Delineation of Preventative Landslide Buffers Along Steep Streamside Slopes in Northern California[1]

Jason S. Woodward[2], David W. Lamphear[3], and Matthew R. House[4]

Abstract
Green Diamond Resource Co (GDRCo) applies tree retention buffers to steep slopes along fish bearing (Class I) and non-fish bearing (Class II) streams that are in addition to the standard riparian management zones associated with timber harvest plans. These Steep Streamside Slope (SSS) buffers were designed to reduce the amount of sediment delivering to watercourses as a result of landslides generated by forest management related operations. Initial default buffers were developed through a landslide study during the planning stages of GDRCo's Aquatic Habitat Conservation Plan (AHCP). The continued evaluation of streamside landslides across the property is one of the AHCP's long term research projects, which is aimed at re-defining the SSS "default" prescriptions using a spatially distributed probability based sampling design. Through continued research, our goal is to refine the minimum slope gradients and maximum slope distances associated with the Steep Streamside Slope criteria for each of the 11 Hydrographic Planning Areas (HPA) identified in GDRCo's AHCP.

The HPA to be re-evaluated was the Coastal Klamath HPA, which is a grouping of several watersheds near the mouth of the Klamath River in Humboldt and Del Norte Counties. Sampling consisted of 93 half-mile long stream segments that represent roughly ten percent of the lineal distances of Class I streams and five percent of the lineal distances of Class II streams within this HPA. The sampling method used insured both random selection and spatial distribution of the half mile segments within the study area. The study focused on those landslides that were non road-related, active to historically active, and had observably delivered sediment to a watercourse. The landslide data collected included causal factors, slope characteristics, cross sections, and dimensions of the source and debris, of more than 400 landslides in this region.

Using a topographic ruggedness model on a 50 m LiDAR-based DEM and field-based geologic mapping of the area, we divided the area into distinct morphologic units. The results from the analysis of the landslide data provide new slope gradient and distance thresholds for the SSS default prescriptions. These new SSS prescriptions are unique to each of these morphologic units and provide site specific protections to areas prone to streamside landsliding within the Coastal Klamath HPA. A similar approach will be used for the remaining 10 HPAs.

Key words: shallow landslides, steep streamside slope buffers, LiDAR, topographic ruggedness model, Klamath River

---

[1] This paper was presented at the 2011 Coast redwood forests in a changing California: a symposium.
[2] PG, Green Diamond Resource Co, P.O. Box 68, Korbel, CA 95550. (jwoodward@greendiamond.com).
[3] Research Analyst, Green Diamond Resource Co. (dlamphear@greendimond.com).
[4] Aquatic Biologist, Green Diamond Resource Co. (mhouse@greendimond.com).

Introduction

The Steep Streamside Slope Delineation Study is the analysis of streamside landslides across the portions of GDRCo ownership that are bound by the AHCP. The results of this analysis determine the new SSS default protection measures. The primary goal of the initial landslide study, which led to the development of the AHCP SSS "default" prescriptions, was to attempt to reduce the amount of sediment delivering to watercourses as a result of streamside landslides generated by forest management related operations. The AHCP objective of the SSS prescription is to achieve a 70 percent reduction of delivered streamside landslide volumes in comparison to historic management related streamside landslides. The initial study took into account slope distances from the main scarp of observed landslides to the affected watercourse transition line and slope gradients associated with the observed landslides. In addition, the initial study was intentionally biased towards areas that exhibited high concentrations of landslides due to the limited scope and compressed time frame to conduct the study. In order to more accurately define these protection measures and achieve the AHCP objectives directed at streamside landslides, the SSS Delineation Study expands upon the initial landslide evaluation effort. This report presents the findings of the initial phase of the SSS Delineation Study, which was directed at the eighty-thousand acre Coastal Klamath HPA.

Purpose and scope

The purpose of this study is to refine the minimum slope gradients and maximum slope distances associated with the Steep Streamside Slope prescriptions for the Coastal Klamath HPA.

The scope of work for this study is based on the initial "inner-gorge" study that was aimed at delineating an expanded protection zone adjacent to watercourses that would reduce the amount of streamside landslides related to timber harvesting. The study focuses on shallow streamside landslides that were not caused by roads or historic skid trails, were active to historically active, and have observably delivered sediment to a Class 1 or Class 2 watercourse.

Methods

Development of sample reaches

Our sample area involves hillsides adjacent to Class 1, Class 2-2 and Class 2-1 watercourses within the Coastal Klamath HPA. As defined in GDRCo's AHCP Class 1 watercourses are current or historic fish bearing streams and domestic water supplies, Class 2 watercourses contain no fish but support or provide habitat for aquatic vertebrates. Class 2 watercourses are further broken into 1st and 2nd order streams. A Class 2-1 (1st order) watercourse is defined as the first 1,000 ft of a Class 2 stream. Beyond the first 1,000 ft of a Class 2 stream the watercourse becomes a second order Class 2 which we define as a Class 2-2. In addition a Class 2-2 may be formed when two Class 2-1 streams converge. From the point of convergence of the two Class 2-1 watercourses, the watercourse is considered a Class 2-2.

In order to sample random hillside areas within the Coastal Klamath HPA we broke the mapped Class 1 and Class 2 watercourses into half-mile survey reaches throughout the HPA. At the time, the Class 2 watercourses within our hydrography layer had not been broken up into the Class 2-2 and Class 2-1 designations. Therefore we sampled the Class 2 watercourses as a whole and visually checked for a reasonable distribution of Class 2-2 and Class 2-1 watercourses. Once our LiDAR derived hydrography was developed we assessed the actual distribution of the Class 2-2 and Class 2-1 watercourses, which is discussed later under Results.

At the time of development, there were 191 miles of mapped Class 1 and 619 miles of mapped Class 2 watercourses within the Coastal Klamath HPA. Our goal was to survey roughly ten percent of the lineal distance of Class 1 streams (19 miles) and five percent of the lineal distance of Class 2 streams (31 miles) within this HPA. The geographically distributed systematic random sampling method used, insured both random selection and spatial distribution of the half-mile segments within the study area. This method involved delineating whole streams, from the confluence to the upstream end of a Class 2, breaking these streams into approximate half mile sample reaches, sorting them tabularly according to the confluence coordinates and position within the individual stream, and then systematically selecting reaches to gain the appropriate sample percentage. In addition, we stratified the Class 1 watercourses to ensure an even distribution of sample reaches from the lower, middle, and upper portions of these streams. Due to their abundance this was not necessary for the Class 2 watercourses. In all, there were 93 half-mile long stream reaches along Class 1 and Class 2 watercourses. The sample reaches are shown on *fig. 1*.

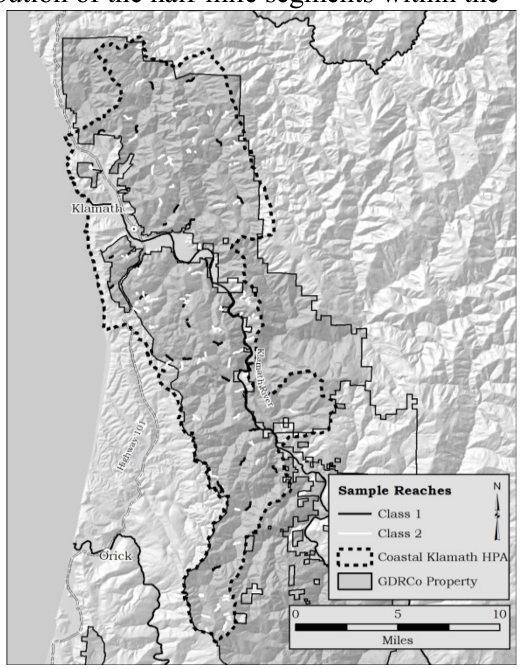

Figure 1—Coastal Klamath HPA sample reaches.

Review of existing documents

Our review of existing documents included a review of published geologic mapping in the area and a comprehensive landslide inventory using aerial photographs from the 1954, 1958, 1969, 1975, 1984, 1997, 2001, and 2004 sets and was focused on the areas within the vicinity of our sample reaches. As is common practice we mapped only landslides that were visible at the scale of the photographs which is 1:12,000 for each of the photo sets. We found that this typically equates to a landslide roughly 50 ft wide by 100 ft long or 5,000 square ft. These landslides were transferred into our GIS landslide layer with associated tabular data that included; photo year and label, land use and stand age at the time of failure, road and/or skid trail association, landslide type, slope curvature, geomorphic association, watercourse association, feature certainty and delivery. Landslide types are based on definitions modified from Cruden and Varnes (1996).

Review of the aerial photographs indicates that the areas west of the Klamath River from Saugep Creek south to Tectah Creek were clearcut beginning in the 1950s and slowed down by the late 1970s. The primary harvest method was ground-based tractor-yarding likely due to the more subdued topography in this region. There are however several areas in this region that are much steeper and were subject to cable yarding in the late 1960s and 1970s such as portions of Ah Pah Creek and the lower portion of Tectah Creek. Along the Klamath River we observed early harvesting in the 1950s and 1960s that consisted of ground-based tractor clear cutting. East of the Klamath River from Mynot Creek south to Bear Creek, timber harvesting began in the mid to late 1960s and continued through the 1980s and slowing down in the 1990s. Mainly clearcut with few selections were observed in these areas with ground-based tractor yarding as the main harvest methods. Cable-yarding however was the primary yarding method being utilized in the steeper terrain within the Hunter and Terwer Creek drainages.

Throughout the Costal Klamath HPA, lay-out construction was also common practice. Lay-outs were mounds of earth constructed in the direction of felling that softened the landing of old-growth timber and helped reduce breakage from the landing. This resulted in a significant amount of ground disturbance throughout the area. Road construction also resulted in significant ground disturbance throughout the area. Until the early 1980s side-cast construction was the common practice. This was a practice where earth materials from road construction were simply pushed off the downhill side of the road rather than being hauled to a stable location. Due to the dense skid road network involved with this initial entry and poor road-building practices, such as side-cast construction, road-related failures were very common throughout the region.

Published mapping in the area includes mapping from Aalto and Harper 1982, Aalto and Kelsey 1981, Dell'Osso et al. 2002, and Ristau 1979a, 1979b. This mapping indicates the majority of the Coastal Klamath is underlain by the broken formation of the Franciscan Complex. Aalto and Harper describe the broken formation as tectonically fragmented interbedded graywacke, shale, and conglomerate. In general the topography in the area becomes more incised and rugged to the east where bedrock is less fragmented. In the western portion of the area topography is more subdued, bedrock is more fragmented, and ridges are frequently capped with alluvial deposits.

Field work, measurements, and calculations

Field work involved surveying the hillsides adjacent to the sample reaches for shallow streamside landslides. Our study focused on those landslides that were non road and non skid-trail related, active to historically active, and had observably delivered sediment to a watercourse. Only landslides greater than 10 ft by 20 ft were included in the survey. The data collected for each landslide included a field-developed cross section using a tape measure and clinometer, causal factors, slope characteristics, dimensions of the source area and slide debris, a field estimate of the delivery volume, distance from the crown of the slide to the watercourse transition line, and the average slope gradient of the hillside.

Cross sections show the main scarp, projected failure surface, the estimated original surface, extent of slide debris and the associated watercourse. Cross sections were utilized to determine the length of the rupture area, length of debris, estimated thickness of the failure, estimated thickness of the remaining slide debris, and an estimated slope gradient of the hillside.

As mentioned above landslides that were thought to have been caused by roads or skid trails were not included in the analysis. Determining whether or not a slide has been caused by a road is a difficult task; especially if the failure is not a recent one. There are inferences that must be made in attributing a causal mechanism such as roads to the failure of a landslide. As a result we attempted to attribute road caused only to failures that appeared to have a reasonable or obvious negative association with a road or skid trail. Our determination of road caused failures took into account several factors. Fill slope related failures had to truncate a portion of the running surface of the road in order to be considered. In general it is difficult to determine if a failure emanating from the fill slope was caused by the road as most of these failures are older. Therefore we focused on slides that had observably offset at least a portion of the road. Cut bank related failures are typically easier to determine as most slides will take out a cut slope and fail onto or over the road prism or may take out a portion of the road as well. These types of cut bank failures were considered road caused. Skid trails, although no longer being constructed on GDRCo timberlands, were commonly cut across steep terrain adjacent to watercourses and regularly used side-cast construction. In such areas skid-trail related slides were common and fairly easy to distinguish and were considered road-caused. Patterns of failure can typically be captured in aerial photographs. For instance, we observed that road related and skid trail failures were common in the early harvest entries where side-cast construction was the common practice and in areas with dense skid road networks or tall cut banks. Thusly, aerial photographs were also used to assist in the determination of road caused failures.

Volume estimates were derived from a calculation based on the length, width, and depth of both the rupture area and the remaining slide debris observed in the field. The calculation treats the slide rupture area and debris as a half of an ellipse and was obtained from published work by Cruden and Varnes 1996.

Development of morphologic units

The initial default SSS prescriptions were applied uniformly across the Coastal Klamath HPA regardless of morphology or bedrock type, both of which can vary dramatically across the region. Looking at the hillshade model from a 1 meter LiDAR DEM we determined that the morphologic complexity of the region could be separated into at least three discreet units. By doing so we could develop multiple SSS buffers within the HPA that would be more accurately applied to specific areas based on their morphology. In order to help define these areas we chose to use a topographic ruggedness model developed by Riley et al. 1999, using a 50 m resampled LiDAR DEM. The topographic ruggedness model computes the Terrain Ruggedness Index (TRI); the average change in elevation (meters) within a three by three kernel (150 m by 150 m area) at each 50 m cell within the region. The resulting TRI's were classified into three groups (0 to 38 m, 38 to 63 m, and 63 to 170 m) using Jenks natural breaks (Jenks 1967). Jenks natural breaks, developed by cartographer George Jenks, are a data classification method that minimizes variance within groups of data and maximizes variance between groups of data. We characterized the resulting three TRI values as subdued, moderately subdued to slightly rugged, and rugged terrain, noting that this characterization is specific only to this HPA and portions of its surrounding areas. Next, we manually divided the HPA into large morphologic blocks based on our observations of the morphology observed in the LiDAR DEM, our observations in the variation of the local bedrock, and the TRI's. These larger blocks have been termed "Steep Streamside Slope Morphologic Units" (SSSMU).

Once the SSSMU's had been delineated we overlaid them with the landslide data. At that time we noticed that we did not have enough landslide data in each of the SSSMU's to define the SSS buffers and slope thresholds. This is not to say that we did not have enough sample area, we simply found very few landslides in certain areas. In one of the SSSMU's there were only 14 landslides to characterize the Class 2-1 streams and only 28 landslides to characterize the Class 2-2 streams. As a result SSSMU 1 and SSSMU 2 were grouped together. For the final grouping SSSMU 1 and SSSMU 2 were combined and renamed SSSMU 1 with TRI values of 0 to 63 and SSSMU 3 was renamed SSSMU 2 with TRI values of 63 to 170. The final SSSMU's are shown on *figure 2*.

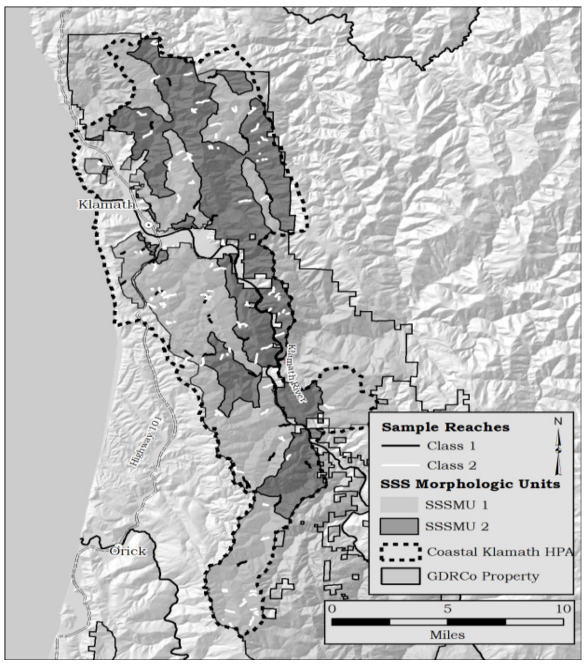

Figure 2— Coastal Klamath HPA.

Cumulative volume

This study included 423 landslides to characterize landslide patterns and develop the SSS buffers for the Coastal Klamath HPA alone. We found that of the 423 landslides, 42 (or 10 percent) of the slides fall in the cumulative volume distribution above the 60 percent threshold. Of those 42 landslides, 33 percent were observed on 1978 photos or earlier, 74 percent of them were observed on the 1997 photos or earlier and 12 percent were not observed in the photo record. Each of the slides observed on the 1997 or earlier photos occurred in areas that were clearcut prior to the retention of riparian buffers of any kind. Although primarily intended for riparian habitat, these buffers also help reduce the potential for streamside landslides. The slides observed on the 1997 and earlier photographs failed under management conditions that have not existed since the mid-1990s and certainly not under current management practices (i.e., those within the last 15 years that have been afforded various protection measures including riparian and geologic). Under current management practices these areas would have been, all or in part, protected by various retention buffers and likely received some level of geologic oversight at the THP level. These data suggest that these larger landslides are rare and may be attributed to historic logging practices. Based on these observations it is our judgment that using the 60 percent cumulative volume threshold will be adequate to derive the SSS distance buffers and be able to achieve the SSS objective of a 70 percent reduction in sediment delivery from management related streamside landslides in the Coast Klamath HPA. It should also be noted that the effectiveness of these new buffers will be evaluated during the AHCP's SSS Assessment project which will take place over the next 11 years.

With the exception of the Coastal Klamath HPA group and Smith River HPA, a cumulative sediment delivery volume of 80 percent was used to determine initial default SSS gradients. In these areas the data from the initial SSS study suggested slope gradient thresholds of 85 percent and 70 percent, respectively. It was assumed that the initial data were biased towards steeper slopes that would not accurately characterize these areas as a whole. The actual slope gradients assigned to the initial SSS default buffers for these areas were reduced to 70 percent and 65 percent respectively. Like what was done for the maximum distance threshold, this was a conservative approach based on limited data to ensure that the SSS buffers would be able to meet the overall sediment objectives from the streamside slopes until a more robust analysis was conducted. Based on the observations described above, it is our judgment that using a cumulative volume threshold of 80 percent will be adequate to derive the SSS minimum gradient thresholds and be able to achieve the SSS effectiveness objectives.

Results

Our sample reaches were mapped in the field and end points marked using a Garmin 60Cx GPS. After transferring these endpoints into the GIS and onto the LiDAR corrected hydrography layer we found that the spatially upgraded sample came very close to our target. Our surveys captured 13 percent of the mapped lineal distance of Class 1 watercourses (target of 10 percent) and 5 percent of the mapped lineal distance of the Class 2 watercourses (target of 5 percent) with a fairly even distribution between the Class 2-1 and Class 2-2 watercourses capturing 4 percent of the Class 2-1 and 6 percent of the Class 2-2 mapped watercourses.

As noted above we used a cumulative volume of 60 percent to determine the new SSS slope distances. There were a total of 423 landslides included in our analysis of the Coastal Klamath HPA. The distribution of landslides by watercourse and SSSMU are shown in *table 1*.

The majority of these landslides occurred along the Class 1 and Class 2-2 watercourses. Few landslides were found along the Class 2-1 watercourses, in fact there were 70 slides observed along the selected sample reaches with a near even split of 34 slides in SSSMU 1 and 36 slides in SSSMU 2. After reviewing the Class 2-1 landslide data within the individual SSSMU's we noticed a high variability within the measured SSS criteria. It became apparent that this would be an insufficient amount of data to delineate buffers for each of the SSSMU's. Therefore

Table 1—*Distribution of landslides by watercourse and SSSMU.*

Watercourse Class	SSSMU	Number of Slides
I	2	67
I	1	68
2-2	2	133
2-2	1	85
2-1	1&2	70

we combined the data for Class 2-1 watercourses and came up with prescriptions for the HPA as a whole for this watercourse class. The remaining landslides provided a sufficient distribution to characterize the SSS buffers in both of the SSSMU's.

Review of the Class 2-2 and 2-1 watercourses and their adjacent slope gradients using the LiDAR indicates that average slopes adjacent to Class 2-1 and Class 2-2 watercourses are essentially the same. However, when we looked at the average maximum slope gradient adjacent to these watercourses we found that Class 2-2 watercourses are located in proximity to much steeper slopes, by up to 22 degrees. This suggests that there may be fewer steeper slopes adjacent to Class 2-1 watercourses and may explain why there were fewer landslides observed in these areas. However at this point this is simply a correlation and requires more investigation which we may be able to address at a later date.

The revised SSS slope distances have been calculated. The distribution of cumulative volume of delivered sediment versus landslide distances from crown to watercourse is shown on *figure 3* and a summary table of these results is shown in *table 2*.

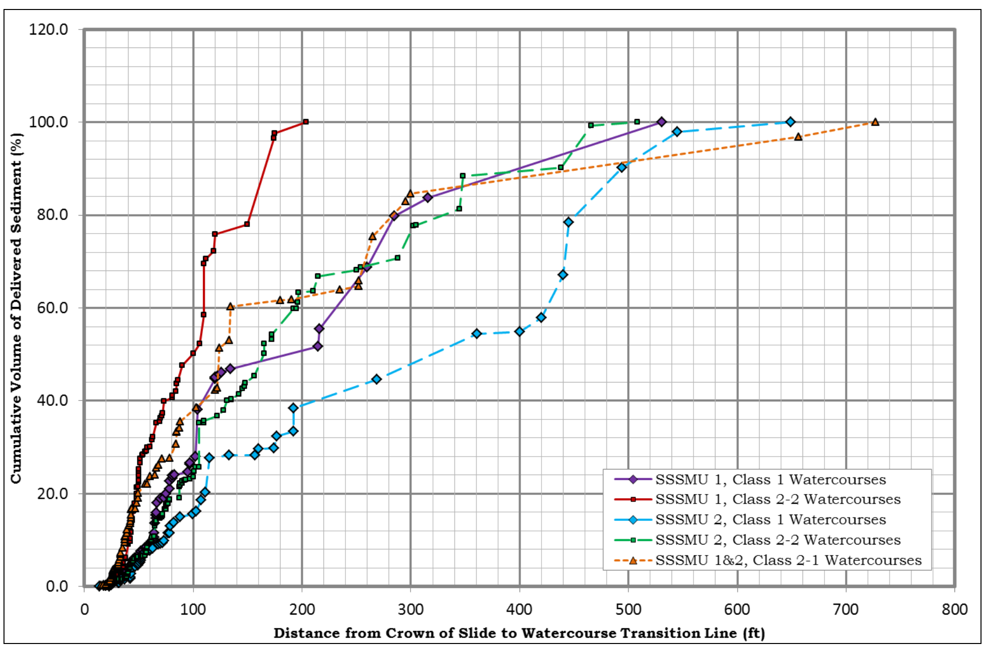

Figure 3—Cumulative volume of delivered sediment versus landslide distances from crown of slide to watercourse transition line for Class I, Class 2-1 and Class 2-2 watercourses.

Table 2—*New SSS thresholds & a comparison of the revised Coastal Klamath SSS buffers with initial default buffers.*

Coastal Klamath SSS Maximum Slope Distances (feet) & Minimum Slope Gradient (%) Thresholds			
SSSMU	**Class I**	**Class 2-2**	**Class 2-1**
1	240' & 65%	110' & 70%	135' & 75%
2	425' & 75%	195' & 85%	
Initial Default Buffers	475' & 70%	200' & 70%	100' & 70%

Slope Gradient thresholds were based on a cumulative volume of delivered sediment of 80 percent. With a significantly larger data set than the initial study, it was our judgment that we had sufficient data to characterize the SSS gradient thresholds by watercourse type as well as SSSMU. As was the case for the SSS slope distances we combined the data for the Class 2-1 watercourses to come up with an HPA wide slope threshold for this watercourse class. The distribution of cumulative volume of sediment delivered versus landslide slope gradients are shown on *figure 4* and a summary table of the slope gradient thresholds is shown in *table 2*.

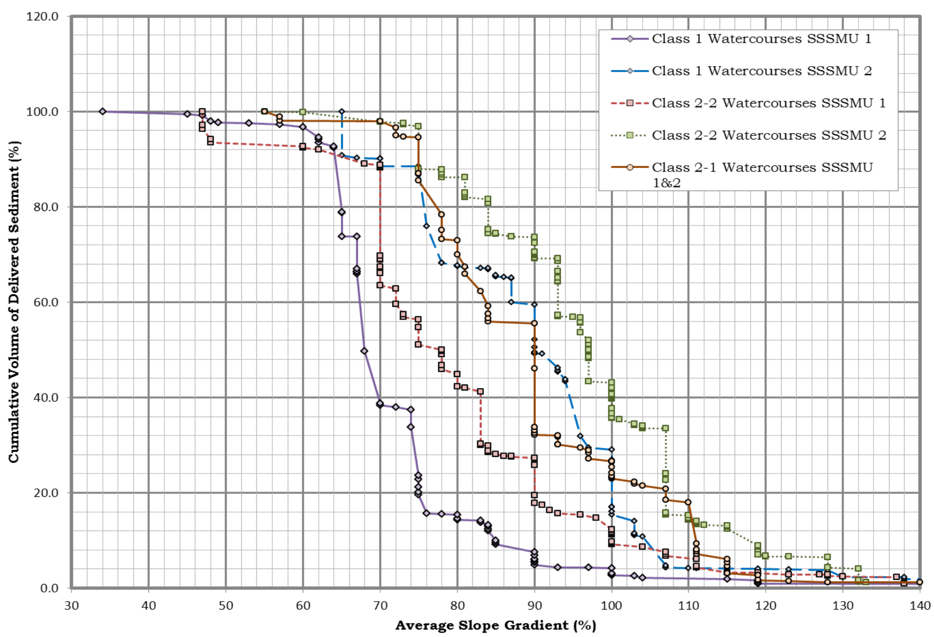

Figure 4—Cumulative volume of sediment delivered versus average slope gradient from SSSMU 1& 2 for Class I, Class 2-1 and Class 2-2 watercourses.

Discussion

Looking at the different slope distances and slope gradient thresholds we can see justification for the rationale behind the development of the SSSMUs. *Table 2* also outlines a comparison of the Initial Default SSS distance and slope thresholds as well as the new slope distances and associated slope thresholds.

Both slope distances and slope gradient thresholds vary significantly between SSSMUs. Within SSSMU 2 we can see the effects of the more competent sandstone and shale of the broken formation of the Franciscan complex. In these areas, we observed landslides occurring on steeper slopes with longer slide run out distances. In contrast within SSSMU 1 we observed more fragmented earth materials of the broken formation of the Franciscan complex as well as uplifted alluvial sediments, which resulted in slacker slopes and shorter run out distances with the associated landslides. In the future, our observations from this study coupled with more detailed mapping of the local bedrock may lead to differentiation of multiple bedrock units within the broken formation of the Franciscan complex. In the meantime, these varying buffer criteria offer more site specific protection measures where they are warranted.

Conclusions

Our analysis of landslides in the Coastal Klamath HPA has resulted in changes to both the slope distance and slope gradient criteria associated with the default SSS prescriptions. These new criteria offer specific protection to morphologically discrete areas within the Coastal Klamath HPA which we termed SSSMUs. Our sampling methods reduced bias and spatially distributed the samples about the HPA such that we were able to produce a robust data set that more accurately characterizes the geomorphic conditions of the region as they pertain to streamside landsliding. The goal of the SSS buffers was to achieve a 70 percent reduction in management-related sediment delivery from landslides compared to delivery volumes from landslides in appropriate historical clearcut reference areas. It is our judgment that these new default buffers will allow GDRCo to meet this goal set forth in the AHCP.

Acknowledgments

We would like to thank our field crew; Scott Matheson, Scott Kirkman, Evan Saint-Pierre, Nick Graehl, Daniel Hadley, William Troxler, and Esther Stokes for producing quality field data through inclement weather and the steep and challenging terrain of the interior Klamath River region.

References

Aalto, K.R.; Harper, G.D. 1982. **Geology of the Coast Ranges in the Klamath and Ship Mountain quadrangles, Del Norte County, California.** California Division of Mines and Geology Open File Map QFR 82-16-SF, scale 1:62,500.

Aalto, K.R.; Kelsey, H.M. 1981. **Geologic map of the Tectah Creek 15-minute quadrangle, northern California.** Unpublished. California Division of Mines and Geology, scale 1:62,500.

Cruden, D.M.; Varnes, D.J. 1996. **Landslide types and processes.** In: Turner, K.A.; Schuster, R.L., editors. Landslides - investigation and mitigation. Special Report 247. Washington, DC: National Research Council Transportation Research Board. National Academy Press: 36-75.

Dell'Osso, D.R.: Falls, J.N.; McGuire D.J. 2002. **Geologic and geomorphic features related to landsliding Redwood Creek watershed (north, central, and southern portions), Humboldt County, California.** California Geological Survey, watershed mapping series, map set 6, Plate 1, 3 sheets.

Falls, J.N.; McGuire, D.J.; Dell'Osso, D.R. 2000**. Geology and geomorphology for the Redwood Creek watershed assessment, Humboldt County, California.** California Geological Survey.

Jenks, G.F. 1967. **The data model concept in statistical mapping.** International Yearbook of Cartography 7: 186-190.

Riley, S.J.; DeGloria, S.D.; Elliot, R. 1999. **A terrain ruggedness index that quantifies topographic heterogeneity.** Intermountain Journal of Sciences 5, No.1-4.

Ristau, D. 1979a. **Geologic map of the Klamath 15 minute quadrangle, California.** Department of Forestry Title II Geologic Data Compilation Project, scale 1:62,500.

Ristau, D. 1979b. **Geologic map of the Ship Mountain 15 minute quadrangle, California.** Department of Forestry Title II Geologic Data Compilation Project, scale 1:62,500.