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Attachment 1
Shoreline Erosion Technical Memorandum

Geologic Technical Report

Shasta Lake Water Resources Investigation, California

Prepared by:

United States Department of the Interior
Bureau of Reclamation
Mid-Pacific Region

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Abbreviations and Acronyms

CP	Comprehensive Plan
NSR	North State Resources, Inc.
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RED	Redding, California weather station
SLWRI	Shasta Lake Water Resources Investigation
USACE	U.S. Army Corps of Engineers

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Chapter 1
Introduction

North State Resources, Inc. (NSR) prepared this Technical Memorandum to document an analysis of existing shoreline erosion rates of Shasta Lake and predicted rates associated with raising Shasta Dam. Data collected for this study will be used to assist the U.S. Department of the Interior, Bureau of Reclamation (Reclamation) in determining potential impacts to the environment related to the Shasta Lake Water Resources Investigation (SLWRI) report. The following evaluation is based on a review of existing literature and data, supplemented with site specific information obtained from the shoreline erosion investigation.

This memorandum is organized as follows:

- Introduction
- Methods
- Results and Discussion

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Chapter 2 Methods

2.1 Shoreline Erosion Conceptual Model

This analysis included the development of a conceptual model of the spatial and temporal components of shoreline erosion as a framework for field investigations, quantifying present erosion rates, and predicting future erosion rates. This is a process based model where the primary causes of shoreline erosion are characterized and the external erosion triggers are used to weight the relative erodibility of the shoreline. This model was developed using results from similar studies, the available precipitation, wind, and lake level data, engineering properties of the bedrock geology and soils, shoreline and hillslope topography, and measured erosion processes and rates from sequential historical aerial photographs and field investigations. There are very few existing reservoir shoreline erosion studies for a reservoir as large as Shasta Lake available to use as background and support for this analysis. This analysis uses readily available references to help characterize the process of shoreline erosion, verify the predicted shoreline erosion rates, and design mitigation measures.

2.1.1 Shoreline Zone Classification

The shoreline is broken into two zones for modeling purposes which helps account for the episodic nature of erosional events. The near shore zone is classified as the area above the 1,070 foot contour and represents the “bath tub” ring around the reservoir (Figure 2-1). The drawdown zone is classified as the area between the 1,070 foot contour and the 1,020 foot contour. The latter contour is used to represent the drawdown level that typically occurs to meet the U.S. Army Corps of Engineers (USACE) flood storage capacity requirements. The near shore zone is eroded by wave action when the reservoir is full. During drawdown periods, this zone erodes as a result of upland surface runoff, subsurface flow, and fluvial incision along stream channels and gullies. The drawdown zone is subject to reoccurring erosional forces as the reservoir level falls and rises. Wave action caused by wind and boat traffic is the dominant erosional force within this zone (Figure 2-1). This zone is also a depositional area during full pool conditions. Sediment deposited in this zone is remobilized as the reservoir is drawn down. Channel incision is common in this zone especially where stream channels intersect it, or the slope is steep and convergent.

Figure 2-1. Picture of Shoreline Showing near Shore and Drawdown Zones

2.1.2 Shoreline Erosion Lithotopo Units

The climate, bedrock geology, soils, and topography were used to stratify the shoreline into lithotopo units to spatially compartmentalize the landscape into areas with similar erosion processes and rates (Montgomery 1999). These units are used as the basis for the potential shoreline erosion calculations. Around Shasta Lake, the rate of shoreline erosion is highly dependent on the engineering properties of the underlying geology. These properties control the hillslope steepness and shape of the local topography, and influences the types and density of vegetation. Field measured erosion volumes at selected sites around the reservoir were used to predict erosion from areas of shoreline with similar geology, soil, slope, and vegetation characteristics. For the final potential erosion calculations, slope gradient was used to predict the erosion rate for areas not included in the field investigations.

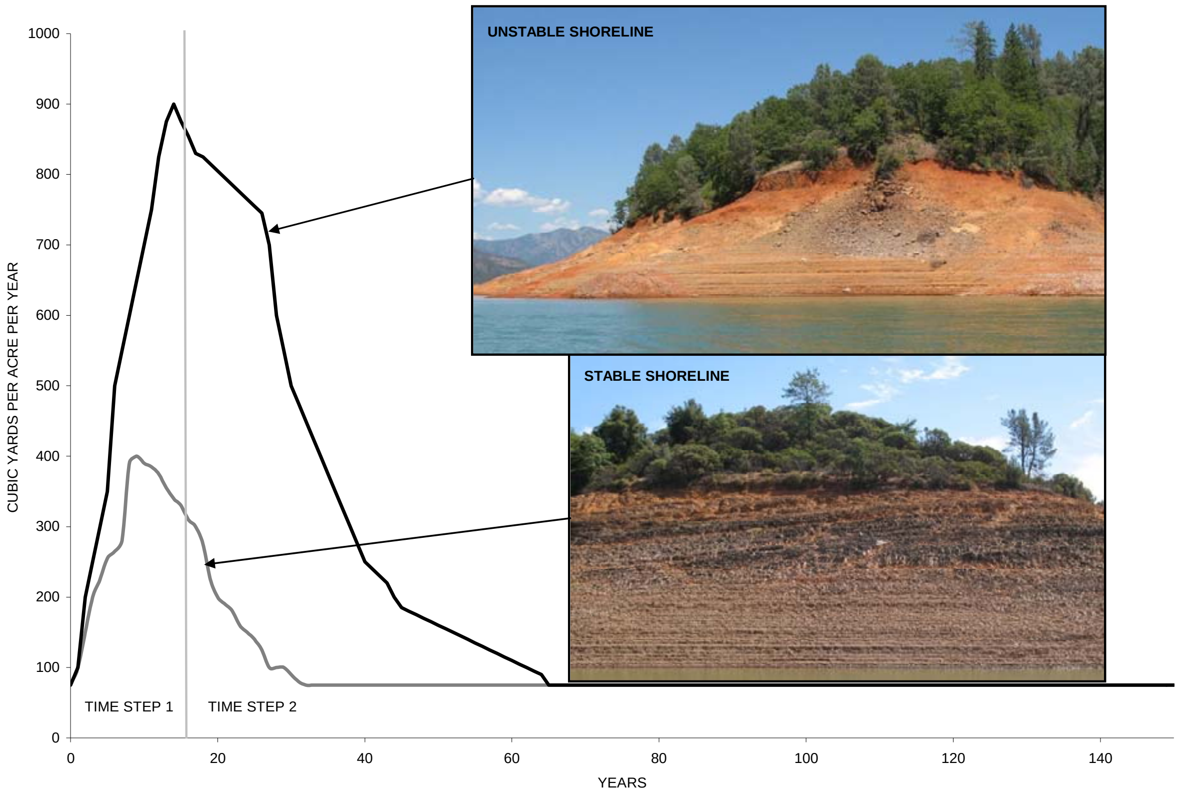
2.1.3 Shoreline Erosion Formation Time Steps

Shoreline formation is triggered when a reservoir is filled for the first time, and the long-term rate of shoreline erosion typically decreases as a reservoir ages (Morris and Fan 1997). The shoreline configuration is a function of both the landscape being inundated, size of the reservoir, and frequency and magnitude of fluctuations in reservoir level.

The lithotopo units described previously are used to represent the spatial distribution of shoreline erosion. In an attempt to represent the temporal component of shoreline erosion, this model compartmentalized shoreline development into three time steps. The first time step lasts for about 15 years and is when most of the erosion occurs (Morris and Fan 1997) (Figure 2-2). During this time, the inundated soils are fully saturated: as a result they lose cohesion and are subject to rapid erosion, transport, and deposition. Shoreline exposed in this drawdown zone is typically eroded to bedrock or resistant soil layers leaving an exposed surface that supports a limited amount of vegetation. Within this zone, stream channels and gullies rapidly incise into the underlying soil and rock.

The second time step can last between about 0 and 150 years. During this time the stable shoreline topography is developing through a sequence of slope forming events (Figure 2-2). For modeling purposes, the types of slope forming events were classified by lithotopo unit since there are several common processes that trigger and control erosion. The shoreline erosion inventory data suggest that stable hillslopes are typically associated with shallow soils on coherent bedrock forming steep topography (i.e., > 65 percent slope gradient), and unstable hillslopes are associated with deep soils on moderately steep areas (i.e., between 30 percent and 65 percent). Around Shasta Lake, stable shoreline formed rapidly during the first 15 years after inundation. Conversely, about 60 years later unstable hillslopes are still are still responding to erosional forces, and in various locations continue to erode at a very high rate (i.e., > 900 cubic yards/acre/year).

The third time step is used to represent the time frame when the shoreline slope is stable and the soil shear strength remains greater than the shear stresses acting on the slope. During this time frame, the erosion rate continues to decrease and eventually equals the upslope erosion rates. This analysis assumes that most of the shoreline around Shasta Lake will become stable as the reservoir ages, and the data suggests that currently,, about half of the shoreline has reached equilibrium.



Note: Approximate Location of Time Steps one and two shown. These Curves do not Represent Actual Time Series of Erosion

Figure 2-2. Hypothetical Curves Showing Short- and Long-Term Shoreline Erosion Rates for Stable and Unstable Lithotopo Units

2.1.4 Shoreline Erosion Causes and Triggers

This analysis classified slope forming events within the confines of the primary and external factors controlling slope stability. Unstable slopes occur when the shear strength of a soil layer is less than the shear stress acting on the layer. Shear strength is influenced by the soil cohesion, the soil to rock contact, vegetation types and root depths, and subsurface moisture content (Sidle and Ochiai 2006). For modeling purposes, this analysis assumes that the primary factors that cause slope failure along the shoreline are related to the climate, topography, engineering properties of the bedrock geology and soils, and vegetation. It also assumes that external factors that trigger slope failure include erosion at the toe of the slope due to wave action and surface runoff, vegetation removal by land management and wildland fire, and increased groundwater levels as a result of upslope seasonal groundwater recharge and lake level management. Shoreline vegetation is most often altered by fire: however, land development; mining; and logging activities remove shoreline vegetation as well.

Reshaping of the shoreline toe by wave action reduces the shear strength of the slope and is one of the main external factors triggering shoreline erosion (Morris and Fan 1997 and Elci and Work 2003). These events occur when the reservoir is full and waves caused by wind and boat traffic are able to erode the exposed soils. For Shasta Lake, annual water level data show that the reservoir is likely to fill 20 percent of the time, the reservoir is normally filled between mid-April and mid-May, and it remains full for two to four weeks on average. During wet water years when the reservoir is filled, the shoreline toe is eroded by waves. Typically, during this time period the upland soils are not fully saturated like they as they would be during the wet season. Subsequently, during dryer years when the reservoir does not fill the slopes readjust to a stable angle. In extreme cases, debris flows and slides have formed that continue to migrate upslope and laterally (Figure 2-2). Typically, it takes several decades for these mass wasting features to reach a stable balance between shear strength and shear stress.

There are several other external disturbance factors that can trigger shoreline erosion as a result of their impact on wave action, surface runoff, upland erosion, and groundwater recharge. These processes can both re-activate shoreline erosion and extend the amount of time it takes for a given slope to reach a state of equilibrium.

Boat traffic is a significant source of wave action that causes erosion along the shoreline. Since Shasta Lake is in a drawn down from about June through November, boat generated waves provide erosional forces during the timeframe beyond the period when winter storms are generating wave action.

Land development around Shasta Lake triggers shoreline erosion. Grading, vegetation removal, and paving increase the hardscape around the shoreline and can cause increased surface runoff and erosion. Roads associated with land development can impact the surface runoff patterns and concentrate flow causing channel incision and gully erosion. Landscape disturbances associated with mining activities contribute to shoreline erosion as well. Around the reservoir, large areas were denuded of vegetation and continue to be subjected to erosional processes 80 years after the mining operations ceased. Hard rock and surface mine operations have left a footprint on the hillslopes around Shasta Lake. One of the main impacts is from smelting on soil productivity. Many of these disturbances precede dam construction. Several large landslides have formed below mined areas and the shoreline is destabilized as a result.

Disturbance associated with severe wildland fire contribute to shoreline erosion. Large severe fires strip the uplands of vegetation and often cook the soils making them hydrophobic (less capable of absorbing precipitation). Following severe fire, upland runoff and erosion increase and cause channel incision and gully erosion along the near shore and drawdown zones. Removal of vegetation by fire along the shoreline reduces the shear strength of shoreline slopes as well.

2.2 Shoreline Erosion Field Inventory

2.2.1 Shoreline Erosion Reconnaissance Inventory

The shoreline erosion reconnaissance inventory was conducted on all of the arms of Shasta Lake. Inventory sites were chosen to characterize major and minor erosional features. Physical and erosional characteristics were gathered at each site by manual measurement or direct observation and then recorded. The categories of physical and erosional features are listed in Table 2-1. Where applicable, the descriptions and examples of the features are used in lieu of an actual method description because the methods used for characterizing some features are often based on an assessment of the terrain by the observer. These assessments often compared the features at each site to a field identified type locality for the varying grades of each feature. The data collected at each site was further used to delineate which sites to use as erosion plot sites and to determine which characteristics had the highest positive correlation with erosion rates.

Table 2-1. Summary of Shoreline Erosion Reconnaissance Inventory Site Counts by Feature and Lake Arm

Feature Attributes		Lake Arms							Totals Summary	
Feature	**Feature Category**	*Big Backbone Creek Arm*	*Main Body East Arm*	*Main Body West Arm*	*McCloud River Arm*	*Pit River Arm*	*Sacramento River Arm*	*Squaw Creek Arm*	**Site Count**	**% of Total Sites (1538 sites)**
Erosion Severity	High	23	50	43	57	10	64	17	264	17%
	Moderate	42	118	38	119	67	103	33	520	34%
	Low	62	195	30	125	129	146	65	752	49%
Slope Height	0'-3'	62	198	31	123	108	137	57	716	47%
	3'-6'	34	110	35	108	85	103	37	512	33%
	> 6'	31	55	45	70	13	73	21	308	20%
Erosion Activity	Chronic	125	363	110	295	204	308	109	1514	98%
	Episodic	13	45	40	53	27	47	5	230	15%
	Historic	12	4	1	6	1	3	2	29	2%
Dominant Erosion Types	Mass Wasting	29	70	50	82	41	64	3	339	22%
	Surface	13	88	16	64	30	66	1	278	18%
	Rill	0	0	0	0	1	1	0	2	0%
	Ravel	48	211	63	139	110	160	11	742	48%
	Gulley	15	2	1	6	0	4	0	28	2%
	Sapping	24	14	7	35	28	42	1	151	10%
	Wave	67	354	106	267	178	265	13	1250	81%
	Other	0	0	0	0	1	6	0	7	0%
Slope Angle	0-30%	43	165	42	103	40	122	51	566	37%
	31-60%	70	171	61	164	114	163	50	793	52%
	>61%	14	27	7	34	52	29	14	177	12%
Slope Break Type	Oversteep	80	197	49	82	60	116	52	636	41%
	Undercut	7	60	21	78	53	64	33	316	21%
	Both	36	99	38	132	87	129	29	550	36%
Material Types	Bedrock	3	1	2	3	4	31	6	50	3%
	Cobble-Boulder	21	2	1	19	35	46	2	126	8%
	Soil	103	361	108	281	169	249	108	1379	90%
Slope Armor	0-30%	101	354	110	276	173	260	107	1381	90%
	31-70%	26	9	1	24	33	53	6	152	10%
	>70%				1			2	3	0%
Vegetative Cover	Dense	9	71	53	75	40	65	14	327	21%
	Moderate	94	214	54	190	136	205	48	941	61%
	Sparse	23	78	4	36	30	43	52	266	17%

Erosion activity qualitatively measures the frequency of erosion at each site, and is divided into chronic, episodic, and historic frequency classes. The activity at each site was determined by evidence of recent erosional processes. For example, a site where silt is visibly deposited in the lake due to wave erosion is called chronic erosion activity. A site with a large gully incised into the slope with no visible signs of erosion is called episodic erosion activity. A site with a large slump with an established stand of mature vegetation growing on the slump block and the scarp is called historic erosion activity.

The dominant erosion type identifies the dominant mode of sediment transport at each site. Mass wasting was the dominant erosion type at a site if there was evidence of slope failure. Surface erosion was the dominant process if any evidence of sheet flow was present. Rill and gully are essentially the same erosional type and differ only in the depth of their incision into the soil. Here, a rill is an incision into soil caused by the overland flow of water where the width of the incision is generally greater than the depth. A gully is also an incision into soil caused by overland flow, but the depth is much significantly greater than the width. Ravel is the transport of sediment by rolling, bouncing, or sliding down the slope. Slopes with noticeable volume of fine unconsolidated sediment at their bases and no noticeable transport conduits have ravel as the dominant erosion type. Wave erosion and sapping are both caused by wave action. A site has wave action as its dominant erosion type if wave terraces are present or sediment was present in the water adjacent to the bank, but if wave action formed an overhang of the shoreline then the dominant erosion type was sapping. Other dominant erosion types were present along the shoreline of Shasta Lake, but the criterion for identification was based solely at the discretion of the observer.

Erosion severity is a qualitative measure of the rate and total volume of erosion. A site with a high erosion severity contains abrupt erosional features with physical evidence of a consistently high erosion rate. In short, a high erosion severity feature is an erosional feature that is actively eroding and enlarging and has not reached a state of equilibrium. A site with medium erosion severity has well defined erosional features where the activity is episodic or beginning to stabilize. Generally, moderate erosion features are not enlarging. For example, a slope with partially vegetated gully would be designated as medium erosion severity. Low erosion severity sites are sites with defined erosional features that are near a state of equilibrium. For example, a shoreline that is armored by bedrock or a site that has a slope gradient less than 30 percent are considered a low erosion severity sites.

Slope angle is a measure of the percent slope from the edge of water to the highest elevation of the site. Slope angle was measured using hand held clinometers by sighting the top of the slope from the edge of water at the time of survey.

Slope break type is categorization of the type of slope that was formed adjacent to the shoreline due to the seasonal water-level fluctuations within Shasta Lake. An oversteepened slope break is a slope where wave action or inundation has eroded the bases of a slope and caused a subsequent head-cut or upslope migration of the dominant erosional process. An undercut slope break is a slope that has been eroded by wave action or inundation causing an overhang within the slope. Any slope showing features of oversteepened and/or undercut slopes was designated in both categories.

Material type and the relative amount of slope armor were recorded for sites with un-eroded slopes. Initially, the dominant material size that composed the slope was determined by ocular assessment and recorded as one of three categories: bedrock, boulder-cobble, or soil. The aerial extent of area of the slope that was covered by the dominant material was determined by ocular assessment and recorded as one of three categories: 0-30 percent; 31-70 percent; and > 71 percent.

For sites with eroded slopes, the height of the eroded slope was measured from the bottom of the near shore zone (i.e., wave cut bank) to the highest point on the slope where evidence of erosion is visible using a survey tape. Each site was then recorded as one of three slope height categories: 0-3 feet; 3-6 feet; or 6 feet.

The aerial extent and density of vegetative cover was determined for each site using relative vegetative cover classes of: sparse; moderate; or dense. These categories were a qualitative measure of the proportion of vegetation cover to the amount of area at each site. The extent of vegetation cover was determined by assessing how much native surface could be seen if the observer looking down at the site surface from above the canopy. The type of vegetation was not taken into consideration when determining the amount of vegetation cover. If less than 20 percent of native surface could be seen, the site had dense vegetation cover. If between 20-80 percent of the native surface could bee seen, the site had moderate vegetation cover. If more than 80 percent of the native surface could be seen, the site had sparse vegetation cover.

2.2.2 Shoreline Erosion Plot Survey Methods

Shoreline profile surveys of selected areas along the shoreline of Shasta Lake were completed to characterize and directly measure existing and potential erosion volume. Erosion sites were selected to provide representation of the three erosion severity classes (low, moderate and high) mapped during the of Shasta Lake shoreline erosion inventory.

In 2002 and 2004, surveys were conducted on Big Backbone and Squaw Creek Arms using standard survey instruments (auto level, stadia rod, and survey tape). In 2007, additional surveys were completed on the Main Body East, Main Body West, McCloud, Pit, and Sacramento River arms using a Nikon 522 Total Station. The total station is accurate to +/- 0.01 feet at 500 feet and +/- 0.1 feet at 1000 feet. Both survey methods surveyed known local control points to ensure horizontal and vertical accuracy. The 2004 surveys also established benchmark elevations or control points using a sub-foot accuracy Trimble GPS and constructed permanent survey monuments for future use.

Up to two profiles were surveyed at each site to construct an average topographic representation of each site. Benchmark monuments were established, consisting of about one meter lengths of rebar driven into the ground. The benchmarks are assumed to represent the maximum reservoir elevation (1,070-feet mean sea level, NAVD88) in the absence of wind-generated waves. Transect distances were recorded along the profile sections, upslope to an estimated position twenty vertical feet above the benchmark (to correspond to the 1,090-feet elevation considered in the SLWRI), and downslope to the water surface. In 2004, several profiles in both Big Backbone Creek and Squaw Creek arms were re-surveyed from the benchmark monuments to the reservoir surface. The reservoir surface elevations recorded by the Reclamation gage at Shasta Dam at the time of the re-surveys were used to back-calculate the benchmark elevations for the re-surveyed profiles. For those profiles that were not re-surveyed, benchmark elevations were assigned based on the mean benchmark elevations of the re-surveyed profiles. Big Backbone Creek profiles were assigned the Big Backbone Creek mean benchmark elevation; Squaw Creek profiles were assigned the Squaw Creek mean benchmark elevation.

2.3 Existing and Potential Shoreline Erosion Calculations

Several steps were required to determine existing shoreline erosion volumes, rates, and erosional rates per acre at each site surveyed. The first step was to plot the existing slope surfaces from the erosion site surveys. Standard trigonometric survey calculations were performed to derive profile distances and elevations recorded from the surveys conducted in 2002 and 2004. Profile distances and elevations were directly recorded from the Nikon Total Station during the 2007 surveys. All horizontal distances were referenced from an arbitrary zero value at the benchmark, with down-slope (towards lake) distances assigned negative values and upslope distances assigned positive values. The length of the existing slope surface was surveyed from above the maximum anticipated water level (1,090 feet) down to the water level of the lake. Subsequently, the length and angle of the existing slope was estimated and projected down to a drawdown level of 1,020 feet.

The second step was to determine the projection of the pre-inundation slope surface. Calculations were made to generate curves representing estimated ground surfaces prior to inundation and wave erosion using two key assumptions:

- The height of the shoreline bank is representative of the depth of weathered material that was eroded following inundation.

- The weathered depth exposed on the shoreline bank remains uniform up- and down-slope. Consequently, the slope of the present wave-eroded shoreline bank is parallel to the slope of the pre-inundation surface. This suggests that erosion depth may be modeled based on the present shoreline bank height.

The third step was to calculate the volume of sediment removed since the inundation of the slope at each erosion site. The cross-sectional area was calculated between the existing surface and the projected pre-inundation surface along the transect line and between the 1,020 foot drawdown level and the existing full pool elevation of 1,070 feet. The actual cross-sectional area was calculated for each site using a built-in area-under-the-curve function available in Grapher™ software.

The cross-sectional area was used to calculate the total erosion volume produced at each erosion site under existing conditions. Each erosion transect was assigned a width of half of the transect length between the measured water level and the highest existing shoreline (1,070 feet). This designation standardized all of the erosion sites by creating an erosion plot area that is directly proportional to the length of the survey transect. The cross-sectional area was multiplied by the width of each erosion site to calculate the total eroded volume of sediment for the period of time since the reservoir was constructed, with respect to each site.

The existing annual shoreline erosion volume (in cubic yards per year) was calculated by dividing the total volume of eroded sediment by the number of years since the site was initially inundated. Shasta Lake was fully inundated about 60 years ago, so yearly erosion rates were determined by dividing total volume of sediment eroded at each site by 60 years. This model acknowledges that erosion rates most likely did not remain constant over the 60 year period, therefore the 15 year erosion rate was calculated as well, since most of the erosion occurs during time step one of the conceptual model. This also helps account for the episodic nature of shoreline erosion that has high annual variability.

The erosion rate was also calculated for each site (in cubic yards per acre per year). The erosion rate was calculated for each erosion site by dividing the yearly erosion rate by the area (in acres) of its erosion plot. In this manner, an existing unit erosion rate could be applied to other shoreline erosion inventory sites with similar attributes in order to estimate existing shoreline erosion within the footprint of Shasta Lake.

The potential shoreline erosion volumes and rates were calculated using the same assumptions that were used to calculate the existing rate. A critical assumption is that the landform upslope of the 1,070 foot elevation is similar to the slopes subject to erosion below this point. The transects that depicted the existing and estimated original ground surfaces from the maximum drawdown level (1,020 feet) to the projected highest shoreline (1,090 feet) were also used to calculate potential shoreline erosion. For transects that were used to calculate potential shoreline erosion, further calculations were made to generate curves that represented the subsurface layer below the present ground surface. This analysis assumes that the subsurface layer would be exposed after a twenty foot rise in the maximum reservoir water surface level (1,090 feet) and shoreline forming events. In most cases, a parallel model based on the vertical angle of the shoreline bank was employed. This means that the current angle where the bank meets the water surface will eventually be the same angle formed on the new inundated surface. A problem with this model involved some sites where a twenty foot rise in reservoir levels would completely inundate the site (the maximum upslope ground surface elevation was less than twenty feet above the present highest shoreline). In this case, it was assumed that the volume of future erosion could be based on the shoreline height, up to the highest ground surface elevation of the profile.

After the estimated subsurface layer was plotted against the existing ground surface, the annual volume of sediment eroded from the newly inundated slope was calculated. The cross sectional area was calculated between the existing surface and the subsurface along the transect line and between the highest existing shoreline level (1,070 feet) and projected highest shoreline level (1,090 feet). The actual cross-sectional area was calculated for each site using Grapher™. Each erosion site was assigned a width of ½ the transect length. The cross-sectional area was multiplied by the width of each erosion site to calculate the total predicted volume of sediment erosion after inundation of the slope to the projected highest shoreline.

The potential shoreline erosion rates (in cubic yards per year) were determined by dividing the total volume of eroded sediment by the number of years since the site was inundated. Two time spans, 15 and 60 years respectively were used to calculate the yearly erosion rates. These spans were selected to provide a range of erosion rates based on the relative rate at which a slope erodes to reach a state of equilibrium.

The unit potential erosion rate was also calculated for each site (in cubic yards per acre per year). The unit erosion rate was calculated for each erosion site by dividing each respective yearly erosion rate (15 or 60 years) by the area (in acres) of its erosion plot. In this manner, an existing unit erosion rate could be applied to other shoreline erosion inventory sites with similar attributes in order to estimate potential shoreline erosion within the footprint of Shasta Lake.

In an attempt to characterize the potential erosion volume and rate for 52 erosion plot survey sites that are based on the physical or erosional features of any area of shoreline within Shasta Lake, the potential shoreline erosion rates from each erosion plot were compared to the categorical data collected from the shoreline erosion reconnaissance inventory. Individual categories of physical and erosional features were plotted against potential erosion rates to determine if a strong correlation was present. Erosion severity and eroded slope height had the strongest correlation of all categories. This relationship was used to assign each erosion plot to one of eight categories based on the combined data of erosion severity and eroded slope height. The combined potential erosion rates from the plots are illustrated in Figure 2 for both time steps. New potential erosion rates (cubic yards per year) were assigned to each category by adding the average potential erosion rate to half of the standard deviation and rounding to the nearest increment of 50 feet. Low severity sites were all assigned the same potential erosion rates because there were no low erosion severity sites with an eroded wave height above three feet, and it is assumed that eroded slope height would have little impact on low erosion severity slopes.

Using this relationship, potential erosion rates can now be assigned to any of the shoreline survey reconnaissance sites based solely on its erosion severity and eroded slope height values. This allowed for an estimation of total volume of sediment eroded by arm and for the entire lake.

Chapter 3
Results and Discussion

3.1 Climate Data

3.1.1 Precipitation

Shasta Lake and the surrounding landscape experiences a Mediterranean-type climate with wet mild-winters and hot dry summers. The average annual precipitation measured at Shasta Dam is 64.1 inches. 80 percent of the precipitation occurred between the months of November and March. About 30 percent of the annual precipitation falls during September through December, and the remaining 50 percent falls between January and March. Large extended precipitation events are frequent during the wet months. Between the years of 1995 and 2007, the largest annual recorded 24-hour precipitation events ranged between 8.3 inches and 3.5 inches with a median event of 4.7 inches.

Based on existing historic climate data, it is assumed that enough precipitation falls to saturate most of the soils on the slopes within and adjacent to Shasta Lake by the end of December. A majority of the annual precipitation and large storm events occur after this time, between January and March, when the soils are saturated (Table 3-1). This suggests that large amounts of surface runoff and subsequent surface erosion occur during large storm events. Using this premise, it is assumed that a majority of the surface erosion is caused by large storm events between the months of January and March.

Table 3-1. Shasta Lake Average Annual and Monthly Precipitation Summary

Month	Average Precipitation (inches)	Percent of Total
January	11.47	18%
February	10.76	17%
March	10.79	17%
April	4.18	7%
May	2.8	4%
June	1.25	2%
July	0.26	0%
August	0.42	1%
September	1.63	3%
October	2.97	5%
November	7.86	12%
December	9.01	14%

3.1.2 Wind

Average annual wind speeds and wind directions were calculated for Shasta Lake for the period of 01/01/2003 to 12/31/2007. All calculations were made using historical data from a Redding, California weather station (RED) maintained by the USFS. Data from the RED station is used because it is the closest weather station to Shasta Lake that records wind speed and direction. The data used from the RED station are assumed to be representative of the reservoir, but variation in the average wind speeds and direction of travel are expected due to differences in local topography. Initially, raw wind direction data was given as a wind source direction, but in the summaries, 180 degrees was subtracted from the averages to calculate a direction of travel.

The median of the average annual wind speed for the study period is 6.1 mph, and the median annual direction of wind travel is 36 degrees (southwest to northeast). Average annual wind speeds vary slightly and range between 5.6 miles per hour and 6.4 miles per hour. The average direction of wind travel has some variation ranges between 33 and 70 degrees.

Annual average wind speeds and wind directions are plotted on a wind chart (Figure A-3) to further characterize the wind patterns of the study area. Wind speeds are divided into two categories based on a median annual wind speed of 6.1 mph. The orientation of the polygons on the chart represents the direction of travel within a range of 5 degrees. The relative length of each polygon (from the center of the chart) represents the number of years, or frequency, that the average annual direction of wind travel was within a specific 5 degree range. Within the wind chart, frequency is expressed as a percentage of the entire data set. The corresponding average annual wind speed is also projected and represented as smaller shaded polygons within the larger wind travel polygons. Their relative length, compared to the larger polygon represents the frequency at which a specific wind speed class coincided with the direction of wind travel.

The wind chart clearly shows that the dominant direction of wind travel is from southwest to northeast. From this trend, the assumption is made that the southwest facing shorelines of Shasta Lake will receive most of the energy produced by wind waves. However, one year within the data set varied noticeably from the median direction of wind travel. This could indicate that dominant wind patterns fluctuate regularly, but this assumption is not made here due to the limited size of the data set. In addition, there doesn’t appear to any correlation between the direction of wind travel and wind speed within the data set.

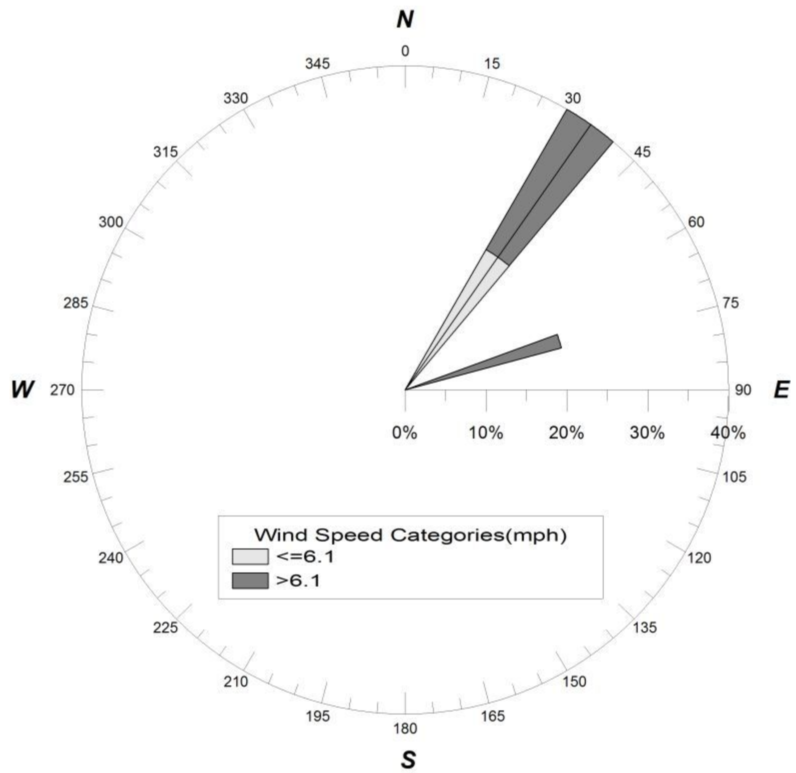


Figure 3-1. Wind Chart Showing Average Annual Azimuth of Wind Travel by Frequency Percentage and Proportionate Wind Speed Category for Redding, California Weather Station for 2003 – 2007

3.2 Shoreline Erosion Inventory Results

A total of 1,538 shoreline erosion reconnaissance sites were surveyed within the seven lake arms of Shasta Lake between 2002 and 2007 (Table 3-1). Site locations were defined in the field at any location where visual evidence of erosion was observed along the entire shoreline of Shasta Lake (420 miles). Additionally, the number of sites inventoried within each arm is proportional to the size of each arm relative to the footprint size of Shasta Lake. Of the 1,538 sites surveyed: 363 sites (about 24 percent of all inventoried sites) are located within the Main Body East Arm; 313 sites (20 percent) are located within the Sacramento River Arm; 301 sites (20 percent) are located within the McCloud River Arm; 207 (13 percent) sites are located within Pit River Arm; 128 sites (8 percent) are located within the Big Backbone Creek Arm; 115 (7 percent) sites are located within the Squaw Creek Arm; and 111 sites (7 percent) are located within the Main Body West Arm of Shasta Lake.

Site locations were selected to characterize the erosional features of each arm and Shasta Lake. Data was gathered at each site for the following erosional features: erosion severity, slope height, erosion activity, dominant erosion types, slope angle, slope break type, material type, slope armor, and vegetative cover (Table 3-1). At least one categorical value was recorded for each erosional feature, but multiple values were recorded for erosion activity, dominant erosion types, and material types. This redundancy occurs because more than one type of each category can be present at each site. Here, it is assumed that the summarized data of the shoreline erosion reconnaissance inventory accurately represents the shoreline features of Shasta Lake.

Erosion severity and slope height are related. If the frequency of categorical erosion severity sites is compared to the frequency of categorical slope height sites, the relationship is apparent. The data shows a total of 752 sites (or 49 percent) with low erosion severity, and 716 sites (47 percent) with a slope height of 0 to3 feet. A total of 520 sites (34 percent) have moderate erosion severity, compared with 512 (33 percent) sites that have a slope height of 3 to 6 feet. Additionally, 264 sites (17 percent) have high erosion severity, and 308 sites (20 percent) have a slope height of greater than 6 feet. Not only are the frequencies of the categorical features related, but they often occurred in discrete pairs at each site. This suggests that erosion severity, and possibly the erosion rate, increase as bank height increases. Erosion severity and slope height also correlated with measured erosion rates, and erosion severity and slope height combinations were the variables used to predict erosion rates.

Nearly all inventoried sites have at least one feature that is chronically eroding. For example, 1514 sites (98 percent) have evidence of chronic erosion activity. Additionally, 230 sites (15 percent) have evidence of episodic erosion activity, and 29 sites (2 percent) have evidence of historic erosion activity. The data indicate that the shoreline of Shasta Lake is actively eroding.

Wave erosion is the dominant erosion type of the sites inventoried, and dry ravel is present at nearly half of the sites. Evidence of wave action is recorded at 1250 sites (81 percent). Dry ravel is a dominant form of erosion at 742 (48 percent) sites. Mass wasting is evident at 339 sites (22 percent), and 278 sites (18 percent) have surface erosion as dominant form of erosion. Gullies, rills, or other forms of erosion are actively eroding the shoreline 37 sites (2 percent)

Nearly all (89 percent) of the sites of have a slope less than 60 percent, with 793 sites (52 percent) having a slope angle between 31 percent and 60 percent. Slope angles between 0 percent -30 percent are present at 566 sites (37 percent), but 177 sites (12 percent) have a slope angle greater than 60 percent.

There appears to be no visible trend with regards to the type of slope break present on the slopes of the sites. An oversteepened slope break occurs at 636 sites (41 percent), and 316 sites (21 percent) have an undercut slope break. However, 550 sites (36 percent) have examples of both types.

A soil horizon covers nearly all sites inventoried; 1379 sites (90 percent) of the sites have soil covering the slope. A cobble to boulder sized substrate covers 126 sites (8 percent), and 50 sites (3 percent) are exposed bedrock slopes.

There is limited amount of armor present on the shoreline slopes at the sites. Armor covers 0 percent to 30 percent of the surface area at 1381 sites (90 percent). A small portion, 152 sites (10 percent), have 31 percent -70 percent of the surface covered with slope armor, and only 3 sites have more than 70 percent of the surface armored.

Most (82 percent) of the sites have moderate or dense vegetation. Moderate vegetation cover occurs at 941 sites (61 percent), while dense vegetation covers 327 sites (21 percent). Sparse vegetation cover occurs at 266 sites (17 percent).

For a typical site, the average shoreline has less than a 60 percent slope which is covered by a soil horizon, moderately vegetated, with limited amounts of shoreline armor. Chronic erosion occurs on the slope due to wave action at the shoreline, and dry ravel occurs on the slopes above after drawdown of the water level. Erosion creates a slope height of 0 to 3 feet above the maximum water level of the lake. Even though erosion does occur, the nature of the erosion on the slopes causes erosion severity to be low.

3.3 Existing Shoreline Erosion Calculations

There are over 420 miles of existing shoreline around Shasta Lake, and about 50 percent of the shoreline has a low erosion severity. The remaining shoreline has moderate (35 percent) to high (15 percent) erosion severity. Most of the shoreline that is exposed during routine drawdown periods (i.e., drawdown zone) has been subject to substantial erosion and there is very little soil remaining after more than 60 years of reservoir operations.

The measured volume of existing shoreline erosion is summarized for the erosion inventory sites located around the entire reservoir. The measured shoreline erosion rate over the past 60 years, averages about 90 cubic yards per acre per year, per site. Within the first 15 years of dam construction (i.e., 1960) the average rate was likely about 360 cubic yards per acre per year. Most of the shoreline has reached a steady state of erosion similar to the uplands and erodes at a rate between 30 and 90 cubic yards per acre per year. Areas with high erosion severity that continue to migrate upslope, some of which are already above the 1,090 foot contour, are still eroding at rates greater than 400 cubic yards per acre per year.

The highest rate of shoreline erosion is occurring in the Sacramento River arm. For time step one (i.e., first 15 years), the average erosion rate for this arm was about 900 cubic yards per acre per year. For time step two the average erosion rate has decreased to about 230 tons per acre per (i.e., last 50 years). The McCloud River and Pit River Arms have the lowest rate of erosion at about 180 tons per acre per year for time step one, and about 45 tons per acre per year for time step two.

Presently, the shoreline erosion analysis indicates that at least half of the shoreline is in quasi-equilibrium and is in time step three of the conceptual model (Figure 2-2). For these stable areas time step two likely lasted between 15 and 30 years. About one quarter of the shoreline continues to erode at moderate rates. The remaining quarter of shoreline is eroding at very high rates. The shoreline erosion survey results suggest that the primary causes of continued shoreline erosion appear be oversteepened deep erodible soils where the slope shear strength is reduced by toe erosion and vegetation removal by fire and anthropogenic activities. The erodible soil types tend to be Holland Family, characterized as deep, with Fine-loamy texture and a meta-sediment parent material. The primary external trigger of this erosion is continued reshaping of the slope toe by waves and surface runoff. The combination of steep and tall banks formed by erodible soils limit the slope stability of these areas.

Erosion inventory results indicate that wave action was causing near shore and drawdown zone erosion at 87 percent of the sites. These data suggest that the prevalence of wave erosion appears to be independent of aspect and location within the reservoir. The severity of wind erosion appears to be greatest on shoreline facing south-west. During full pool conditions (i.e., May – June) winds tend to blow at above average speeds in a south-westerly direction (Figure 3-1). Sites with deep erodible soils that face west and south frequently have mass wasting features where wave erosion removes lateral support along the toe of the slope. Most of the mass wasting features are shallow debris slides or vertical bank collapse. Some of these features have an erosion rate greater than 1,000 cubic yards per acre per year.

The shoreline erosion plot survey results were summarized and analyzed to quantify the historic and existing rate of shoreline erosion and predict the future rate. Data from the erosion plot sites were used to calculate the existing eroded volume of shoreline in the drawdown zone. For each erosion plot, a survey form was completed, and the results were analyzed using categorical statistical methods to determine which variables measured as part of the survey could be used to predict the rate of erosion where erosion plot surveys were not completed. This analysis found that bank height and erosion severity observations tended to correlate with the measured erosion volume. The other measured parameters did not have enough variability to provide a predictive relationship. For example, 87 percent of the sites have waves as a dominant erosion mechanism and most of the bank material was classified as soil. Bank height and erosion severity were concatenated to produce a lookup table of measured erosion rates. For all the survey sites this relationship was used to estimate total shoreline erosion as described below.

3.4 Potential Shoreline Erosion Calculations

Inundation of additional lands surrounding Shasta Lake could result in increased soil erosion, mass wasting, and subsequent sedimentation of the reservoir and the tributaries that are influenced by fluctuating lake levels. Shoreline erosion commonly contributes a large portion of the sediment to reservoirs (Morris and Lan 1997). Sediment sources from receding shoreline contributes to reservoir sedimentation, can degrade water quality, result in loss of soil productivity, and impact infrastructure, cultural sites, and wildlife habitat.

Within the framework of the shoreline erosion conceptual model for Shasta Lake, this analysis used direct measurements of shoreline erosion to predict the potential shoreline erosion volume and the average annual erosion rate for the entire shoreline for the 15 year and 60 year time periods. In addition, potential shoreline erosion was calculated for three different dam raise alternatives: Comprehensive Plan (CP)1 (1,070 feet – 1,080 feet); CP2 (1,070 feet – 1,084 feet); and CP3 (1,070 feet – 1,090 feet) for each time period. The maximum raise of 20 feet was calculated first and these results were used to calculate erosion from the other alternatives. The eroded volume was proportioned based on the area of shoreline inundated by the CP1 and CP2 alternatives. Table 3-2 lists the 15 year time period shoreline erosion volume calculation results by Lake Arm and erosion severity risk. Table 3-3 lists the results for the 60 year time step.

Three different vegetation treatments have been proposed, common to all action alternatives: no treatment; overstory removal; and complete vegetation removal. This model assumes that the erosion rate will be higher for areas with partial or complete vegetation removal. Shoreline areas with overstory removal are assumed to erode 25 percent faster than no treatment areas, and areas with complete vegetation removal area assumed to erode 40 percent faster than no treatment areas. For areas with vegetation removal the shear strength of a treated hillslope will be less than a fully vegetated slope, and the treated slope is predicted to erode faster during the first time step of the conceptual model.

Table 3-2. SLWRI Potential 15-Year Shoreline Erosion Volume Calculations Between the 1,070 feet – 1,090 Feet Contours by Lake Arm and Erosion Severity Risk

Erosion Severity	Sacramento River Arm	McCloud River Arm	Mainstem East Arm	Pit River Arm	Squaw Creek Arm	Big Backbone Creek Arm	Mainstem West Arm	Total Erosion	% of Total Shoreline Erosion
High	47,176	34,782	27,102	18,900	12,487	16,354	22,965	179,767	23%
Moderate	116,561	81,595	88,809	69,026	39,393	33,110	19,107	447,601	58%
Low	41,815	23,932	36,190	11,099	16,305	6,725	3,623	139,689	18%
Total Annual Erosion	205,552	140,309	152,102	99,026	68,184	56,188	45,696	767,056	100%
% of Total Shoreline Erosion	27%	18%	20%	13%	9%	7%	6%	100%	

Table 3-3. SLWRI Potential 60-Year Shoreline Erosion Volume Calculations by Lake Arm and Erosion Severity Risk Assuming no Vegetation Treatment

Erosion Severity	Sacramento River Arm	McCloud River Arm	Mainstem East Arm	Pit River Arm	Squaw Creek Arm	Big Backbone Creek Arm	Mainstem West Arm	Total Erosion	% of Total Shoreline Erosion
High	11,204	8,419	5,970	4,308	3,150	3,722	5,004	41,777	19%
Moderate	29,176	19,416	19,958	18,752	10,768	8,527	3,698	110,295	51%
Low	18,273	11,468	15,398	6,613	7,295	3,513	1,703	64,262	30%
Total Annual Erosion	58,653	39,302	41,326	29,673	21,213	15,762	10,404	216,333	100%
% of Total Shoreline Erosion	27%	18%	19%	14%	10%	7%	5%	100%	

Assuming the available vegetation removal prescriptions between the 1,070 feet – 1,090 feet contours, for the first time step (i.e., 15 years after raising Shasta Dam) there will be about 767,000 cubic yards per year of shoreline erosion (Figure 3-2). After about 15 to 20 years, depending on water year type and operational variability, the expanded shoreline will develop, and to varying degrees stabilize (Figure 2-2). The total reservoir erosion is predicted to decrease by 70 percent between 15 and 60 year after raising the dam. The wetter the climate cycle the more rapid the shoreline is predicted to form. This analysis also calculated the 15 year erosion volume using the prescribed vegetation treatments and modeled higher erosion rates for shoreline with partial and complete vegetation removal.

Overall, a substantial portion of the shoreline is rated as having moderate erosion severity and most arms follow this trend. The Mainstem West Arm and the Pit River Arm are the exceptions, where over half of the Mainstem West has a high erosion rating and the Pit River has predominantly low to moderate rates. Shoreline erosion volume calculation results suggest that the total amount of erosion is directly a function of the shoreline area inundated independent of the severity of erosion. A positive linear relationship was found between the shoreline area inundated and the predicted erosion volume for the CP3 raise where:

$$y = 260.9x + 16{,}482$$

$$R^2 = 0.977$$

The model predictions indicate that the Sacramento River, McCloud River, and Mainstem East Arms will produce about half of the shoreline erosion. For the second time step (i.e., up to 60 years), the predicted annual shoreline erosion for the reservoir is 216,000 cubic yards per year (Figure 3-2). The long term erosion estimates reflect the first and second time steps of the shoreline erosion conceptual model where most of the erosion occurs in the first 15 years. After 60 years this model assumes that most of the shoreline has reached a state of equilibrium.

The highest rates of erosion are predicted to occur for the first 15 years after raising Shasta Dam (CP3, 1,090 feet) with a reservoir average of about 300 cubic yards per acre per year (Figure 3-3). The Mainstem West Arm has the highest predicted rate of erosion for the first time step. The predicted erosion rates for Big Backbone Creek, Pit River, and McCloud River Arms are greater than the reservoir average (Figure 3-3).

Shoreline erosion would increase as a result of implementing CP1, CP2, or CP3. For the first 15-years after raising the dam, the average rate of shoreline erosion would increase substantially. This increase varies between 90 cubic yards per acre per year to about 300 cubic yards per acre per year. For the first time step (i.e., 15-years), the total average annual volume of potential shoreline erosion from CP3 is about 767,000 cubic yards per year (Figure 3-2). Within 60 years of raising the dam, the average annual volume is predicted to decrease to 216,000 cubic yards per year (Figure 3-2).

Sediment delivery from shoreline erosion would likely be greatest in the Sacramento River Arm, Main Body East Arm, and McCloud River Arm. These three arms are predicted to deliver more than 66,000 cubic yards per year for the first 15-years after raising the dam (Figure 3-2). Within 60 years of raising the dam, the average rate for these arms is predicted to decrease to 19,000 cubic yards per year (Figure 3-2). The Mainstem West Arm and Backbone Creek Arm are predicted to have the lowest shoreline erosion rates, a 15-year average annual potential erosion volume of less than 26,000 cubic yards per year. The Pit River Arm is predicted to produce about 50,000 cubic yards per year and the Squaw Creek Arm about 35,000 cubic yards per year (Figure 3-2).

Assuming the available vegetation removal prescriptions between the 1,070-foot and 1,080-foot contours, for the first time step (i.e., 15-years after raising Shasta Dam) there would be about 421,000 cubic yards per year of shoreline erosion (Figure 3-2). After about 15 to 20 years, the new shoreline would develop and begin to stabilize (Figure 2-2). The total reservoir erosion is predicted to decrease by 70 percent between 15 and 60 years after raising the dam. The wetter the climate cycle, the more rapidly the shoreline is predicted to form.

The analysis also calculated the 15-year erosion volume using the prescribed vegetation treatments and modeled higher erosion rates for shoreline with partial and complete vegetation removal (see Methods and Assumptions above). Most of the shoreline would not have vegetation clearing which is about 60 percent of the total predicted shoreline erosion. The Big Backbone Creek, Squaw Creek, and Pit River Arms would have very little vegetation removal. The Mainstem West, Sacramento River, Mainstem East, and McCloud Arm would have substantial amounts of vegetation removal, which would result in higher short-term erosion rates. For these arms, areas treated by vegetation removal represent about half of the total predicted erosion for each alternative (Figure 3-4).

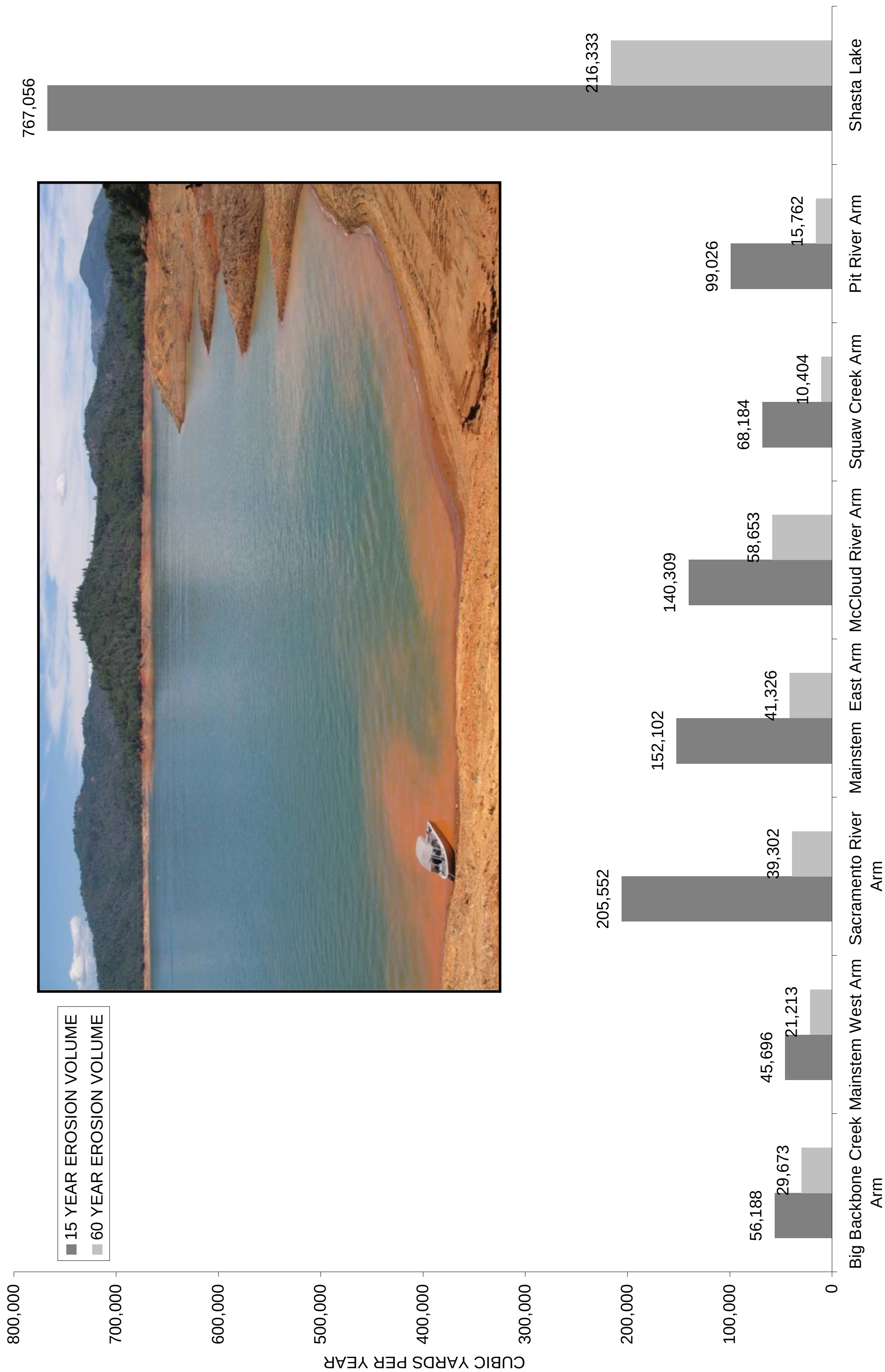


Figure 3-2. SLWRI 15- and 60-Year Potential Shoreline Erosion Volume Calculation Results by Lake Arm for the Shoreline Between the 1,070 feet – 1,090 Feet Contours

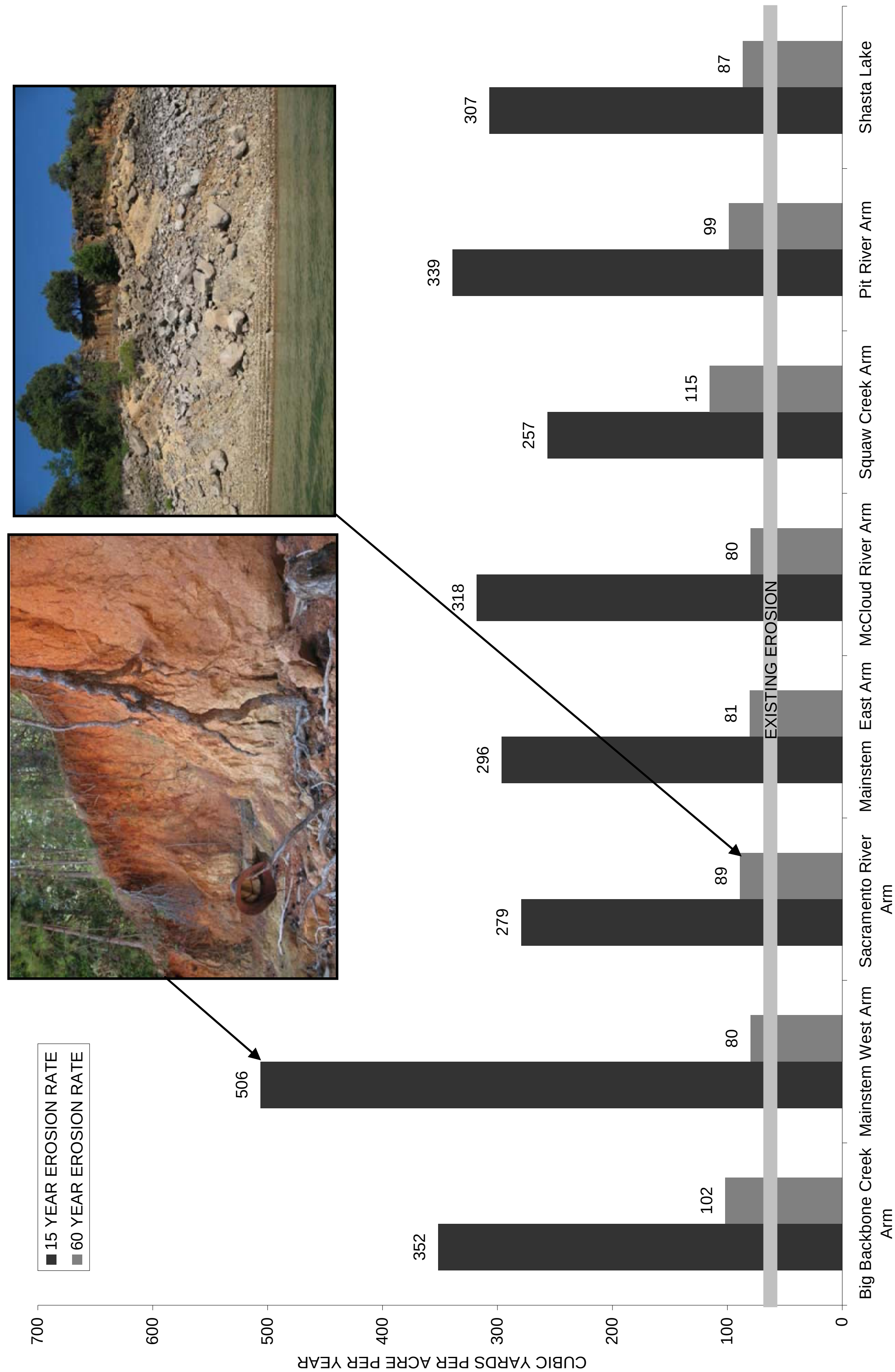
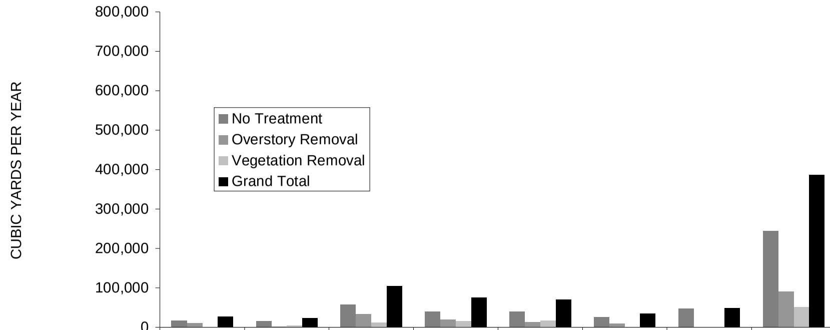


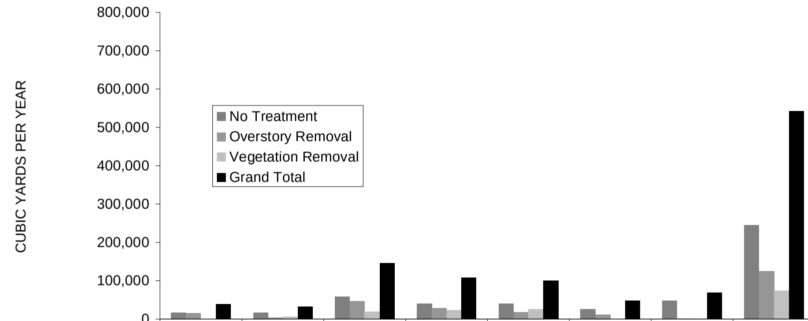
Figure 3-3. SLWRI 15- and 60- Year Potential Shoreline Erosion Rate Calculation Results by Lake Arm for the Shoreline Between the 1,070 feet – 1,090 Feet Contours

CP-1



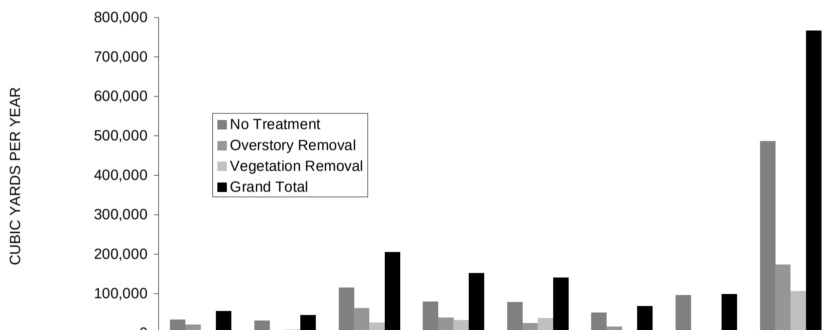
	Big Backbone Arm	Mainstem W Arm	Sac Arm	Mainstem E Arm	McCloud Arm	Squaw Arm	Pit Arm	Total Erosion
No Treatment	16,585	16,255	58,004	40,225	39,555	25,897	47,727	244,248
Overstory Removal	10,839	2,650	34,289	20,523	13,151	9,147	639	91,239
Vegetation Removal	0	4,324	12,820	15,537	17,916	0	813	51,410
Grand Total	27,425	23,229	105,113	76,285	70,622	35,043	49,179	386,897

CP-2



	Big Backbone Arm	Mainstem W Arm	Sac Arm	Mainstem E Arm	McCloud Arm	Squaw Arm	Pit Arm	Total Erosion
No Treatment	16,585	16,255	58,004	40,225	39,555	25,897	47,727	244,248
Overstory Removal	15,195	3,679	46,686	28,234	17,942	11,730	901	124,367
Vegetation Removal	0	6,403	18,476	22,921	25,882	0	1,175	74,857
Grand Total	38,599	32,491	146,390	107,568	99,585	48,117	69,000	541,750

CP-3



	Big Backbone Arm	Mainstem W Arm	Sac Arm	Mainstem E Arm	McCloud Arm	Squaw Arm	Pit Arm	Total Erosion
No Treatment	34,168	31,458	115,469	79,966	77,983	51,626	96,032	486,702
Overstory Removal	22,020	5,054	63,708	39,524	25,046	16,558	1,338	173,248
Vegetation Removal	0	9,183	26,375	32,612	37,280	0	1,656	107,106
Grand Total	56,188	45,696	205,552	152,102	140,309	68,184	99,026	767,056

Figure 3-4. SLWRI 15-Year Potential Shoreline Erosion Volume Calculation Results for CP1, CP2, and CP3 by Lake Arm

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Chapter 4
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