, it has less impact on root strength and slope stability than clearcutting. Further, harvesting in redwood or hardwood forests, which maintain a viable root network and generally sprout vigorously after cutting, should have less impact on slope stability.

Few studies have been conducted that evaluate the impact of different residual stand densities on slope stability and shallow landslides. The ODF study of the effects of the 1995-96 storms revealed that comparatively few landslides originated in partially cut areas (Robison et al., 1999). Similarly, little change in landslide rates was documented in partial cuts in the *Draft Freshwater Creek Watershed Analysis* (PALCO 2001).

When relating landslide occurrence to changes in vegetation crown cover, studies in Idaho revealed that landslide frequency increases only slightly as overstory crown cover is reduced from 100 percent to 11 percent. However, a notable increase in landslides occurs when crown cover is reduced below 11 percent (Megahan et al. 1978). The Idaho study may not be applicable to the north coast area because of differences in geology and vegetation; nonetheless, it illustrates that in some areas, even a rudimentary root network can increase soil stability on a hillside. The relatively low impact that partial cuts have on landslide occurrence is also supported by the preliminary data from the Green Diamond MWA pilot watersheds.

Modeling studies of shallow landslides and the effects of different silvicultural systems on root strength suggest that partial cutting results in substantially greater residual root strength and a substantially lower probability of slope failure compared to a clearcut scenario (Krogstad 1995; Schmidt et al. in review; Sidle 1991, 1992; Ziemer 1981a, b). For example, Sidle (1992) reports “A 75 percent partial cut reduced the maximum probability of failure more than five times compared with clearcut simulation." Ziemer (1981a) suggests that under shelterwood removal silviculture, where 70 percent of the original stand is harvested followed by removal of the remaining trees 10 years later, root reinforcement dropped to about 70 percent of its uncut value at 2 to 3 years post harvest, then rose to about 10 percent above the uncut value after about 7 years after harvest as the residual trees quickly expand. About 15 years after the residual trees were harvested, root reinforcement again dropped to about 50 percent of the uncut value. Under a light selection harvest where 20 percent of the trees were cut every 10 years, root strength would decrease by about 3 percent 2 years after harvest, then increase to about 7 percent above the uncut strength as a result of rapid expansion of the roots of the remaining trees. It is important to recognize that the foregoing modeling results are for maximum short-term impact. Long-term impact over complete rotations (i.e., 50 years) would be substantially less.

Table F1-5. Summary of clearcut harvest ratios.

Study	Clearcut Harvest Ratio ($HR_{clearcut}$)
Early Oregon and Washington Studies (summarized in Sidle et al. 1985)	1.9 – 8.7[a]
Oregon Department of Forestry (ODF): 1996 Storm Impacts in Oregon	0.3 – 5.1[b]
Amaranthus et al. (1985)	6.8[c]
North coast TMDL Studies	N/A[d]
PALCO: Bear Creek Sediment Source Assessment (source data from PWA 1998b)	11.5[e]
PALCO: Jordan Creek Sediment Source Assessment (source data from PWA 1999b)	3.0[f]
PALCO: Elk River Sediment Source Assessment (source data from PWA 1999a)	2.3[g]
PALCO: Draft Freshwater Watershed Analysis (source data from PALCO 2001 and PWA 1999)	2.3[h]
Green Diamond: Hunter Creek (unpublished)	1.0 – 1.7(max)

Notes

a: Includes older harvest practices. Impact of skid trails may not have been factored out. Uncertain whether landslide rates include delivered sediment volume or mobilized sediment volume.

b: Evaluates short-term impact of a large storm, likely not representative of long-term average. Ratios based on delivered sediment volume.

c: Includes older harvest practices.

d: Landslide rates are not normalized by harvest acreage; it is not possible to compute HR from these data.

e. Very high HR value reflects extraordinarily large debris slides that occurred in 1996/1997 in unusual storms on steep terrain shortly after harvest, and may therefore represent worst case scenario. Not all harvest areas in source data are clearcuts, most areas have some history of tractor harvest, and landslide rates are calculated for a 22-year period (1975-1997). Ratio calculated for delivered landslide volume. See also section 4 below.

f. Value represents the period 1975-1997. Not all harvest areas in source data are clearcuts and most areas have some history of tractor harvest. Ratio calculated for delivered landslide volume. See also section 4 below.

g. Value represents the period 1969-1997 (28-year period of record). Not all harvest areas in source data are clearcuts and most areas have some history of tractor harvest. Ratio calculated for delivered landslide volume. See also section 4 below.

h. Value represents the period 1969-1997 (28-year period of record). Not all harvest areas in source data are clearcuts and most areas have some history of tractor harvest. Ratio calculated for delivered landslide volume. The same ratio (to two significant digits) was computed for the period 1988-1997 in a comparison of landslide rates (not sediment delivery volume) in clearcuts and advanced second growth forest. See also section 4 below.

Modeling studies have also shown that understory vegetation often represents an important component of total root cohesion and that the retention of the understory canopy can substantially reduce the probability of slope failure (Schmidt et al. in review; Krogstad 1995; Sidle 1992). Because shallow landslides might opportunistically exploit gaps in the root network when partial harvesting is employed, uniform spacing of trees to minimize “gaps” that might develop in the root network between trees is important to provide the greatest root strength benefit (Burroughs and Thomas 1977; Schmidt et al. in review).

Based on the foregoing, it is appropriate to make adjustments in the clearcut HR to account for different stand densities and overstory retention resulting from partial harvest silviculture. Although the effect of tree roots is highly variable, it was assumed that on a regional level, the impact of harvesting can be related to overstory retention as a surrogate for the completeness of the root network and total root strength. The basic assumption is the more trees retained, the greater the root reinforcement.

Table F1-6 lists assumed corrections factors to the average long-term clearcut HRs for different levels of overstory retention. Vegetation retention assumes uniform or "square spacing" of conifers. Table F1-7 outlines overstory retention under pre- and post-Plan conditions, and forms the basis for estimating sediment delivery. For simplicity, it was assumed that all slopes within the riparian management zone (RMZ) are greater than the critical slope gradient (i.e., > 60 percent for Salmon Creek, > 65 percent for Little River, and >70 percent for Hunter Creek). Although this would overestimate the acreage of ground within the prescription zone, it is not expected to have a large impact on the estimate of sediment delivery. This is because at least 80 percent of the total volume of sediment delivered from streamside landslides is generated from landslides originating on slopes greater than the critical slope gradient.

Table F1-6. Assumed correction factors for different stand densities: overstory retentions compared to clearcut harvesting on shall landslide sediment delivery.

	Expected multipliers for landslide delivery rates relative to clearcutting		
Stand Density	***Lower***	***Most Likely***	***Upper***
85% to 100% Overstory Retention	100%	100%	100%
70% to 85% Overstory Retention	90%	90%	100%
50% to 70% Overstory Retention	60%	70%	80%
Selection Harvest	50%	60%	70%
Hardwood and Understory Retention	25%	35%	45%
Understory Retention	0%	10%	20%
Clearcut	0%	0%	0%

F1.2.1.6 Adjustments for Slope Position

Adjustments are needed to account for expected differences in the impact of harvesting on different MWPZs. MWPZs are broken down into Steep Streamside Slopes (RMZ and SMZ), Headwall Swales (SHALSTAB areas) and "Other" areas. The impact of harvesting is expected to be different in each of these areas. The impact of harvesting is likely slightly less than average along streamside slopes because some of the failures in this area are attributed to undercutting of the hillside by bank erosion and thus are likely to occur independent of vegetation cover. This is not to say that vegetation has no effect on hillslope stability in these areas, but rather the *relative* importance of vegetation in controlling overall hillslope stability along streamside slopes is less compared to the regional average.

Similarly, the impact of harvesting also appears to be slightly greater than average in headwall swale areas. The reported impact of clearcut harvesting in headwall areas in Freshwater Creek was 5.0 times background. The measured impact in Hunter Creek does not appear to be as large. Assumed correction factors for MWPZs are listed in Table F1-8.

Table F1-7. Summary of modeled streamside slope vegetation retention under existing and proposed Plan conditions.

	HPA Group[1]	*Slope Distance (feet)* [2]	*Slope Gradient*	*Name*		*Overstory Retention*	
				Existing	**Plan**	**Existing**	**Plan**
CLASS 1	ALL	0-70	ALL[4]	WLPZ	RSMZ	70%	100%
	ALL	70-100	ALL[4]	WLPZ	RSMZ	70%	85%
	ALL	100-150	ALL[4]		RSMZ	0%	85%
	HUM	150-200	>60%		SMZ	0%	Selc
	KOR, SR	150-200	>65%		SMZ	0%	Selc
	CKLM	150-475	>70%		SMZ	0%	Selc
CLASS 2-2	ALL	0-30	ALL[4]	WLPZ	RSMZ	~70%	100%
	ALL	30-75	ALL[4]	WLPZ	RSMZ	~70%	85%
	ALL	75-100	ALL[4]		RSMZ	0%	85%
	HUM	100-200	>60%		SMZ	0%	Selc
	KOR,SR	100-200	>65%		SMZ	0%	Selc
	CKLM	100-150	>70%		SMZ	0%	Selc
CLASS 2-1[3]	ALL	0-30	ALL[4]	WLPZ	RSMZ	~70%	85%
	ALL	30-70	ALL[4]	WLPZ	RSMZ	~70%	75%
SHALSTAB	ALL	N/A	ALL[4]		SHALSTAB	0%	Selc

Codes

1 HUM Humboldt Bay and Eel River Hydrographic Planning Areas (HPAs)
KOR Mad River, Little River, Redwood Creek, Coastal Lagoons and Interior Klamath HPAs
CKLM Coastal Klamath and Blue Creek HPAs
SR Smith River HPA

2 Assumes 50% sideslopes to calculate horizontal distances
Assumes valley bottom width of 30’ for Class 1, 20’ for Class 2-2, and 10’ for Class 2-1
Watercourse and Lake Protection Zone (WLPZ) distance assumes cable yarding

3 There is no Class 2-2 SMZ in Smith River

4 Assumes all slopes within the RMZ and SHALSTAB areas are greater than the critical slope gradient. This would overestimate the amount of ground in a prescription zone but is unlikely to have a large impact on associated sediment delivery. This is because at least 80% of landslide-derived sediment is from failures on slopes greater than the critical slope gradient.

Table F1-8. Assumed adjustments in the harvest ratio to account for different MWPZs.

Mass Wasting Prescription Zone	**Multiplier Relative to Average**		
	Lower	***Most Likely***	***Upper***
Streamside Slopes (WLPZ, RMZ)	80%	80%	100%
Headwall Swales (SHALSTAB)	100%	150%	150%
Other Areas	100%	100%	100%

F1.2.2 Deep-Seated Landslides

Deep-seated landslides are features with a basal slip plane that extends below the surficial mantle of weathered earth material and into bedrock. They include translational/rotational landslides and earthflows. Translational/rotational slides are characterized by a somewhat cohesive slide mass. In contrast, earthflows are characterized by slow progressive deformation or creep of the slide mass in a semi-viscous, plastic state. Combinations of the two are common. Most deep-seated failures move incrementally, with catastrophic failure being relatively rare.

F1.2.2.1 Methods

Most deep-seated landslides deliver sediment to the stream system by streamside erosion (bank erosion and streamside landslides). Sediment is delivered primarily along watercourses bounding the toes of and, to a lesser extent, by drainage from the interior of the slides. There are few studies, however, that have estimated sediment delivery rates from deep-seated landslides on a landscape scale.

Estimated average long-term deep-seated landslide delivery volumes were estimated for Green Diamond ownership within four pilot watersheds: Salmon Creek, Little River, Upper Mad River and Hunter Creek. It is assumed that sediment delivery from deep-seated landslides can be estimated by multiplying the length of stream channel bordering the toe and lateral margins of the slides by the average depth of the failure (approximate height of banks/gully walls) and average movement rate (Equation 4).

Equation 4: $$\mathbf{SED_{tot} = Stream\ Length * Slide\ Depth * Rate\ of\ Slide\ Movement}$$

Because of the lack of data, estimates of sediment delivery from deep-seated landslides should be viewed as approximate. Moreover, because some of the sediment from deep-seated slides is a result of small shallow landslides (i.e., debris flows, debris slides, and channel bank failures) occurring along the toe of the larger landslide, it is likely that some “double counting” of sediment will occur when the results of deep-seated landslides are combined with shallow landslide volumes. At present, however, there is little data to differentiate between the two sediment sources.

The impact of harvesting on sediment delivery from deep-seated landslides was evaluated based on a review of published and unpublished reports, and using professional judgment.

F1.2.2.1.1 Landslide Acreage

Deep-seated landslides in Salmon Creek, Little River, and Hunter Creek were mapped from the historical set of aerial photographs using standard methodologies. Pertinent data associated with each mapped landslide were recorded into a database for further analysis. This information included landslide type (i.e., translational landsliding and earthflows), certainty of identification, and inferred level of activity. Limited field verification of mapped landslides was undertaken in Hunter Creek. Additional fieldwork in the other watersheds is pending.

The Upper Mad River pilot watershed is located upstream of Boulder Creek and encompasses the Boulder Creek Planning Watershed. Identification of deep-seated landslides in the Upper Mad River pilot watershed was initially based on published reconnaissance-level landslide mapping by the California Department of Water Resources (CDWR) (1982). The Mapping by CDWR revealed that roughly a third of the watershed is underlain by deep-seated failures. However, discussions with Green Diamond forestry staff revealed that the mapping of deep-seated landslides in pilot watershed by CDWR likely underestimates the landslide acreage and that as much as 60 percent of the watershed may be underlain by deep-seated landslides. For the purpose of this study it was assumed that 60% of the pilot watershed is underlain by deep-seated landslides.

CDWR (1982) did not differentiate between the two different classes of deep-seated landslides (translational landslides and earthflows). Review of aerial photographs and discussions with Green Diamond staff indicate that roughly 70 percent of the deep-seated landslides in Upper Mad River pilot watershed are earthflows.

Landslide acreage for each of the studied watersheds is summarized in Table 9. With the exception of the Upper Mad River pilot watershed, low and mid-range values were based on measured acreage for definite and probable landslides. For Little River and Salmon Creek, upper range values included acreages for questionable landslides. For Hunter Creek, questionable landslides were not mapped; therefore, upper range values were estimated. For Upper Mad River pilot watershed, the lower range was based on CDWR (1982) mapping; mid- and upper ranges were estimated based on qualitative field and air photo observations by Green Diamond staff.

F1.2.2.1.2 *Landslide Activity*

The range of landslide activity is classified as historically active, dormant, or relic. A slide with documented movement within the past 0 to 100 years (roughly the time frame of modern harvesting practices) is classified as a historically active landslide. In the field, these slides are recognized by some or all of the following features: recent scarps or cracks (>6 inches), leaning second growth trees, or sag ponds and/or offset road prisms (see appendix B for a more complete discussion). Slides with very low rates of movement that do not show signs of obvious movement within the past 50 to 100 years are classified as dormant or relic. It is assumed that harvest activities have the greatest relative impact on the more active slides and that impacts on dormant or relic slides are negligible.

It is usually not possible to accurately evaluate the level of deep-seated landslide activity using air photos alone. Therefore, estimates of slide activity were based on limited field observations, discussions with Green Diamond staff, review of completed geologic reports for timber harvesting plans (THPs), and professional opinion. Slide activity for each pilot watershed and landslide type is summarized in Table F1-9.

Table F1-9. Deep-seated landslide acreage, stream channel length, and level of activity.

			TRANSLATIONAL/ROTATIONAL LANDSLIDE				**EARTHFLOW LANDSLIDE**			
Watershed		**Range**	**Slide Acres**	**Watercourse Length (miles)**	**Activity % of Slide Class**		**Slide Acres**	**Watercourse Length (miles)**	**Activity % of Slide Class**	
					Historically Active	***Dormant/ Relic***			***Historically Active***	***Dormant/ Relic***
Salmon Creek		Lower	2880	11.7	5%	95%	61	0.6	5%	95%
		Most Likely	2880	11.7	10%	90%	91	0.6	15%	85%
		Upper	3447	14.5	20%	80%	91	1.1	25%	75%
Little River		Lower	6271	30.7	5%	95%	119	0.9	5%	95%
		Most Likely	6271	30.7	5%	95%	119	0.9	15%	85%
		Upper	7595	39.6	15%	85%	347	2.4	25%	70%
Upper Mad River[1]	**Conifer**	Lower	320	1.6	20%	80%	746	3.7	?	?
		Most Likely	575	2.8	20%	80%	1343	6.6	20%	80%
		Upper	815	4.0	30%	70%	1902	9.4	?	?
	Grassland/ Hardwood	Lower	594	3.1	65%	35%	1385	7.2	?	?
		Most Likely	1069	5.5	65%	35%	2493	12.9	65%	35%
		Upper	1514	7.8	75%	25%	3532	18.2	?	?
Hunter Creek		Lower	338	3.8	5%	95%	0	0	N/a	N/a
		Most Likely	338	3.8	5%	95%	0	0	N/a	N/a
		Upper	500	5.7	15%	85%	0	0	N/a	N/a

1: 49% of the ground in Upper Mad River pilot watershed is grassland or native oak and is not proposed to be harvested. Moreover, disproportionate percentage of the landslides in the watershed are located in these areas. Therefore, the conifer ground has been delineated out separately from grassland and oak.

About half of the Upper Mad River pilot watershed (49 percent) is grassland or native hardwood. Fifty one percent of the area is conifer. Green Diamond staff report that deep-seated landslides underlie about 60 percent of the pilot watershed, and that the slides, and particularly the more active earthflows, are preferentially located in the grassland and hardwood areas (65 percent versus 35 percent). As a result, sediment delivery from grassland/hardwood areas is significantly higher in comparison to conifer areas, and is considered the dominant source of sediment.

Sediment delivery from grassland/hardwood areas was evaluated separately from conifer ground. This is because 1) timber harvesting is not expected to occur in the grassland/hardwood areas and therefore there would be no management-derived sediment from harvesting occurring in these areas, and 2) the grassland/hardwood areas deliver a disproportionate amount of sediment to watercourses because of the high proportion of active earthflows, substantially overwhelming management-derived sediment generated from the conifer ground.

F1.2.2.1.3 *Stream Channel Length*

Sediment delivery from deep-seated landslides is assumed to correlate to the length of all watercourses bounding the toes and lateral margins of these features. This may slightly underestimate the length of stream channels delivering sediment from earthflows because it would not account for sediment eroded from streams draining the interior of the slide. Work by Kelsey (1977) indicates that well-developed gully systems on active earthflows could produce more sediment than erosion along the toe of the slide. However, this is in contrast to work presented by Nolan and Janda (1995) that suggests that less than 10 percent of the measured sediment leaving earthflows was delivered by fluvial processes operating in the small tributaries in the interior of the slide.

The length of streams bordering the toe and lateral margins of large landslides in Salmon Creek, Little River, and Hunter Creek were measured from watercourse maps available in Green Diamond's GIS database. Upper, mid-, and lower range values were based on the degree of certainty of landslide identification. The length of watercourses bounding the toe of large landslides in the Upper Mad River pilot watershed is not available at present and therefore was approximated based on average stream lengths measured in the other three pilot watersheds. Estimated stream lengths bordering landslides for all four pilot watersheds are summarized in Table F1-9.

F1.2.2.1.4 *Slide Depth*

The depth of deep-seated landslides is variable across the landscape depending on landslide size, local terrain, and processes. Swanston and others (1995) reported shear depths along earthflows and block glides in Redwood Creek to be between 12 and 40 feet. Past studies in the Eel River Basin found an average height of earthflow toes of 30 feet (SWS 1999; USACE 1980; USDA 1970).

Professional experience suggests that the depth of deep-seated translational landslides can vary considerably, from between 10 to greater than 100 feet. In general, translational landslides are much deeper than earthflows. An average slide depth subject to toe erosion of 40 feet was assumed for translational landslides, and 25 feet for earthflows. Upper and lower bounding depths were estimated at 10 feet deeper and 10 feet shallower, respectively.

F1.2.2.1.5 *Slide Movement Rates*

Deep-seated slide movement is highly variable and episodic, depending on storm history, underlying geology, and slide process. At present, very limited data are available for estimating average long-term movement rates of deep-seated landslides in northern California. In this preliminary analysis, the average creep rates on the west side of Redwood Creek was used.

Swanston and others (1995) monitored several sites in the Redwood Creek Basin to quantify natural creep and earthflow rates. A concerted effort was made to avoid areas of current, clearly definable active earthflows; however, Green Diamond's review suggests that several of these sites appear to have been on slides that may have been classified as historically active under the Plan's slope stability measures.

Progressive earthflows on the east side of Grogan Fault in Redwood Creek that are underlain by pervasively sheared sandstone and mudstone have movement rates from 3.0 to 131 mm/yr. These rates are assumed to be representative of active earthflows on Green Diamond property. Sites dominated by block slides displayed movement rates ranging between 2.5 and 16.4 mm/yr. These rates are assumed to be representative of active translational landslides on Green Diamond property. Progressive creep rates on the west side of the Grogan Fault in Redwood Creek that are underlain by sheared and foliated schists range between 1.0 to 2.5 mm/yr. These rates are assumed to be representative of natural soil creep and of dormant earthflows and translational landslides.

Regional data sources on active grassland earthflows report much higher average movement rates of 2.4 to 4 m/yr [Van Duzen River Basin (Kelsey 1980)] and 4 m/yr [Eel River Basin (Scott 1973, referenced in SWS 1999)]. It is doubtful that these rates are representative of all earthflows, because in these studies there was a bias toward monitoring the most active slides. Moreover, the rates are for earthflows in open grassland areas and not representative of forested slides where rates are much lower to support a timber stand.

Limited field reconnaissance of the deep-seated landslides in Hunter Creek, Little River, and Salmon Creek revealed that most of the large slides are dormant or relic, and have very low rates of movement. Where movement is observed, it is typically manifested by small discontinuous ground cracks along the head of slide blocks. Lobate toes or zones of accumulation are rarely present.

Estimated deep-seated landslide rates are summarized in Table F1-10. High and low range values are based primarily on data presented by Swanston and others (1995). Most likely values are from published data and were modified based on professional judgment. Most of the slides on Green Diamond property do not appear to be as active as those studied in the professional literature, as is indicated by the simple fact that most roads crossing large landslides are not disturbed by slide movement. Therefore, the most likely rate of movement on forested slides is assumed to be lower than the published average. Because few measurements of deep-seated landslides in northern

California exist, these rates should be viewed as very approximate. Additional research is required to refine these numbers and to increase the confidence in their accuracy.

Table F1-10. Average deep-seated landslide slip rates.

Slide Type	Activity	Average Slip Rate (mm/yr)		
		Lower	*Most Likely*	Upper
Translational/Rotational Landslide	Historically Active	2.5	4	16.4
	Dormant/Relic	0.5	2	2.5
Earthflow Landslide	Historically Active	3.0	20	130
	Dormant/Relic	0.5	2	2.5

F1.2.2.1.6 *Harvest-Derived Sediment*

Published work concerning the effects of timber harvesting (i.e., logging) on deep-seated landslide activity is sparse. Deep-seated landslides can theoretically be affected by hydrologic changes associated with reduced evapotranspiration and reduced canopy interception during rainstorms (California Department of Conservation 1997). Descriptions of conditions affecting deep-seated landslides have been discussed briefly by Swanston and Swanson (1977), Sidle and others (1985), and Miller and Sias (1998), but few studies exist that quantitatively address how timber harvesting affects deep-seated landslide stability.

Short-term increases in ground displacement following clearcutting have been documented on an active earthflow in southwestern Oregon (Swanston et al. 1988; Swanston 1981). Swanson and others (1988) report substantial short-term increases in ground displacement rates beginning the second year after harvesting, with movement rates returning to background rates in the third year following harvest. Post-harvest rates are reported to be more than two to four times the pre-harvesting rate (Swanston 1981). The short-term nature of the increase was probably the result of dry conditions and the small regolith blocks involved in accelerated displacement. In contrast, work by Pyles (1987) on the Lookout Creek earthflow in the central Cascades in Oregon concluded that timber harvesting was unlikely to induce a large increase in movement, primarily because the slide was well-drained.

Miller and Sias (1998) modeled the effect of timber harvest on groundwater conditions and slope stability of a large, deep-seated landslide in glacial lacustrine sediments adjacent to a large river channel in the western Washington Cascades. They predicted that timber harvest in the groundwater recharge area of the landslide would produce very small decreases in the factor of safety, suggesting that harvest would contribute to landslide movement only if the landslide were at or near the threshold of stability. This suggests that active deep-seated landslides are most likely to be affected by harvest-induced changes in groundwater, while inactive and dormant slides are less likely to be affected.

There may be some impact from clearcut harvesting on sediment delivery from deep-seated landslides; however, to what extent is difficult to quantify at present. For the purpose of this study it was assumed that harvesting will have an impact only on historically active slides and negligible impact on dormant or relic features, and that the level of impact will be proportional to the level of harvest. It was assumed that clearcutting the entirety of the slide will increase the rate of slide movement by a factor of two on historically active slides, diminishing linearly to pre-harvesting rates in 30 years. Based on this assumption, the average increase in deep-seated slide movement over the 50-year period of the Plan would be 1.3 times background if the slide were entirely clearcut.

It is assumed that the impact of harvesting on deep-seated slide activity is a function of percentage of canopy retained on a slide, which in turn is expected to be directly related to evapotranspiration rates. In this analysis, it was assumed harvesting will take place on the entirety of a slide. This is considered a worst-case scenario because many slides exceed the maximum 40-acre size of clearcuts under current California Forest Practice Rules, and harvest blocks would rarely have boundaries that coincide with slide boundaries. It is unlikely that all of a slide would be harvested at any given time; therefore, the impact of the harvest is expected to be less than modeled.

Under current conditions, vegetation retention results primarily from the required 70 percent overstory canopy retention along Class I and Class II WLPZs under Green Diamond’s Owl HCP. The amount of vegetation retained on any given slide is quite variable, depending on the density and class of watercourses transecting or bordering the slide, existing stand density and composition, and silviculture prescriptions. Additional retention has often been provided on the more active slides in the interest of slope stability. On average, however, it is estimated that a minimum of 5 percent to 10 percent of the total canopy cover is currently retained on deep-seated landslides. Therefore, the sediment delivery under existing management conditions is estimated to be about 1.28 times background.

Under proposed Plan prescriptions, vegetation retention on historically active slides will be primarily from RMZ, slope management zone (SMZ), and SHALSTAB areas. Additional protection is provided by 25-foot no-cut zones along historically active toes and scarps (see Section 6.2). The proposed Plan prescriptions are estimated to be 15 percent effective in reducing the management component of sediment delivered from deep-seated landslides relative to existing conditions.

F1.2.3 Results

This section presents the results of a modeling effort designed to estimate average long-term landslide sediment delivery volumes to watercourses from the historical road network and from various silvicultural treatments. As previously mentioned, the information presented below is specific to sediment delivery from shallow and deep-seated landslides; sediment delivery from other processes, such as surface erosion, channel bank erosion, or erosion of watercourse crossings is not addressed in this appendix. The results represent long-term totals for each pilot watershed.

Average long-term sediment delivery volumes from shallow and deep-seated landslides were estimated for both existing and proposed Plan conditions for three pilot watersheds: Salmon Creek, Little River, and Hunter Creek. Sediment delivery from deep-seated landslides was also estimated in the Upper Mad River pilot watershed. Work in Ryan Creek and Tectah Creek was used to examine the effects of road building on landslides, but could not be used to examine the effects of silviculture at the time of the statistical analysis. Results from shallow-seated landslides are reported separately from deep-seated landslides.

F1.2.3.1 Shallow Landslide Results

Road-related and non-road-related shallow landslides were evaluated separately from one another. Shallow landslide data was gathered primarily from aerial photograph interpretation. Landslides that occur near roads were assumed to have been triggered by road construction (i.e., grading activity). Landslides in harvest areas were not assumed to be caused by harvest effects (e.g., loss of root reinforcement). Instead, the proportion of landslides in harvest areas that were likely triggered by harvest effects is estimated using the harvest ratio HR(n) (see Equation. 3). A spatial analysis of non-road- related landslides assesses the proportion of slides that originate in different Plan MWPZs. Finally, the expected sediment reductions resulting from the Plan's mass wasting prescriptions pertaining to harvest effects were estimated.

F1.2.3.1.1 Road-Related Landslides

Estimated shallow landslide delivery volumes from shallow landslides resulting from all grading activities are summarized in Tables F1-11 and F1-12. The data are presented in two forms. In Table F1-11, the average sediment delivery from shallow landslides is summarized for the entire (long-term) photoperiod. However, these values may not be representative of recent conditions because of improvements in road management and increased road densities. The relative impact of grading is most likely best represented by a more recent (1997) photoperiod, covering a roughly 7- to 12-year time span (Table F1-12). A summary of the relative percentage of each grading activity to the total volume of shallow landslide sediment delivered to watercourses is summarized in Table F1-13.

Table F1-11. Shallow landslide delivery from the long-term period of record.

Watershed	Period of Record (years)[1]	# of Shallow Landslides	Sediment Delivery (cy)				
			Total	Road and Landing	Skid Trail	Other[2]	Non-Grading[3]
Salmon Creek	58	756	156732	40398	1174	78	115082
Ryan Creek	46	1260	27903	6893	1248	1100	18663
Little River	64	419	139457	20230	2546	5714	110966
Hunter Creek	54	598	494523	216584	90167	0	187772
Tectah Creek	--	--	--	--	--	--	--

Notes
1. Landslides visible in the earliest set of air photos are assumed to have occurred within the previous 15 years based on the level of revegetation
2. Other includes failures along the old railroad lines and failures from non-harvesting-related grading activities.
3. Non-grading summarizes sediment not generated from grading activities

Table F1-12. Shallow landslide delivery from the 1997 photoperiod.

			Sediment Delivery (cy)				
Watershed	**Period of Record (years)**	**# of Shallow Landslides**	**Total**	**Road and Landing**	**Skid Trail**	**Other[1]**	**Non-Grading[2]**
Salmon Creek	6	329	55515	9241	333	0	45941
Ryan Creek	7	152	10014	3967	527	1100	4420
Little River	10	34	14525	5844	0	0	8681
Hunter Creek	13	301	29497	9729	1680	0	18088
Techtah Creek	?[3]	631	104121	18589	550	0	84982

Notes
1. Other includes failures along the old railroad lines and failures from non-harvesting-related grading activities.
2. Non-grading summarizes sediment not generated from grading activities
3. This period of record is uncertain because only one set of aerial photographs (1997) was examined

Table F1-13. Percentage of each grading activity relative to total shallow landslide delivery.

		Long-Term Period of Record			1997 Photoperiod		
Watershed	**Acreage**	Roads and Landings	Skid Trails	Other[1]	Roads and Landings	Skid Trails	Other[1]
Salmon Creek	7889	26%	1%	0%	17%	1%	0%
Ryan Creek	7590	25%	4%	4%	40%	5%	11%
Little River	28755	15%	2%	4%	40%	0%	0%
Hunter Creek	10126	44%	18%	0%	33%	6%	0%
Tectah Creek	12675	-	-	-	18%	1%	0%

Note
1 Other includes failures along the old railroad lines and failures from non-harvesting-related grading activities.

Roads and Landings

The data suggest that roads and landings (combined) are responsible for the majority of landslide-derived sediment that is generated from grading activities. Skid trail failures, in comparison, are infrequent. For the long-term period of record, landslide-derived sediment from roads and landings ranges between 15 percent and 44 percent of the total sediment delivered from shallow landslides. As expected, the impact of roads is greatest in the steeper gradient watersheds (e.g., Hunter Creek) and less in the lower gradient watersheds (e.g., Little River). In the 1997 photoperiod, road and landing failures comprise 17 percent to 40 percent of the shallow landslide delivery.

A decrease in the relative importance of road-related failures was observed in Salmon Creek and Hunter Creek, which have inherently high rates of landsliding, even though road densities have increased in both watersheds. The decrease in road-related failures (both volume and size) in these watersheds may be attributed to improvements in forest practices and the implementation of Forest Practice Rules over the past 25 years. Because of these regulations, new roads are more likely to be located on more stable ridge tops that have much lower rates of landsliding rather than less stable mid to lower slope areas, and constructed using end-haul construction techniques when steep slopes cannot be avoided. New roads and reconstructed (repaired) roads also have restrictions on fill depth, compaction of fill, more frequent cross drain and waterbar spacing, and increased culvert sizes. Steep ground is commonly cable yarded rather than tractor yarded, resulting in much less ground disturbance.

An increase in road and landing failures was observed in Ryan Creek and Little River; however, both of these watersheds have inherently low rates of slide activity. In both of these watersheds, it is believed the relative importance of shallow landslide processes to the total sediment budget is less than in the steeper watersheds such as Hunter Creek and Salmon Creek. In Little River, and to a lesser extent in Ryan Creek, it is also difficult to draw definitive conclusions on changes in sediment delivery over time because of the relatively small sample size in the 1997 photoperiod (see Table F1-2), and because much of the observed sediment from that period was generated from just a few slides.

Preliminary results show that mean landslide volumes for road and landing failures have decreased over time from 400 cy/slide in the long-term photoperiod to 275 cy/slide in the 1997 photoperiod. Additional work would be required to further evaluate whether the reduction is a result in improved road management or simply a product of storm history.

Skid Trails

Skid trail-related failures comprise a substantially smaller portion of the total volume of sediment delivered from landslides compared to roads and landings (Table 14). In the long-term period of record, skid trail failures comprise between 1 percent and 18 percent of the total volume of sediment delivered from shallow landslides. Additional unquantified sediment would be generated from surface erosion of the skid trail. The majority of this impact resulted from the early failures in the Hunter Creek watershed. Excluding Hunter Creek, the measured long-term impact of skid failures averages less than 2 percent of the total shallow landslide delivery volume.

In the 1997 photoperiod, skid trails comprise 0 percent to 6 percent of the landslide sediment delivered to watercourses. Mean landslide delivery volumes for skid trail failures have decreased from a long-term average of 275 cy/slide to a recent short-term average of 57 cy/slide. Again, the decrease in the size of slide may be due to changes in forest practices, such as a greater reliance on cable yarding rather than tractor yarding, or be a product of storm history. Skid trail failures were also substantially smaller than road failures, probably because skid trails tend to have smaller fill prisms.

Comparison of Road and Skid Trail Failures

One of the goals of this analysis was to gain insight into the relative importance of road failures compared to skid trail failures. In other words, how important are road failures to the total sediment delivery compared to skid trail failures? This is an important question when allotting resources to address legacy problems.

Comparing Table F1-14 summarizes the relative importance of road failures normalized against skid trail failures. This simple ratio was generated by dividing the volume of sediment delivered from road failures by the volume of sediment delivered from skid trail failures. The data is based on total landslide sediment delivered and has not been normalized against length of road or skid trail.

Table F1-14. Summary of sediment delivery from road and landing failures normalized against skid trail failures.

	Long-Term Period of Record		1997 Photoperiod	
Watershed	Road and Landing	Skid trail	Road and Landing	Skid trail
Salmon Creek	34.4x	1x	27.7x	1x
Ryan Creek	5.5x	1x	7.5x	1x
Little River	7.9x	1x	∞	1x
Hunter Creek	2.4x	1x	5.8x	1x
Tectah Creek	--	1x	33.8x	1x
AVERAGE[1]	**3.1X**	**1X**	**13.4X**	**1X**

Note
1 Average is calculated from the sum of all inventoried landslides with no weighting given to watershed area.

The ratio of road-derived sediment to skid trail-derived sediment is quite variable between watersheds. Much of this variability is likely attributed to relative differences in road and skid trail densities in each watershed. Nonetheless, the data do indicate for all watersheds there has been a sustainable decrease in sediment delivery from skid trails in comparison to road and landing failures (Table F1-14). One possible explanation for the measured reduction is the stricter forest practice rules that limit tractor yarding on slopes steeper than 65 percent. By avoiding tractor operations on such slopes, the potential for new skid trails to trigger slides has been greatly reduced, as documented in Table F1-14.

It is important to point out that the results in Table F1-14 are based on sediment volumes. A similar analysis based on frequency (number) of landslides would reveal that roads generate two to four times as many landslides as skid trails for both the long-term period of record and 1997 photoperiod, respectively. The difference between the analysis based on sediment volume and frequency of slides is a product of larger landslides occurring on roads compared to skid trails.

The results based on frequency of landslides are consistent with the results of the California Department of Forestry and Fire Protection's (CDF's) Hillslope Monitoring Program (1999), which documented 4.5 times as many large debris slides occurring on roads and landings compared to skid trails. Sediment volumes were not presented in the CDF report. The Hillslope Monitoring Program was based on a comprehensive field evaluation of erosion features identified on 292 random road transects (53 miles), 26 skid trail transects (33 miles), and 291 landing transects.

There are several possible explanations for the lower rate of skid trail failures compared to road failures. First, the majority of shallow landslides occur on slopes over 60 percent to 65 percent. This is ground that under the Forest Practice Rules must be cable or helicopter yarded rather than tractor yarded. By avoiding such steep slopes, the potential for future skid trails to trigger shallow landslides has been greatly diminished. Because Green Diamond began to employ cable yarding techniques on much shallower slopes than many of the other timber companies, the effect of skid trails may be much less than for other areas. Roads, on the other hand, often cannot avoid steep ground.

In addition, the landslide inventory suggests a reduction in skid trail failures compared to road and landing failures over time. One explanation for this is that many of the legacy skid trails that were located on steep slopes have since failed and comparatively few skid trails are constructed on steep slopes under present management practices. Many of the skid trail failures observed in the 1997 set of aerial photographs are associated with legacy skid trails. To address the potential for future skid trail failures, Green Diamond proposes to exclude tractor operations on slopes greater than 45%.

The lower rate of skid trail failures in relation to road failures may also be a product of the differences in the amount of ground disturbance required to cut a skid trail vs. a road. The average width of a skid trail is about 10 feet compared to a 20+ width for roads. A 10-foot-wide skid trail contouring across a 65 percent side slope would displace 0.7 cy of earth per foot of skid trail, resulting in a 1.8-foot-deep fill prism. A skid trail descending the same hillside at a steep gradient would generate much less fill. In comparison, a 20-foot-wide haul road contouring across the same slope on balanced cut and fill would generate four times as much sidecast, with a fill prism of over 4 feet. Moreover, thicker fill prisms on roads often exist at watercourse and swale crossings, which is where many of the larger fill failures originate.

F1.2.3.1.2 Harvesting-Related Sediment

Estimates of sediment delivery from shallow landslides are based primarily on a review of aerial photographs. The harvesting components (tree removal alone) of shallow landslide sediment delivery volumes were estimated for three pilot watersheds (Salmon Creek, Little River, and Hunter Creek) by applying non-road-related shallow landslide sediment delivery volumes measured from aerial photographs to several empirical models that relate management activities to increased erosion rates. Harvesting-related sediment delivery was estimated for existing and proposed Plan conditions. The results of this modeling effort are summarized in Tables F1-15 and F1-16.

Table F1-15. Non-road-related shallow landslide sediment delivery per mass wasting prescription zone under existing conditions.

			MWPZ			
WATERSHED	**ACRES**	**RSMZ Cy/yr %**	**SMZ cy/yr %**	**SHALSTAB cy/yr %**	**NONE cy/yr %**	**TOTAL cy/yr %**
Salmon Creek	7889	798	2	268	916	1984
		40.2%	*0.1%*	*13.5%*	*46.2%*	
Little River	28755	768	31	195	740	1734
		44.3%	*1.8%*	*11.2%*	*42.7%*	
Hunter Creek	10126	235	697	1190	1355	3477
		6.8%	*20.1%*	*34.2%*	*39.0%*	

Table F1-16. Non-road-related shallow landslide sediment delivery under existing and proposed Plan conditions.

WATERSHED	ACRES	BACKGROUND		HARVESTING		TOTAL NON-ROAD		Reduction in Management Component
				Existing Conditions	Proposed Plan	Existing Conditions	Proposed Plan	
		Cy/yr	Cy/ac/yr	Cy/yr	Cy/yr	Cy/yr	Cy/yr	%
Salmon Creek	7889	1174	0.15	810	523	1984	1698	35%
Little River	28755	1054	0.04	680	424	1734	1478	38%
Hunter Creek	10126	1693	0.17	1785	1109	3477	2802	38%

In Salmon Creek and Little River, non-road-related sediment delivery in the RMZ prescription areas is significantly greater than in SMZ or SHALSTAB areas. This contrasts notably with Hunter Creek, where the majority of sediment was generated from failures within SHALSTAB and SMZ areas. There are several possible reasons to account for the higher rate of sediment delivery in the Hunter Creek SMZ and SHALSTAB areas compared to either Salmon Creek or Little River. First, the majority of sediment in Hunter Creek is generated by very large slides that extend well outside the RMZ and therefore are not assumed to be controlled by conditions within the RMZ. Similar large slides are not as prevalent in either Little River or Salmon Creek, possibly because slopes are generally not as steep. Second, the watercourse mapping in Hunter Creek is relatively old and many Class III drainages in that drainage would be reclassified as Class II watercourses under current rules. In the analysis, this results in fewer RMZ slides than probably actually exist. Lastly, the terrain in Hunter Creek is much steeper than in either Little River or Salmon Creek, which results in a greater percentage of SHALSTAB areas.

The data also reveal that a significant volume of sediment (39 percent to 46.2 percent) is generated from failures located outside of any MWPZ. This might be partly explained by the inherent limitations of the existing 10-m digital elevation models (DEMs) used to generate slope gradients in the GIS. The DEM tends to underestimate slope gradients, especially in deeply incised drainages. Because this analysis relies on aerial photo interpretation and topographic and map data, fewer prescription zones may have been mapped compared to field-based mapping, potentially resulting in an underestimate of associated sediment delivery. Nonetheless, the results illustrate the inherent difficulties in identifying landslide hazard areas solely from a remote analysis. A greater level of prediction would be achieved based on site-specific field review.

Based on the HR equation (Equation 3) background, sediment delivery from shallow landslide processes averages between 0.04 and 0.17 cy/ac/year (see Table 16). The higher sediment delivery in Salmon and Hunter creeks likely results from steep streamside slopes (Salmon Creek) and headwall swale areas (Hunter Creek). Background sediment delivery rates in Little River are relatively low in comparison because of the relatively shallow slopes found throughout most of the watershed.

Harvesting (tree removal) over a 50-year period is estimated to be responsible for 39 percent to 51 percent of the total non-road-related shallow landslide sediment delivered to watercourses under existing conditions (1.6 to 2.1 times increase relative to undisturbed or advanced second growth forests). Implementation of the proposed Plan measures is expected to reduce the harvesting-related component of sediment by at least 35 percent to 38 percent. Significantly more sediment savings will be achieved by road upgrades (see Appendix F2).

F1.2.3.2 Deep-Seated Landslide Results

Estimated annual sediment delivery volumes from deep-seated landslides are summarized in Table F1-17. These estimates are based on the deep-seated landslide sediment source model presented earlier in this report. Average long-term sediment delivery from deep-seated landslides is estimated to range between 0.02 cy/ac/yr in Hunter Creek, where few landslides are present, to 0.44 cy/ac/yr in the Upper Mad River pilot watershed, where much of the watershed is underlain by deep-seated landslides, many of which are considered active.

In the Upper Mad River pilot watershed, sediment delivery rates are significantly higher in the oak and grassland areas compared to conifer ground. This is attributed to the much higher percentage of earthflows located in this terrain. In general, the open grassland and hardwood areas are less stable than the conifer ground, and many grassland areas are too active to support viable conifer forest. The impact of harvesting in the grassland areas is negligible because few trees grow in these areas.

For the purpose of this study it is assumed that the impact of harvesting is directly proportional to the amount of vegetation retained on a historically active slide. Based on this assumption, harvesting (tree removal) is estimated to be responsible for an increase of from 1.02 to 1.17 times the amount of sediment delivered by deep-seated landslides in conifer areas under existing conditions (harvesting is generally not proposed in grassland and hardwood areas). This may be an overestimate of the impact of harvesting, because it assumes that the slide block is located wholly within a harvest unit. More often, only a portion of a slide is cut at any given time.

Table F1-17. Deep-seated landslide sediment delivery under existing and proposed Plan conditions.

WATERSHED		ACRES	BACKGROUND		HARVESTING		TOTAL NON-ROAD (Background + Harvesting)		Assumed Reduction in Management Component
					Existing Conditions	Proposed Plan	Existing Conditions	Proposed Plan	
			cy/yr	cy/ac/yr	cy/yr	cy/yr	cy/yr	cy/yr	%
Salmon Creek		7889	706	0.09	42	35	748	741	15%
Little River		28755	1722	0.06	56	48	1778	1770	15%
Upper Mad River	Conifer	4658	767	0.16	135	115	902	882	15%
	Grasslands/ hardwoods	4475	3309	0.74	0	0	3309	3309	N/a
Hunter Creek		10126	204	0.02	5	5	209	209	15%

The variability in landslide delivery between watersheds is primarily a function of the percentage of the watershed underlain by historically active landslides, particularly earthflows. Data indicate that sediment delivery rates on earthflows are much higher than for translational/rotational rockslides. Implementation of the proposed Plan measures is assumed to reduce the management component of sediment by at 15 percent.

Roads can affect the stability of deep-seated landslides by removing toe support and by concentrating and diverting runoff. However, at present there is little data on Green Diamond property to address the significance of roads on deep-seated landslide sediment delivery. Moreover, there are very few published studies that have addressed this question. This analysis does not separately address sediment delivery related to road construction on deep-seated landslides. It was assumed that any sediment delivered by deep-seated landslides as a result of roads is already indirectly addressed in either the shallow landslide section of this report or in the road inventory section presented in Appendix F2.

F1.2.3.3 Summary of Results

Road-related shallow landslides occurring in the most recent photoperiods range from 17 percent to 40 percent in the five watersheds investigated, with a watershed mean value of about 30 percent. The extent to which the Plan measures are expected to reduce road-related shallow landslides is discussed in Appendix F2.

Harvest-related shallow landslides were estimated to constitute 39 percent to 51 percent of non-road-related shallow landslides for the three watersheds investigated. The proposed Plan measures (MWPZs and associated prescriptions) are expected to reduce harvest-related shallow landslides by 36 percent to 44 percent. Shallow landslides occurring outside of MWPZs account for 39 percent to 46 percent of sediment delivery.

Timber harvest on deep-seated landslides is calculated (based on estimates) to increase sediment delivery to streams by 2 percent to 17 percent. Plan measures for harvest on deep-seated landslides are expected to be only 15 percent effective, resulting in small declines in harvest-related sediment delivery from deep-seated landslides. However, management-related sediment from deep-seated landslides is not considered to be a large component of the total volume of sediment delivered by landslides.

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