

DEVELOPMENT OF A MONITORING PROTOCOL FOR BIOENGINEERED
SEDIMENT MITIGATION RELATED TO STREAM ADJACENT BANK FAILURES
ON FOURMILE AND SHOLES CREEKS IN THE MATTOLE RIVER WATERSHED

By

Andrea Z. Davis

A Thesis

Presented to

The Faculty of Humboldt State University

In Partial Fulfillment

Of the Requirements for the Degree

Masters of Science

In Natural Resources: Watershed Management

May, 2006

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By

Andrea Z. Davis

Approved by the Master's Thesis Committee:

E. George Robison, Major Professor

Date

Andre Lehre, Committee Member

Date

William Bigg, Committee Member

Date

Coordinator, Natural Resources Graduate Program

Date

Natural Resources Graduate Program Number

Donna E. Schafer, Dean for Research and Graduate Studies

Date

ABSTRACT

Development of a Monitoring Protocol for Bioengineered Sediment Mitigated Related to Stream Adjacent Bank Failures on Fourmile and Sholes Creeks in the Mattole River Watershed

Andrea Z. Davis

The purpose of this thesis was to develop and test a replicable monitoring protocol for the Mattole Restoration Council. The protocol was used to assess the success of bioengineered sediment mitigation projects. Using the protocol, I evaluated channel adjacent bank failures along Fourmile Creek and Sholes Creek and hypothesized that there would be a difference would be detected between erosion contributions for control and treated sites. This hypothesis was not supported by my study.

I surveyed twenty (ten control and ten treatment) channel adjacent bank failures using total station surveying equipment to obtain topographic x, y, and z coordinates. These coordinates were used to calculate hillslope volume, slope, and hillslope area for the twenty landslides before and after treatment. Overlaying one year's surface over another in Environmental System Research Institute (ESRI) ArcMap 9.1 yielded the hillslope volume change over a year. The overlaid data was used to statistically compare sediment contributions from treated and control sites. The results of the protocol from this project will be used by the Mattole Restoration Council to help assess the

effectiveness of their sediment reduction treatments, as well as to continue monitoring in the future.

First-year monitoring results concluded that the applied treatment did not mitigate erosion. Resulting data was statistically insignificant and demonstrated that there was no real difference between the net gain or loss of hillslope soil volume from either control or treated landslides. Three types of T-Tests were used to compare data: A Two-Sample Hotelling's T-Test, a Hotelling's Paired T-Test, and a Paired T-Test. All three tests resulted in a P value of 0.32. The Two-Sample Hotelling's T-Test used unpaired data, while the other two tests used paired data. In all three statistical tests appropriate for this data set, the resulting P values were significantly out of range of the 0.05 target value to ensure statistical significance. Furthermore, the resulting hillslope volumes retained by the restoration technique was minimal compared to the overall volumes of sediment displaced in these landslides.

These results are not unexpected given this data represents only the first year's worth of data from a long-term monitoring effort. Additional monitoring is required to determine if the applied treatment will prove to be more effective over time.

ACKNOWLEDGEMENTS

Funding for this project was provided by the Mattole Restoration Council through the Humboldt State University Foundation. Academic support for this project was generously provided by Dr. George Robison, Dr. Bill Bigg, and Dr. Andre Lehre. Additional support was also provided by Dr. Bill Bigg for the statistical analysis used in this thesis.

TABLE OF CONTENTS

	Page
ABSTRACT.....	iii
ACKNOWLEDGEMENTS.....	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
INTRODUCTION.....	1
STUDY SITES.....	7
MATERIALS AND METHODS.....	15
Rapid Surveys.....	16
Determining Landslide Elevation Coordinates.....	19
Data Analysis.....	21
RESULTS.....	26
Hillslope Area and Slope Comparison of Paired Combinations.....	26
Slope and Hillslope Volume Results.....	33
Additional Monitoring Results.....	37
Increases in Hillslope Area and Structure Survivability.....	40
DISCUSSION.....	43
Possibilities for Improving Treatment Effectiveness in the Future.....	45
Sources of Error in Monitoring.....	48
Future Monitoring Efforts Utilizing this Protocol.....	50

	Page
CONCLUSION AND RECOMMENDATIONS	51
LITERATURE CITED	53

LIST OF TABLES

Table		Page
1	Relative landslide potential in Sholes and Fourmile Creeks (California Resources Agency 2003).....	13
2	General first-year site characteristics of landslides.....	27
3	Summary of rapid survey results.....	28
4	Pair combinations with slope and hillslope area comparisons.....	29
5	Net change in soil volume from 2004 to 2005.....	38
6	Estimated maximum holding capacity of backfilled willow fences.....	39

LIST OF FIGURES

Figure		Page
1	Fourmile and Sholes Creek locations within the Mattole River Watershed, basemap from the Mattole River Watershed North Coast Watershed Assessment Program Report (California Resources Agency 2003), with the locations of Fourmile and Sholes Creek added.....	8
2	Fourmile Creek site locations, United States Geological Survey Honeydew, California Quadrangle, created in Terrain Navigator Pro.....	9
3	Sholes Creek site locations United States Geological Survey Honeydew, California Quadrangle, created in Terrain Navigator Pro	11
4	Willow fence at the bottom of Site 27, July 26, 2004.....	17
5	Willow fence at Site 27, nearly one year after installation, with willow sprouts, June 28, 2005.....	18
6	Calculating hillslope volume in ESRI ArcMap 9.1 based on arbitrary surface plains created by the software.....	22
7	3-D model of Site 37 created in ESRI ArcMap 9.1 using 2004 baseline data with a 305 meter base elevation.....	23
8	Timestep calculation of net change of hillslope soil volume.....	24
9	Cumulative frequency distribution for change in hillslope volume, control sites.....	32
10	Cumulative frequency distribution for change in hillslope volume, treated sites.....	32
11	Linear regression plot section results, 2004 control site data, R-Squared of 0.52.....	34
12	Box plot of net gain or net loss of soil volume from control and treated landslides, 2004 through 2005.....	36

Figure		Page
13	Estimating willow fence holding capacity.....	41
14	Relationship between hillslope volume and slope.....	46

INTRODUCTION

The North Coast Watershed Assessment Program's March 2003 assessment of the eastern subbasin of the Mattole River watershed found that high sediment levels and other factors such as high summer temperatures and low habitat complexity currently limit salmonid populations (California Resources Agency 2003). The assessment listed among its key recommendations the encouragement of cooperative efforts to reduce sediment yields at stream bank erosion sites, specifically listing Sholes and Fourmile Creeks (California Resources Agency 2003). The assessment also recommended the encouragement of cooperative efforts to reduce sediment yields at stream bank erosion sites, specifically listing Sholes and Fourmile Creeks (California Resources Agency 2003).

Similarly, the United States Environmental Protection Agency's (EPA) Total Maximum Daily Load assessment for the Mattole River also noted extremely high sediment levels as a contributing factor to declining fish populations (Environmental Protection Agency 2003). Between 1984 and 2000, the 79 square mile eastern subbasin lost 1,600 tons per square mile per year due to natural mass wasting (Environmental Protection Agency 2003). The eastern subbasin also lost 270 tons per square mile per year due to stream bank erosion (Environmental Protection Agency 2003).

Working with partnering landowners, the Mattole Restoration Council treated 35 stream bank erosion sites, inaccessible to heavy equipment, with bioengineered willow

and rock structures at the total expense of \$150,000. The Mattole Restoration Council and supporting agencies hoped the bioengineered treatment would stabilize failing banks and reduce sediment contributions into the stream channel. In order to quantify the results of the treatment, the development of a monitoring protocol was necessary. Monitoring stream adjacent bank failures over a long period of time can identify trends in sediment delivery, transport and deposition. Monitoring may also serve as an indicator of the success of sediment reduction projects.

Willow fence bioengineering and bank stabilization is a widely-used stream restoration practice, although the size and scope of the project sites and the fences themselves vary (Franti 1996, Lee *et al.*, 1997, Watson *et al.* 1997). Bioengineering originated in 12th century China. There brush bundles were used to stabilize flooding and eroding slopes along the Yellow River (Franti 1996). Germany has also used bioengineering methods for 150 years and the use of bioengineering in the United States has been documented as early as the 1920s and 1930s (Franti 1996). The emergence of stream restoration over the past twenty years has stimulated a revival of bioengineering, especially given that it is relatively low-cost and low maintenance (Franti 1996).

There are multiple methods available to monitor and measure erosion processes, including measurements of topographic information and physical parameters, qualitative site inspection over time, photographs, remote sensing, and erosion staking among other potential methods (French 2003, Hapke 2005, Henry *et al.* 2002, Lane *et al.* 2003, Lu *et al.* 2004, Madej 2000, Weaver *et al.* 2006). As documented in literature, each of these

methods has attributes that may work well in some field locations and poorly in others. Methods include the use of topographic data, qualitative monitoring, remote sensing and light detection and ranging techniques, and erosion staking.

Madej (2000) developed a topographic protocol for examining the success of road removal projects in Redwood National Park. The intent of the project was to minimize sediment contributions into Redwood Creek, the park's main tributary. She had the benefit of being able to examine a long-term data set, spanning 18 years. She measured post-treatment erosion only, including mass movement, bank erosion, and channel incision at randomly selected treated sites. Sediment delivery was estimated by measuring voids, bank erosion or mass movement features. She also measured the dimensions of the down slope deposit, if it was present. The estimated error of these measurements was +/- 25 percent (Madej 2000).

Madej did not directly examine or measure surface erosion, citing that surface erosion delivered only a small portion of the total sediment in the watershed (Madej 2000). This same assumption is applied to direct topographic measurements in the Mattole monitoring protocol. Methods used in this research are adequate to detect mass movement. They likely will not detect surface erosion, argued by Madej to be an insignificant erosion contributor.

My protocol may not adequately detect surface erosion. The lack of a repeatable grid used when measuring landslides with an electronic total station may cause measurement errors. The type of equipment used and the safety risks posed by the

physical terrain of the landslides prohibited the use of a repeatable grid. Future use of a total station capable of reflecting off the ground without requiring a second person to traverse the landslide with a prism on a stadia rod will allow this protocol to more accurately detect surface erosion.

Qualitative monitoring protocols were also evaluated. The California Department of Fish and Game sponsored an effectiveness manual to monitor the success of a variety of restoration practices, inclusive of slope stabilization and bioengineering (Weaver et al. 2006). In this manual, specific topographic measurements are not taken, but slope stabilization and erosion control projects are monitored by tracking increases in mass wasting and sediment delivery from the treated area. Instead of using topographic or physical measurements, monitors are instructed to use photographs and site observations to evaluate the effectiveness of the project. The survival of the installed erosion control structure over time, the fluctuation of vegetation present at the site, and slope and bank condition are also tracked over time using estimated qualitative descriptors on an effectiveness monitoring checklist (Weaver et al. 2006). While this method is not physically exact and thus does not lend well to statistical or mathematical evaluation of long-term results, its simplicity does allow for cost-effective, accessible, and repeatable monitoring over the long-term.

Using remote sensing to develop digital elevation models or low-elevation aerial photography, researchers are able to monitor erosion from landslides and build models to predict erosion rates (Hapke 2005, Henry et al. 2002, Lane et al. 2003, Lu et al. 2004).

Light detection and ranging data obtained from aerial flyovers can also be used to obtain digital elevation data useful in analyzing landslides and erosion rates (French 2003).

Light detection and ranging studies are becoming more common albeit expensive.

Applying remote sensing to this project was not possible due to the high cost of the technology. Thick forest cover surrounding the landslides may have also impeded the ability of remote sensing to accurately measure erosion rates. Using an electronic total station is more accurate than light detection and ranging data. While light detection and ranging can detect change to the scale of ten centimeters, a total station can detect change to three centimeters or less.

Erosion staking is a common method to measure erosion in stream settings (Amacher and Kotuby-Amacher, 2001, Couper et al. 2001, Moody and Martin 2001, Woltemade 2003). Erosion stakes are inserted into the erosive area, often in a grid pattern, and used to measure erosion in a given area. Erosion stakes were considered for use in this research. Field visits in wet spring months demonstrated physical evidence of extreme mobility on the landslide slopes. Erosion on the slopes during wet months was so substantial that even long erosion stakes could potentially slide down the slope and even wash into the stream. This risk, multiplied by the intention for a monitoring protocol with long-term potential, eliminated the possibility of using erosion stakes to evaluate the success of the bioengineering restoration project over many years.

The goal of the monitoring described in this research is to evaluate the effectiveness of sediment delivery reduction treatments within Mattole subbasins, specifically the

effectiveness of bioengineered treatments on mitigating sediment contributions from stream adjacent bank failures. This research hypothesized that the first-year monitoring effort will indicate there was a detectable difference between erosion from control and treated landslides. The results of my study did not support this hypothesis.

STUDY SITES

Fourmile and Sholes Creeks are located in the eastern subbasin of the Mattole River Watershed, located between Honeydew, California and Bridge Creek (California Resources Agency 2003, Figure 1). Stream elevation in the eastern subbasin ranges between 102 meters and 701 meters at tributary headwaters (California Resources Agency 2003).

Fourmile and Sholes Creek are ungaged streams. During late summer and fall, portions of the stream bed are completely dry in places, with dry season flow occurring subsurface in the hyporheic zone. The stream channel adjoining the study sites are predominantly Rosgen type A and B, with steep V-shaped valleys, lacking well-developed floodplains, possessing few meanders, and exhibiting riffle-dominated step/pool sequences (Rosgen 1994). Large woody debris was abundant in all stream reaches included in this study.

Juvenile coho (*Oncorhynchus kisutch*) and Chinook (*Oncorhynchus tshawytscha*) salmon were observed in all stream reaches. These fish are a major driver for the restoration effort. Coho and Chinook salmon as well as steelhead trout (*Salmo gairdneri*) have all declined since the mid 1950s (California Resources Agency 2003, Environmental Protection Agency 2003).

Control and treatment sites on tributaries of Fourmile Creek are located in Figure 2. Thirty-seven landslides exist along five kilometers of stream reaches (Figure 2).

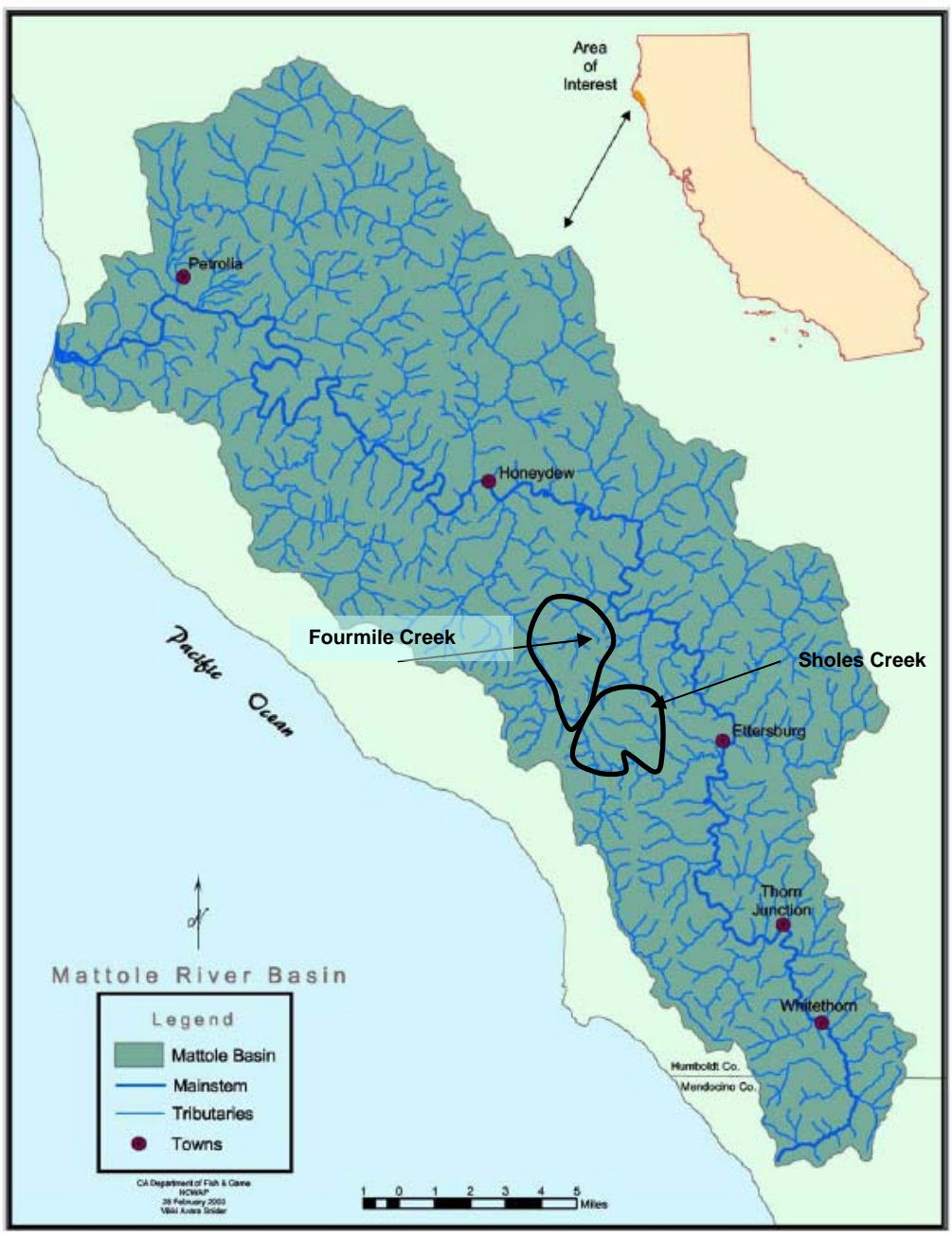


Figure 1. Fourmile and Sholes Creek locations within the Mattole River Watershed, basemap from the Mattole River Watershed North Coast Watershed Assessment Program Report (California Resources Agency 2003), with the locations of Fourmile and Sholes Creeks added.

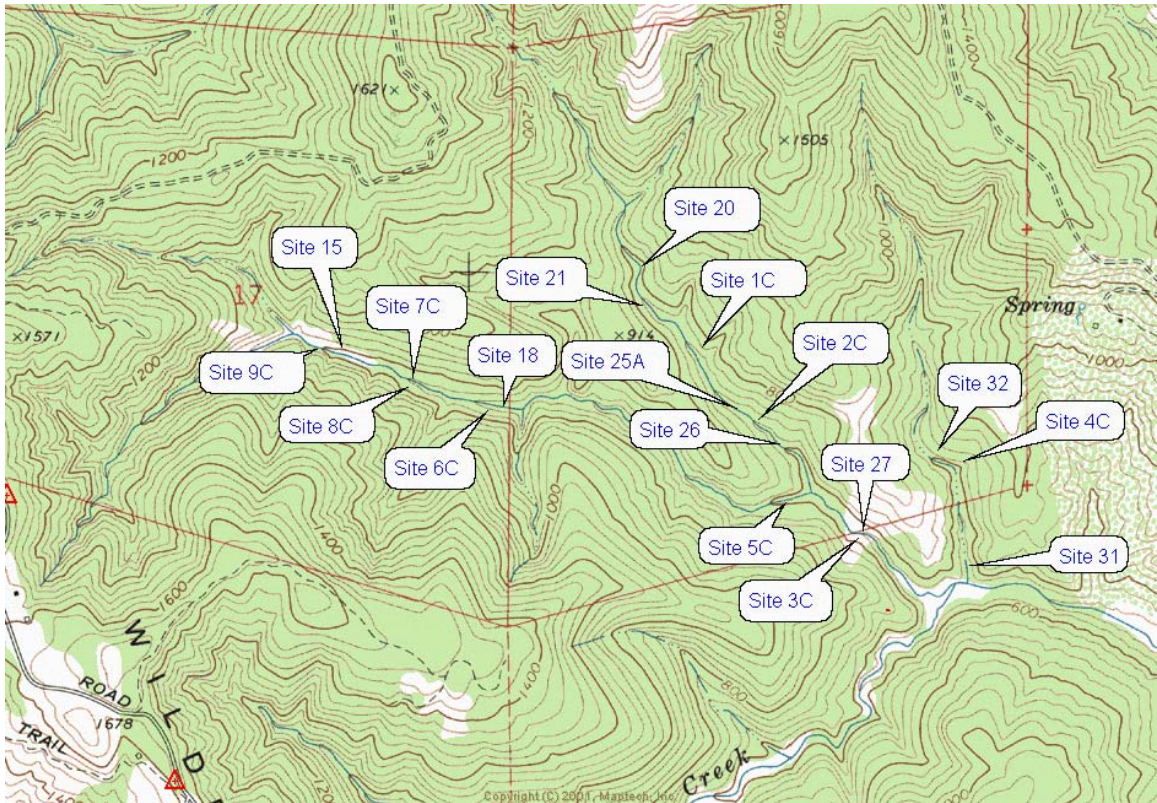


Figure 2. Fourmile Creek site locations, United States Geological Survey Honeydew, California Quadrangle, created in Terrain Navigator Pro.¹

¹ Terrain Navigator Pro software is licensed by MapTech, Inc., 10 Industrial Way, Amesbury, Massachusetts, www.maptech.com.

Figure 3 depicts stream adjacent landslides present along the monitored segment of Sholes Creek. A short segment of Sholes Creek was also monitored. Along this segment, stream adjacent landslide occurrences were less common than on Fourmile Creek.

Rainfall averages are highest in the eastern subbasin, ranging between 216 and 292 centimeters per year (California Resources Agency 2003, Environmental Protection Agency 2003).

Vegetation in the 20,459 hectare eastern subbasin of the Mattole River watershed is comprised largely of mixed conifer and hardwood forests, with a much smaller percentage of grasslands (California Resources Agency 2003). Four percent of the subbasin was harvested between 1990 and 2000 primarily by tractor yarding. Eighty-three percent of the subbasin is characterized as timberland but has not been recently harvested (California Resources Agency 2003). The majority of the harvest in the eastern subbasin occurred from 1945 to 1961 (Environmental Protection Agency 2003), using tractor yarding (California Resources Agency 2003). Subsequent heavy rainfall and flooding in 1955 and 1964 triggered massive erosion from the thousands of miles of logging roads built between 1955 and 1964 (EPA 2003).

Vegetation near my study sites was extremely thick and dominated by Douglas fir, huckleberry, and tan oak. Vegetation on the landslides themselves, if present, was composed of alder, various grasses, horsetail, and foxgloves. In shady areas, ferns were also present.

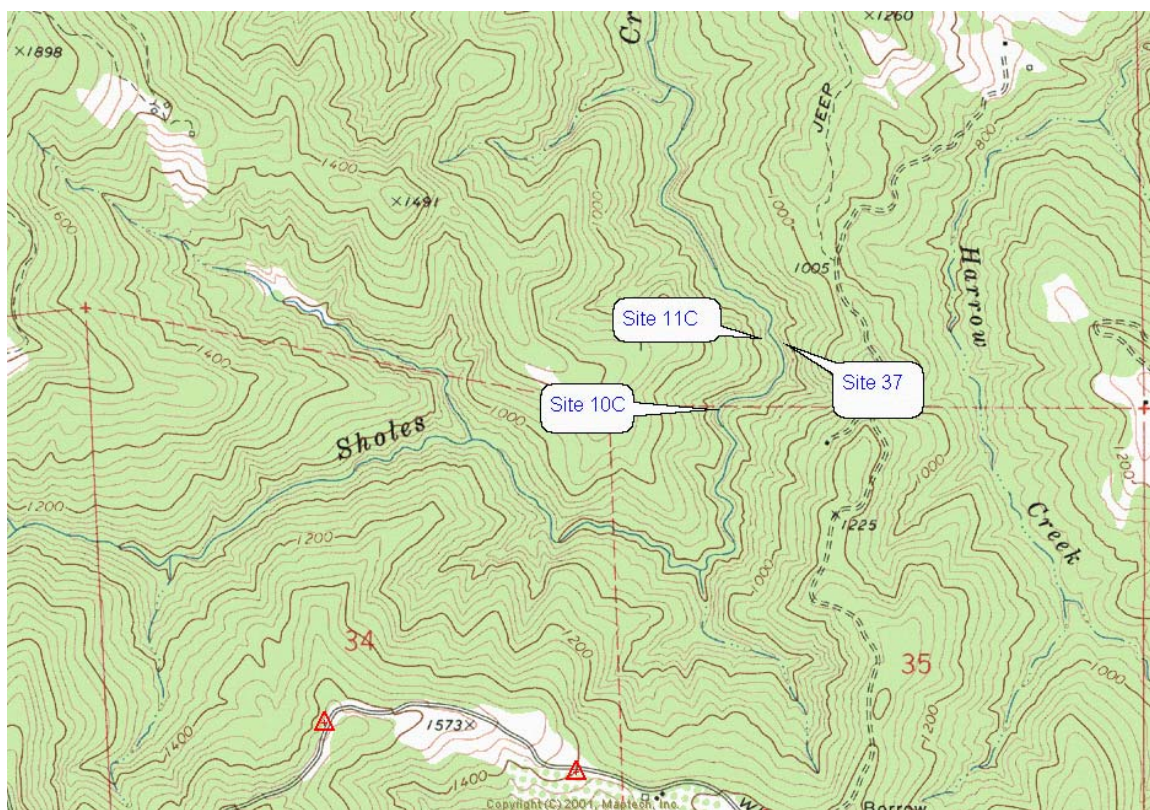


Figure 3. Sholes Creek site locations, United States Geological Survey Honeydew, California Quadrangle, created in Terrain Navigator Pro.

The geology of the eastern subbasin of the Mattole River watershed is predominantly moderate bedrock terrain (42%), with hard bedrock (37%), soft bedrock (17%) and Quaternary surficial deposits (1%) comprising the complete geology of the subbasin (California Resources Agency 2003). Landslide potential in the eastern subbasin varies in Sholes and Fourmile Creeks, ranges from “low” to “high”/“very high” (Table 1). Nearly half of the entire watershed demonstrates at least some landslide potential.

Landslides in the eastern subbasin of the Mattole River watershed are predominantly characterized as an earthflow, rock slide, or debris slide. Sites examined in this study are debris slides. Historically active landslides in the eastern subbasin of the Mattole River watershed total 221 hectares, while another 335 hectares of the subbasin is characterized as active debris slide slope. Five kilometers of eroding banks and 35 kilometers of inner gorge slides have been formally documented in the watershed (California Resources Agency 2003).

Treated, control, and rapid survey sites were used to evaluate the effectiveness of treating stream adjacent landslides. Methods for defining, measuring, and documenting these three categories of sites are discussed in more detail in the Materials and Methods section.

“Treated sites” refer to the ten landslides that were treated by the Mattole Restoration Council with bioengineered willow fences. These sites were measured with a

Table 1. Relative landslide potential in Sholes and Fourmile Creeks, adapted from the Mattole River Watershed North Coast Watershed Assessment Program Report, (California Resources Agency 2003).

Relative Landslide Potential	Hectares	Percent Area
No Landslide Potential	15,875	56.0%
Very Low	117	1.1%
Low	717	6.9%
Moderate	1,620	15.5%
High	1,041	9.9%
Very High	1,089	10.4%
Total	20,459	100%

Topcon GTS-211D electronic total station and additional quantitative and qualitative observations.

“Control sites” refer to the ten landslides that were not treated by the Mattole Restoration Council with bioengineered willow fences or any other treatment. These sites were also measured and documented in the same way as the treated sites. The ten control sites were used for statistical comparison with the ten treated sites.

Control sites were selected based on several factors. Control sites were located along the same tributary as treated sites. Control sites were similar in characteristics to the treated sites, specifically in slope, width, and height. Control sites also met the prioritization criteria for treated sites, including the presence of salmonid habitat, landowner participation, contiguity with other project areas, and the feasibility of watershed restoration treatments.

“Rapid survey sites” refers to twenty sites for which only quick measurements of height, width, and slope were taken. These sites were not treated by the Mattole Restoration Council, nor were they used as control sites in my study. These twenty rapid survey sites were documented in order to better understand the overall erosivity of the watersheds examined in this research.

MATERIALS AND METHODS

In order to mitigate erosion from stream adjacent bank failures and landslides, the Mattole Restoration Council treated sites by constructing bioengineered willow fences along the base of each slide. Fences were three to five meters in length and 0.5 to 1.0 meters tall. Fences were held together with heavy twine and spiked with willow cuttings. The willow cuttings were expected to sprout and grow over time, helping to stabilize the toe of the failing bank, provide filtration for sediment generated from above, and deflect the flowing stream away from the toe of the slope. The fences were constructed of tree branch material found near the treatment site. The main frames of the fences are no larger than ten centimeters in diameter, with much smaller branches comprising the “slats” of the fence.

Rock weirs one and a half to three meters in length were often combined with the willow fences to add additional stability and stream deflection to the treated site. The rock weirs were less than one half meter in height and width. The weirs were built out of a variety of rocks, ranging from cobbles to very small boulders. Site locations were extraordinarily remote and difficult to access, thus requiring most work to be completed with hand tools, chain saws, winches, and come-alongs.

The use of heavy equipment in assisting with the restoration treatments was not possible due to access limitations. Photographs of the willow fence installed at Site 27, indicative of all the fences installed by the Mattole Restoration Council, are shown in

Figures 4 and 5. Figure 4 shows the fence shortly after it was installed in 2004. Figure 5 shows the fence nearly one year later, after it had been backfilled by the slide material from above. New will sprouts are also evident (Figure 5).

Sampling site observations were taken at each control and treated site. These included site location, soil characteristics, access, and sampling point locations. Soil characteristic observations were also noted, including the presence or absence of water at the study sites, the overall soil composition, and movement within the immediate stream reach and longer tributary. Features within the landslide, such as fissures and gullies, were noted and sketched. Relationships between nearby stream adjacent bank failure sites were also noted, such as in the case of the deflection of stream flow off one bank toward the bank failure, causing further slope stress. Observations were documented on data collection sheets.

Rapid Surveys

Stream adjacent bank failures were frequent and numerous along the sampled tributaries. Untreated sites that were not good candidates for controls, usually due to unsafe, steep slopes, poor access, or large size, were surveyed for general characteristics such as height, width, slope distance, and slope. After noting sampling site location with a handheld GPS unit, the size and slope of the stream adjacent bank failure were taken using a tape measure, range finder, and a clinometer. Photo documentation was completed for these sites.



Figure 4. Willow fence at the bottom of Site 27, July 26, 2004.



Figure 5. Willow fence at Site 27, nearly one year after installation with willow sprouts, June 28, 2005.

The total hillslope volume of soil lost by the twenty control and treatment landslides must be compared to the larger erosion context of Fourmile and Sholes Creeks. Even if the applied treatment is proven to be successful through my protocol and future monitoring, erosion in the eastern subbasin will continue to be acute. Ongoing background erosion from the twenty rapid survey sites could very well result in the persistence of a severe erosion problem in the watershed. It is likely the applied treatment may be only partially successful over the long term. The net benefit from the completed restoration project may remain negligible in comparison to ongoing and untreated erosion in Fourmile and Sholes Creeks.

Determining Landslide Elevation Coordinates

Before any total station measurements were taken, benchmarks were installed at the site. Benchmarks were sited in stable locations out of danger of being overcome by the active stream adjacent bank failure. The benchmark was sited upstream, downstream, or upslope of the bank failure. Rebar was used as the benchmark. The rebar was then flagged with orange tape to ensure visibility for future monitoring efforts. The benchmark location was described and sketched along with the site location in the field data form. A secondary benchmark was also installed, flagged, and sketched in the instance that the primary benchmark was consumed by the slide.

After benchmarks were established, a site for the total station was located. A site was selected that allowed clean line of sight for the total station laser to both the

benchmark and the entire bank failure area without having to relocate the total station and tripod. Upon finding a suitable location, the tripod was set up on a stable surface. The total station was located on top of a stable tripod and leveled.

Next one person gently traversed the bank failure site beginning at the top of the site, holding a prism on top of a level rod. The second person used the total station to aim the laser at the prism. Once the laser from the total station hit the prism, the total station provided digital x, y and z coordinates. Coordinates were taken at a density of at least one coordinate per square meter. Coordinate density was increased to every 0.1 to 0.3 meters in instances of uneven ground, changes in slope, or to document the presence of gullies and other features on the hillslope. Using this protocol, two individuals were able to complete two sites in a single day.

Each x, y, and z total station coordinate was recorded. These coordinates were entered into Microsoft Excel. The baseline 2004 coordinates were compared with coordinates from 2005 to track soil movement and loss into streams and calculate the hillslope volume of soil delivered to the streams. Vegetation within any given control or treated site was given a coordinate was also entered into the Microsoft Excel spreadsheet.

Digital photographs were taken of each control and treated site. All photographs were labeled, dated, and cataloged in a project photograph log. Additional photographs were taken of features of interest within each site, such as fissures, gullies, or notable vegetation.

Data Analysis

The Microsoft Excel spreadsheets were imported into Earth System Research Institute (ESRI) ArcMap 9.1 (ESRI, 380 New York Street, Redlands, California, www.esri.com) under the “Add x,y data” function. One spreadsheet contained 2004 data and the second spreadsheet contained 2005 data. The data for each year was converted into a separate TIN file using the 3-D Analysis extension. Once a TIN file had been created for each year, it was possible to obtain calculated values for height, width, and slope. The Cut-Fill tool in the 3-D Analysis toolbar was used to determine the loss and gain of soil hillslope volume throughout the site. ESRI ArcMap 9.1 calculated hillslope volume based on the lowest coordinate points provided (Figure 6). This calculation was based on the creation of an arbitrary plain and not the actual failure plain under the soil surface. A 3-D image of data collected from Site 37 in 2004 is shown in Figure 7. This figure is representative of the 3-D models used to determine net gain or net loss of soil from all twenty hillslopes. One model was created for 2004 data a second model for 2005 data. The models were overlaid, as shown in the timestep process in Figure 8.

Using NCSS statistical software (Hintze 2001), the net gain or loss of hillslope soil volume data obtained from ArcMap 9.1 was analyzed to determine whether treated sites experienced less erosion than untreated sites. In an attempt to control the standard deviation and obtain a reasonable probability level, the log of the hillslope volume data

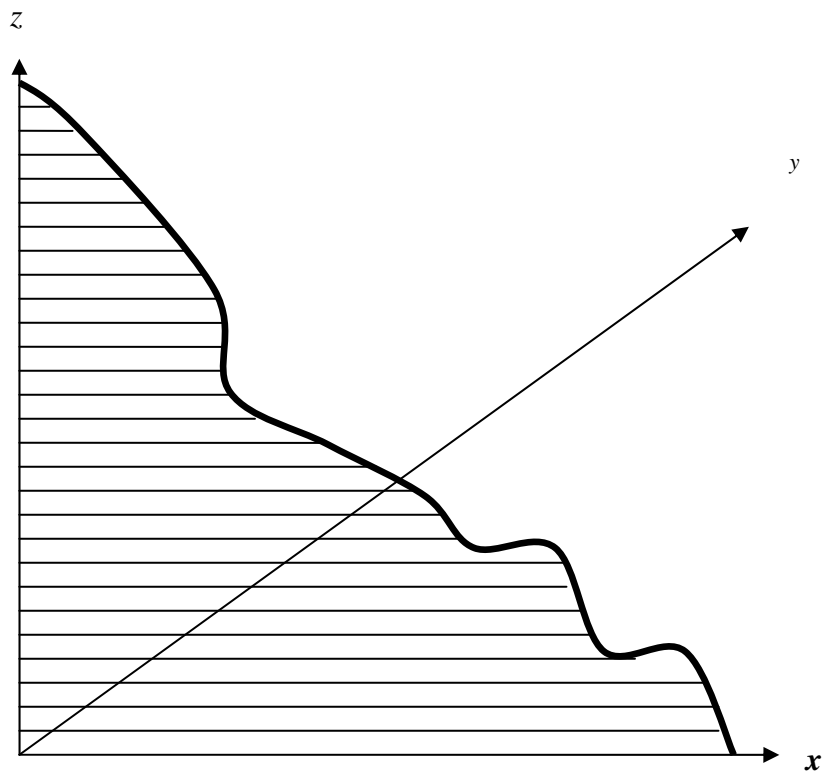


Figure 6. Calculating hillslope volume in ESRI ArcMap 9.1 based on arbitrary surface plains created by the software.

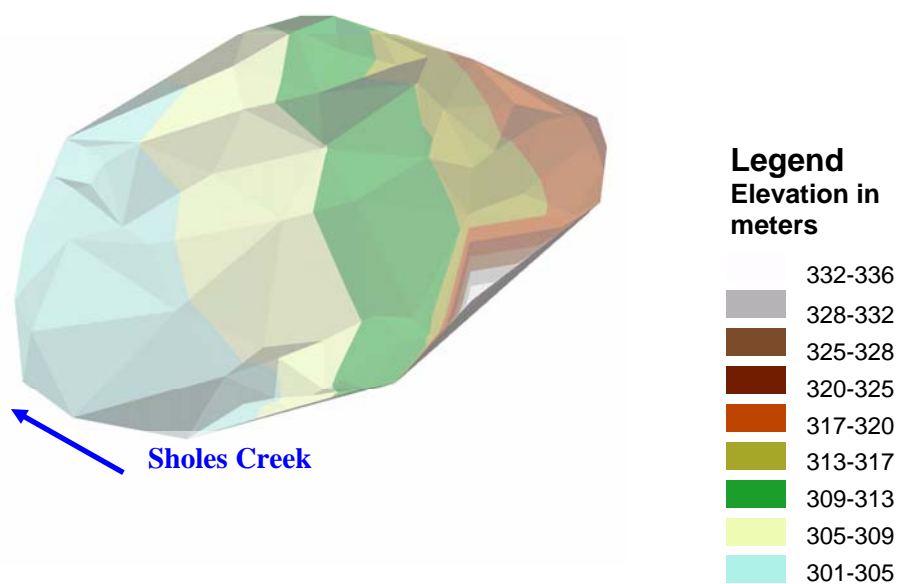


Figure 7. 3-D model of Site 37 created in ESRI ArcMap 9.1 using 2004 baseline data with a 305 meter base elevation.

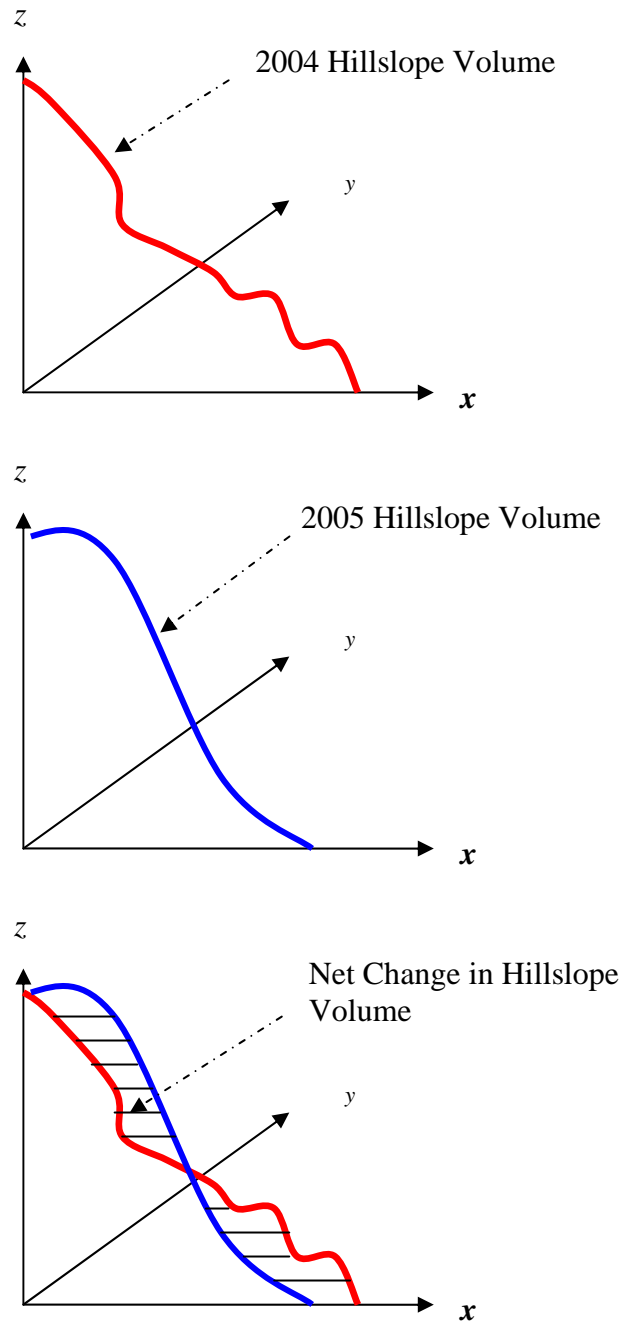


Figure 8. Timestep calculation of net change of hillslope soil volume.

was taken. The data was first analyzed using a Hotellings T-Test, which does not require normality.

After running the Hotellings T-Test, sites were grouped into ten pairs, with each pair containing one treated and one control site. Determination of the pairs was based on combining most-like sites. The first criterion in site pairing was to combine control and treated sites that were closest in proximity. In several instances, a control and treated site were directly across the stream from one another or next to each other. After pairs were matched based on proximity, remaining sites were paired based on similarities in hillslope surface area. The largest remaining control site was paired with the largest remaining control site and so on.

RESULTS

Slopes, hillslope area, and hillslope volume of treated and control landslides were statistically compared to evaluate whether or not bioengineered willow fences successfully mitigate sediment contributions to Fourmile and Sholes Creeks. Documentation of first-year landslide conditions, selected pair combinations, statistical results, and statistical interpretation are presented below. The results do not support the hypothesis of this study.

Data detailing first-year landslides conditions for control, treatment, and rapid survey sites are given in Tables 2 and 3. Table 2 outlines the general first-year conditions of the ten control and ten treated landslides. Documented conditions include hillslope surface area, hillslope volume, slope, and watershed area. When combined, the twenty landslides in Table 2 include to 15,065 cubic meters of hillslope volume.

Table 3 summarizes results of the rapid surveys completed on the additional twenty landslides that were not considered control or treated landslides. Maximum height and width and slope of these sites are also included.

Hillslope Area and Slope Comparison of Paired Combinations

The percentage slope and hillslope surface area values of the paired combinations are detailed in Table 4. In addition to identifying the ten control-treatment combinations,

Table 2. General first-year site characteristics of landslides.

Site	Stream	Hillslope Surface Area <i>Sq. Meters</i>	Hillslope Volume <i>Cubic Meters</i>	Ave. Slope <i>Degrees</i>	Watershed Area <i>Hectares</i>
Controls					
2C	Fourmile	66	175	53	130
3C	Fourmile	53	72	52	434
4C	Fourmile	118	257	53	87
5C	Fourmile	173	309	55	286
6C	NF Fourmile	70	66	53	197
7C	NF Fourmile	338	73	46	169
8C	NF Fourmile	234	547	46	169
9C	NF Fourmile	57	53	53	127
10C	Sholes	105	369	52	571
11C	Sholes	124	876	44	641
Treatments					
20	Fourmile	262	809	44	107
21	Fourmile	150	208	43	111
25A	Fourmile	44	49	53	130
27	Fourmile	968	1434	40	434
31	Fourmile	165	345	43	97
32	Fourmile	196	632	44	81
15	NF Fourmile	518	1877	43	148
18	NF Fourmile	63	92	51	197
26	Fourmile	304	884	39	143
37	Sholes	1108	4525	43	641

Table 3. Summary of rapid survey results.

Site	Tributary	Height <i>Meters</i>	Max Width <i>Meters</i>	Ave. Slope <i>Percentage</i>
A	Fourmile	2	9	109
B	Fourmile	3	4	110
C	Fourmile	9	11	69
D	Fourmile	17	14	39
E	Fourmile	7	9	139
F	Fourmile	18	17	118
G	Fourmile	5	5	96
H	Fourmile	5	10	81
I	Fourmile	14	12	84
J	Fourmile	12	17	75
K	Fourmile	9	7	106
L	Fourmile	52	52	91
M	Fourmile	34	27	84
N	Fourmile	30	25	95
O	Fourmile	55	55	96
P ²	Fourmile	Unknown	59	Unknown
Q	Fourmile	8	11	72
R	Fourmile	23	19	89
S	NF Fourmile	28	28	65
T	NF Fourmile	32	26	95

² The immense size of this earth flow made it impossible to safely measure the slope distance and percent slope with a range finder or a measuring tape. Review of air photos would be necessary to accurately estimate the size of this earth flow.

Table 4. Pair combinations with slope and hillslope area comparisons.

Pair	Control Site Number	Treated Site Number	Control Hillslope Surface Area <i>Sq. Meters</i>	Treatment Hillslope Surface Area <i>Sq. Meters</i>	Control Slope <i>Degrees</i>	Treatment Slope <i>Degrees</i>
1	2C	25A	66	44	53	40
2	3C	32	53	196	52	44
3	4C	31	118	165	53	43
4	5C	15	173	518	55	43
5	6C	21	70	150	53	43
6	7C	27	338	968	46	40
7	8C	37	234	1108	46	43
8	9C	20	57	262	53	40
9	10C	26	105	304	52	39
10	11C	18	26	63	44	51
Average			124	378	50	44

this information helps to determine if the two categories of landslides are similar or dissimilar. The data in Table 4 indicates that the two categories of landslides used in this research were dissimilar. Treated landslides were, when averaged, significantly greater in hillslope surface area than their paired control landslides by 33%.

This assertion is further supported by a Paired T-Test using NCSS Statistical Software (Hintze 2001). The Paired T-Test compared the hillslope surface areas of control and treated landslides, providing a null hypothesis that there was no detectable difference between the surface areas of each group. The Paired T-Test resulted in a probability level of 0.04. As 0.04 is less than 0.05, the null hypothesis is rejected, meaning control and treated sites differ in surface area.

Treated landslides were less steep than their paired control landslides in nine of the ten pairs. The ten control sites averaged a slope of 50 degrees, while treated sites averaged a slope of 44 degrees. The paired comparisons of hillslope surface area and slope are dissimilar between control and treated landslides largely due to three very large treated landslides, Sites 37, 27, and 15. Control landslides of similar scale were simply not present within the study area. Sites 37 and 27 were more than three times as large as even the largest of the treated landslides. The remaining treated landslides were more proportionately scaled in hillslope surface area and hillslope volume relative to control landslides.

Control and treatment slopes were compared using 2004 data to support that the two populations had dissimilar slopes. A Paired T-Test was used to evaluate the null

hypothesis that there was no difference between control and treatment slopes. The Paired T-Test resulted in a probability level of 0.01. Thus the null hypothesis is rejected and the two populations are indeed different.

The primary reason treatment landslides were generally larger in hillslope surface area and hillslope volume than control landslides is that the Mattole Restoration Council consciously decided to treat those landslides that were the largest and most likely to contribute sediment to the watershed. The leftover untreated landslides, from which the controls were chosen, were smaller.

All three types of T-Tests used to compare changes in hillslope volume between control and treated sites yielded the same probability level. Attempts to transform the data by taking the log of the change in hillslope volume and obtain more reasonable statistical results were not successful. Despite the mathematical data transformation, the results remained statistically insignificant. A Two-Sample Hotelling's T-Test, using unpaired data, a Hotelling's Paired Sample T-Test, and a Paired T-Test demonstrated a probability level of 0.32. The Hotelling's Paired Sample T-Test and the Paired Sample T-Test used paired data of control and treated sites. In all three statistical tests appropriate for this data set, the resulting probability level indicated a weak relationship and was significantly out of range of the 0.05 target value required to ensure statistical significance.

Cumulative frequency distributions (Figures 9, 10), of first year change in hillslope volumes for control and treated sites indicate the majority of landslides in both

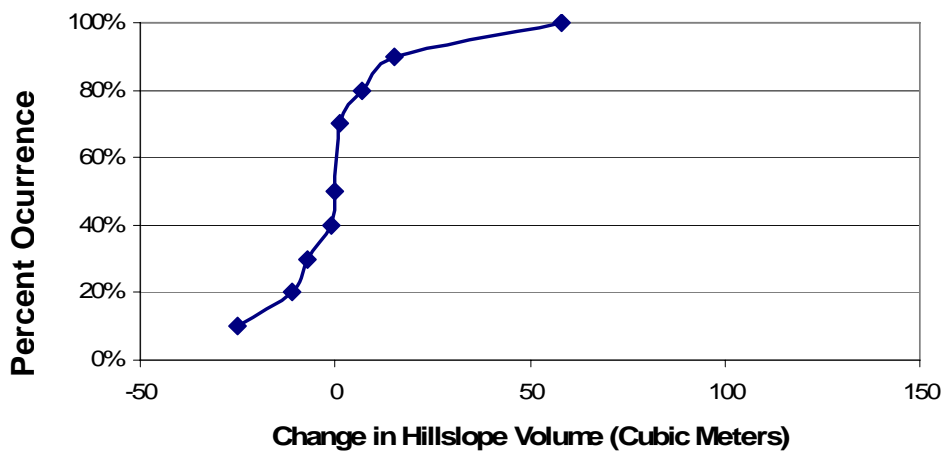


Figure 9. Cumulative frequency distribution for change in hillslope volume for control sites.

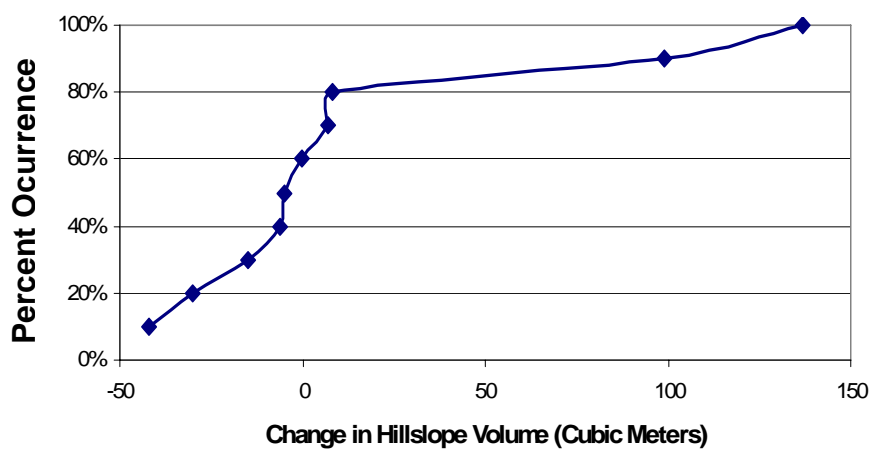


Figure 10. Cumulative frequency distribution for change in hillslope volume for treated sites.

categories experienced a net gain or net loss of hillslope soil volume between -50 and 25 cubic meters. There were several treated site that experienced a significantly larger loss in hillslope soil volume (Figure 10) relative to the change in hillslope volume experienced by control sites.

Slope and Hillslope Volume Results

Among control and treatment sites, landslides with shallower slopes experienced a larger change in hillslope soil volume. This relationship is consistent for control and treatment landslides during both 2004 and 2005.

A linear regression analyzing the relationship between landslide slope and hillslope volume was done for both 2004 and 2005 control and treated site data. A representative linear regression plot section is shown in Figure 11. Data was log transformed in order to improve the large range in standard deviations that otherwise exist.

With linear regressions, an R-Squared value of zero represents no linear relationship. An R-Squared value of one represents a perfect linear relationship. The linear regression illustrated in Figure 9 of 2004 control site data had an R-Squared value of 0.52, while 2005 control site data in 2005 yielded an R-Squared value of 0.60. Similarly, the linear regression of 2004 treated site data had an R-Squared value of 0.58. The corresponding linear regression for 2005 treated site data resulted in an R-Squared value of 0.68. All four R-Squared values indicate that there is a weak relationship

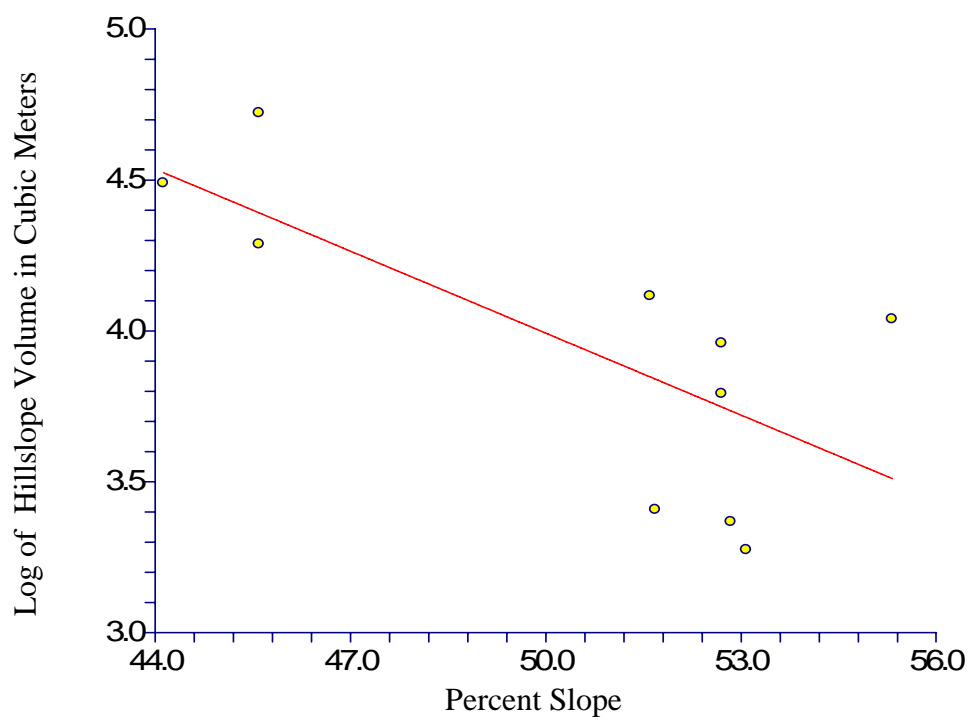


Figure 11. Linear regression plot section results, 2004 control site data, R-Squared of 0.52.

between slope and hillslope volume for landslides in this study. Fifty-two to 68 percent of the observed variation in hillslope volume is explained by the variation in percentage slope for the linear regressions.

Positive hillslope volume values represent a net gain in hillslope soil volume to the landslide. In many instances, the net gain of hillslope soil volume to the site is supported by the slope characteristics of the area surrounding the landslide. As observed in the field, the active slide areas were sometimes surrounded by older slide areas with characteristics of extremely unstable soil and previous erosion. In some instances the surrounding erosion processes immediately above and to either side of a given landslide became active and resulted in the net gain of hillslope soil volume to the slide. A negative hillslope volume value represents a net loss of eroded soil from the landslide and into the stream.

A change in the margins of the landslide could affect reference points used to calculate and compare changes in hillslope volume from one year to the next. However, the changes in landslide margins were not significant enough to cause concern and alter benchmark points used to obtain topographic measurements. Over the long term, if a landslide did continue to expand significantly, benchmark points could be affected.

The box plot in Figure 12 depicts the difference in net gain or net loss of soil volume from the landslide between 2004 and 2005. Figure 12 indicates that treated sites had a much larger range of net loss or net gain of hillslope soil volumes than control sites.

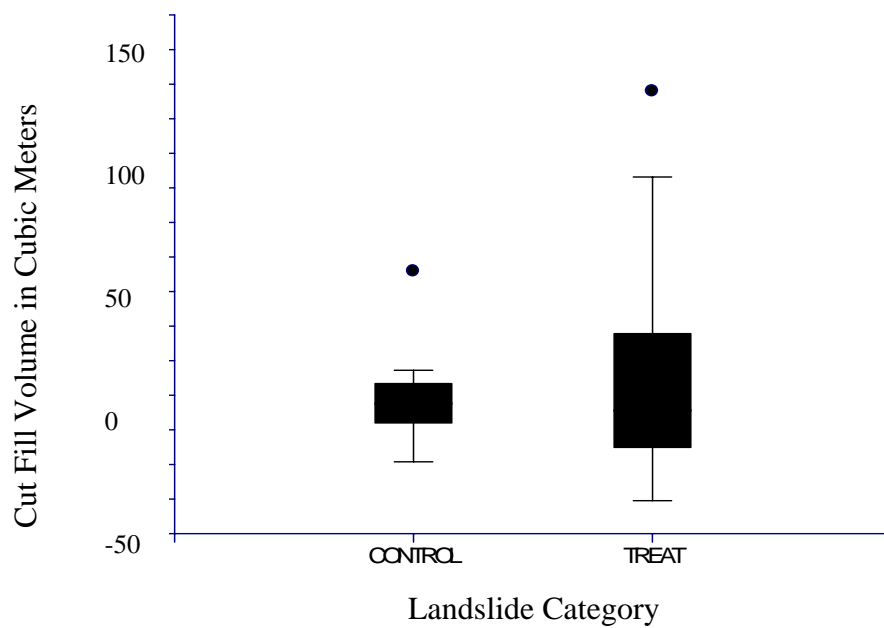


Figure 12. Box plot of net gain or net loss of hillslope soil volume from control and treated landslides, 2004 through 2005.

Table 5 lists the pairs of control and treated sites together with the changes of hillslope volume. There is no statistically significant difference that results from the data in Table 5. First-year monitoring resulted in the conclusion that there is no difference in net gain or net loss of soil volume from either control or treated sites. Thus, the hypothesis used in my research was not supported.

Additional Monitoring Results

Significant physical change was noted for treatment structures on both Sites 27 and 26. Both sites consist of large, active slides with significant gully action. Between 2004 and 2005, willow fence structures on both sites were completely backfilled with soil from the landslides above. Despite backfilling, the willow fences appeared completely intact and the willows sprigs were well sprouted. These physical site observations indicate that fences did result in a positive benefit to Fourmile Creek by withholding sediment from entering the stream.

Given available data, the hypothesis that backfilled willow fences are able to retain the actual amount of sediment gained or lost from a site is testable. To test this hypothesis, Table 6 estimates the total holding capacity of the willow fences at both Sites 26 and 27. Table 6 then compares these values to the actual erosion from the sites to determine if the fences alone actually work. Site 26 can hold up to two cubic meters of sediment (Table 6). The same site actually lost 42 cubic meters of sediment over one year's time—a ratio of 1:21. Similarly, Site 27 can retain up to four cubic meters of

Table 5. Net change in soil volume from 2004 to 2005.

Pair	Control Site	Change in Hillslope Volume <i>Cubic Meters</i>	Treated Site	Change in Hillslope Volume <i>Cubic Meters</i>
	2C	-11	25A	-6
2	3C	7	32	7
3	4C	58	31	-5
4	5C	1	21	-15
5	6C	1	18	0
6	7C	-1	27	137
7	8C	-25	26	-42
8	9C	-7	20	8
9	10C	0	15	-30
10	11C	15	37	99

Table 6. Estimated maximum holding capacity of backfilled willow fences.

Site	Estimate Fence Height	Estimated Fence Distance from Slide	Fence Length	Max. Volume Retained	Hillslope Soil Volume Loss/Gain from Slide	Was Fence Alone Sufficient?
	<i>Meters</i>	<i>Meters</i>	<i>Meters</i>	<i>Cubic Meters</i>	<i>Cubic Meters</i>	
26	0.5	0.3	15	2	-42	No
27	0.5	0.3	27	4	137	No

sediment but gained 137 cubic meters of sediment overall—a ratio of 1:34. The soil volume the willow fences were able to retain from entering the stream at their maximum capacity was significantly outweighed by the volume of soil that was physically observed to have been lost or gained by the site through erosion. For example, the willow fence at Site 26 has an estimated maximum holding capacity of two cubic meters, given its height, width, and distance away from the base of the landslide in 2004.

The basic geometry used to calculate an estimation of fence holding capacity is shown in Figure 13. Erosion at Site 26 between 2004 and 2005 yielded 42 cubic two cubic meters of soil. Despite the fence with a holding capacity of two cubic meters, it is possible that 40 cubic meters of soil was mobilized into Fourmile Creek. This indicates the effectiveness of the fences at mitigating soil contributions to the stream in front of large landslides is poor given the total hillslope soil volume that may be lost or gained.

Increases in Hillslope Area and Structure Survivability

In only one instance was it observed that a slide grew significantly in height or width. Control site 3C was observed to have tripled in height from a small slide five meters tall to a moderate slide nearly 18 meters high.

Given that all bioengineered fence structures were considerably smaller than their associated stream adjacent bank failures, an initial hypothesis was developed, expecting many of the structures to wash away altogether during high winter flows in the first year. Only willow fence washd away. The fence, located at Site 37, succumbed to a scouring

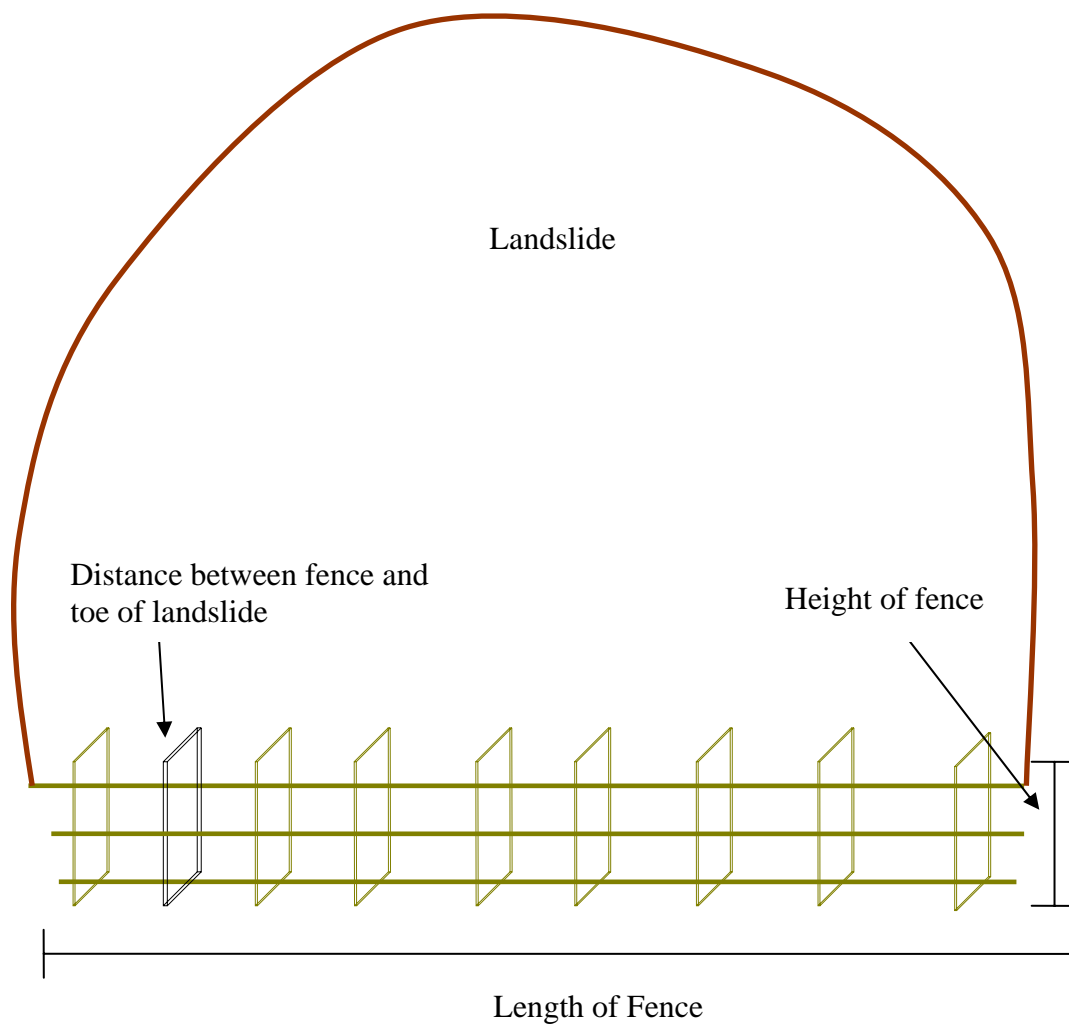


Figure 13. Estimating willow fence holding capacity.

pool immediately in front of the structure. The fences at the other nine treated sites survived. Given only one of the nine fences washed away in the first year, the initial hypothesis regarding fence survivability was not supported for the first year of monitoring. Future monitoring may experience a different result over the long-term.

In general, willow sprig survivability in the fence structures was poor to moderate with several exceptions, such as with Sites 26 and 27, noted previously. This can be remedied in the future by supplying the remaining fence structures with additional willow sprigs to encourage sprouting and riparian development.

In many ways, this one-year monitoring effort is merited by the fact that it was successful in establishing base conditions for the control and treated sites. In addition to acquiring physical topographic measurements, photographs and qualitative observations were also taken for each site. This information will be invaluable in the long-term analysis of the effectiveness of bioengineering treatments.

DISCUSSION

It was hypothesized that differences between control and treatment landslides would be detectable based on first-year monitoring results. This was not supported. First-year monitoring results indicated that the applied treatment did not mitigate the erosion of stream adjacent landslides into Fourmile and Sholes Creek. Resulting data representing changes in hillslope soil volume was not significant relative to whether the landslide was a control or treated site. This is not unexpected given this data represents results from only the first year of a long-term monitoring effort to be continued into the future. The result is further supported by the fact that the applied treatment is unlikely to demonstrate a significant difference in erosion, especially during the first year, given that the scale of the applied treatment relative to the scale of the treated landslides was grossly disproportionate in most cases.

First-year monitoring results indicate that the bioengineered willow fences did not prevent significant amounts of sediment from entering affected streams in this monitoring effort. However, Sites 17 and 26 did retain six cubic meters of sediment (Table 6). There was no detectable statistical significance between data from control sites and treated sites relative to the net gain or net loss of hillslope soil volume.

The statistical insignificance of analyzed data does indicate, however, that there is no detectable difference between erosion volumes from control landslides and landslides treated with bioengineered willow fences. This is to be expected.

It is often difficult to detect statistical results after the first year of an applied restoration treatment. Long-term monitoring and data is much more helpful in accurately determining the failure or success of an applied treatment.

Furthermore, the scale of the applied treatment relative to the scale of the landslides was grossly disproportionate. Eight of the ten treated sites were greater than 200 cubic meters. The largest fences may retain up to four cubic meters (Table 6). Thus, at least eight of ten treated sites were treated disproportionately to the scale of the associated landslide. Even in the two sites where the bioengineered willow fence was observed to have been completely backfilled, the ratio of maximum holding volume to the net gain or loss of hillslope soil volume was high. Given the unbalanced ratio between the maximum holding volume of any given fence and the potential volume of soil in motion, it is unlikely that the treatment, under all practical circumstances, will result in a detectable difference in erosion volumes, especially in the first year. It may be possible that the surviving bioengineered willow fences will have a more significant impact over the long-term as the willow sprouts establish and grow, thus increasing the maximum holding volume of the applied treatment. However, long-term monitoring is required to verify this hypothesis. A net gain or loss of hillslope soil volume between control versus treated landslides was not detectable given my data.

Further statistical analysis of the ten control and ten treated sites did not result in a trend of net gain or net loss of hillslope soil volume. A cross tabulation report generated by NCSS statistical software (Hintze 2001) indicated that of the ten control sites, four resulted in a net loss of soil while six resulted in a net gain of soil. Similarly, of the ten treated sites, six experienced a net loss of soil while four experienced a net gain of soil. These results indicate no difference among control or treated sites relative to preference for a net gain or net loss of hillslope soil volume.

The relationship between hillslope soil volume and slope is largely an artifact of ESRI ArcMap 9.1's calculation of hillslope volume (Figure 6.) This study found that landslides with larger hillslope volumes were less steep than landslides with smaller hillslope volumes. Landslides with larger hillslope volumes, shown in blue, are less steep than landslides with smaller volumes, shown in red (Figure 14).

Possibilities for Improving Treatment Effectiveness in the Future

The maximum holding capacity of successfully backfilled willow fences was negligible when compared to the actual volume of hillslope soil that left or entered the landslide (Table 6). The effectiveness of the treatment may be improved in the future by terracing fences up the base of the landslide to allow for more volume retention over time.

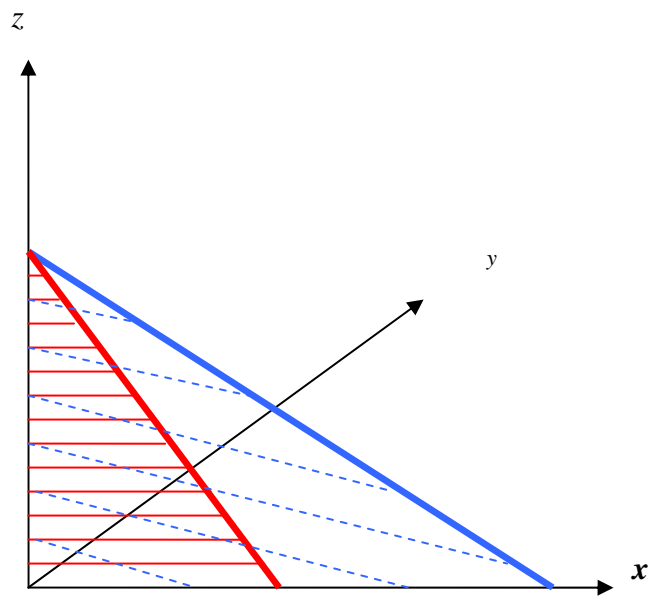


Figure 14. Relationship between hillslope volume and slope.

The combined results of the rapid survey (Table 4) with site observations for control and treated sites (Table 3) demonstrate that Fourmile and Sholes Creek watersheds exhibit extremely high erosive potential and landslide occurrence. Both streams are well saturated with stream adjacent landslides, many of which are quite large. Even if the applied treatment was 100% effective in all applications, there may be a diminished effect in the observed mitigation of soil that would have otherwise entered Fourmile and Sholes Creeks. Because there is so much sediment entering Fourmile and Sholes Creeks from landslides that were either not treated or perhaps are realistically untreatable, any gain from successfully treated sites may be hindered by the unfortunate reality that a disproportionate supply of sediment will still enter the stream each year.

As documented in the 2003 Total Maximum Daily Load (TMDL) assessment for the Mattole River watershed, 1,900 tons per square mile enter the eastern subbasin of Mattole River streams from natural sources alone (Environmental Protection Agency 2003). Natural sources are defined by the US Environmental Protection Agency as mass wasting and stream bank erosion. This is consistent with the considerable landslide density documented in Fourmile and Sholes Creeks, the two largest streams in the eastern subbasin of the Mattole River watershed. Another 6,800 tons per square mile per year enter the same area from road related erosion. An additional 840 tons per square mile per year are contributed from timber-related activities. All together, 9,500 tons per square mile per year are entering the 79 square mile area contained by Mattole River watershed eastern subbasin streams, including Fourmile and Sholes Creeks (Environmental

Protection Agency 2003). Given this context of extraordinary sediment delivery to the streams, it is unlikely the applied treatment will result in a detectable reduction in sediment despite the considerable effort given to the approach.

As a whole, landslides are difficult to mitigate and stabilize, especially when they are located in areas as remote as Fourmile and Sholes Creeks where heavy equipment is not an option and all labor must be done by hand. Additionally, unstable underlying geology may in fact make restoration impossible despite the technique or variety of techniques applied to a particular site. A successful treatment to mitigate sediment throughout an entire watershed such as the Fourmile or Sholes Creek watershed would have to be uniformly applied to all landslides. An effective treatment would also likely have to be more substantial than a short, willow fence. At this point in time, such a remedy is cost prohibitive. This is likely a significant factor in the selection of the bioengineering technique applied to the treated sites in the first place.

Sources of Error in Monitoring

The most significant source of potential error in this analysis is the lack of a repeatable grid that can be used to acquire x, y and z data for a given landslide. Topographic coordinates were taken based on changes in slope throughout the slide body, landslide boundaries, and physical access. Topographic coordinates were not taken equidistance apart. As a result, topographic coordinates for the same slide one year later were often taken in different locations throughout the slide body than the year prior. It is

possible that the lack of a repeatable grid could result in a calculated net gain or loss when in fact the landslide had not changed in hillslope soil volume whatsoever. This potential error may affect estimations of net soil gain or loss when a very small percentage of the total hillslope soil volume experienced change. However, the potential error is likely not substantial enough to inhibit detection of large changes in hillslope soil volume.

In the cases of some landslides, a potential source of error comes from the inability to traverse the entire site due to difficult terrain, vertical slopes, or thick vegetation. At times it was simply impossible to reach a certain portion of the slide with the stadia rod and prism to obtain topographic information with the total station. These instances were documented in field notes for the respective control or treated sites. The lack of topographic information for specific portions of some landslides does constitute a potential source of error. Using a total station with the capacity to take an x, y, and z measurement by reflecting off the ground will help to alleviate this potential source of error in the future.

Oftentimes the designation of the edge of a landslide was obvious. In such cases, the edge was demarcated by a sharp edge or abrupt change in vegetation or soil profile. However, the edges of some landslides were blurred within the same soil or vegetation profile, making it difficult to determine where the landslide began or ended. This created the potential for designating the edge of a landslide in two different locations from year, thus yielding misinterpretation of hillslope surface area and hillslope volume

calculations. This error can best be avoided by careful notation of field observations and photographs of the landslide in question.

ESRI ArcMap 9.1 Geographic Information System (GIS) software was used for computing net gains and losses in slope, area, volume, and change in volume (Cut Fill) for all control and treatment landslides assessed using this monitoring protocol. Many of these 3-D Analyst surfacing functions require the use of averaging. Particularly with small sites, more confidence could be placed in the results of the GIS analysis if more x, y, and z coordinate points were available for ArcMap 9.1.

Future Monitoring Efforts Utilizing this Protocol

Future monitoring efforts utilizing this protocol will be well served to use a total station with the capacity to acquire data by merely reflecting off the surface of the landslide. Surface-based light detection and ranging data may also be useful to this type of application in the future. Eliminating the need to physically traverse the landslide with a stadia rod and prism will allow for data to be more easily obtained using a grid system that is repeatable from one year to the next. A total station that has the capacity to acquire data by reflecting off the surface of a landslide will also save time and labor costs in the field, as data can be acquired quicker.

CONCLUSION AND RECOMMENDATIONS

Long-term monitoring of both control and treated stream adjacent landslides in Fourmile and Sholes Creek will be necessary to determine if the applied treatment is an effective technique to mitigate sediment contributions to the Mattole River watershed. While the analyzed first-year data indicates that the bioengineered willow fences did not reduce erosion, it is possible that erosion rates from treated or control sites could change in the future. For example, as the willow sprigs in the bioengineered fences establish over time to create a riparian buffer between the landslide and the stream, erosion rates may decrease. However, long-term monitoring is needed before any final determination of the effectiveness of the applied treatment can be ascertained.

As observed with Sites 26 and 27, the bioengineered willow fences at both sites were completely backfilled by sediment from the landslide above the applied structure. Even at their maximum capacity, these fences were insufficient to prevent a significant amount of hillslope soil volume from entering the stream proportional to the total net gain or loss of soil from the active hillslopes (Table 6). Using multiple bioengineered fences to create a terrace effect up the toe of the slope may provide for additional volume storage and mitigate possible soil entry into the stream. Such a treatment runs the risk of blowout during heavy rainfall or stream flow. A blowout could result in the delivery of a large volume of soil over a very short period of time, potentially causing ecological harm.

During the summer of 2005, it was observed that many of the fences constructed the previous year contained an abundance of dead willow sprigs and a dearth of surviving willow sprigs. While the fence structure themselves were still standing, they were sometimes lacking live willow sprouts. These willow sprouts, over time, are what lend integrity to the entire project by surviving high stream flows and creating a riparian buffer. The bioengineered willow fences will be more likely to mitigate soil from entering the stream over the long term if willow survivability is high. High willow survivability will result in a more robust riparian buffer between the landslide and the stream in a shorter period of time. It is recommended that some of the bioengineered fences that experienced poor willow survivability between 2004 and 2005 be re-sprigged with willows during wet months.

Bioengineered willow fences in Fourmile and Sholes Creek ranged from 0.3 to 0.5 meters in height. These structures may have had a more significant impact on erosion rates if they would have been taller in some instances, thereby increasing their ability to prevent more soil volume from entering the stream. It is understood in this particular case that an unexpected cut in funding immediately prior to the application of the treatment resulted in the need to construct shorter fences in order to decrease project costs.

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