Bolinas Lagoon Watershed Study

Input Sediment Budget

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1. INTRODUCTION

Whether considering a large drinking water supply reservoir, a small backyard pond, an urban recreational lake, or a small coastal lagoon, the issues of infill and sedimentation of water bodies have challenged community decision-makers and natural resource managers for decades. Countless natural factors, including watershed geology, hydrology, vegetation, and climate, along with anthropogenic influences spanning the spectrum from current policy and management practices to centuries of historic land use activities, come together to affect sediment mobilization and transport. Sediment budgets are based on careful analysis of the relationship among the above-listed factors, potential sediment sources, and the observed rate of sediment delivery to the water body. The Bolinas Lagoon Watershed Study is a partial sediment budget based on inputs from the watershed only. In addition, the Bolinas Lagoon Watershed Study was conducted to identify potential restoration projects in the watershed to reduce the amount of sediment entering the lagoon.

A full watershed sediment budget is a mass balance ($I \pm \Delta S = O$) that includes estimates of sediment input from the watershed (I), changes in sediment storage within the watershed (ΔS), and sediment discharge from the watershed to the waterbody (O) (Reid and Dunne 1996). It is the nature of sediment in steams to remain mobile for a period of time and then to be stored within a stream reach (ΔS) (sometimes for decades or longer) and then remobilize and continue on. Determining the mechanisms behind storage and re-release is known as sediment routing and can be extremely complex, taking years to understand for a given watershed. Partial sediment budgets, based on sediment inputs only, assume that over long periods of time, all sediment released to the stream network is eventually delivered to the downstream body of water; the amount of sediment stored in the watershed remains fairly consistent. Partial sediment budgets are an efficient way of assisting decision-makers in determining the best course of long-term preventative or remedial action when years of data collection time are not feasible.

U.S. Army Corps of Engineers (USACE) commissioned the Bolinas Lagoon Watershed Study to evaluate the sources and magnitude of sediment delivered to the lagoon via erosional processes within the watershed. Though there are several potential sources of sediment to the lagoon, including tidal transport and windborne deposition, this study focuses on watershed sources. A thorough literature review was conducted to determine sediment transport rates from wind, tidal, and watershed sources established in previous studies. Historical land use data was collected and used to establish correlation with rates reported in the literature. Land use history of the watershed and the results of our reviews are presented in Section 2. Extensive field surveys of the watershed were conducted to capture a representative sample of sediment sources throughout the watershed. Both qualitative and quantitative information about landslides, earthflows, gullies, road-related erosion and other erosional processes was collected and used together with regional values for soil creep and stream bank erosion to create an account of the relative significance of each. Field survey data and published rates for soil creep and bank erosion were input into an empirical sediment source model, which was used to normalize the data and produce the resulting annual sediment input rates. These data, calculations, and results were checked against land use history and previous studies of the lagoon, as well as literature values for similar watersheds, to establish the reliability of the results.

The empirical sediment source model was selected because of the unique character of the lagoon and its surroundings. A soil loss modeling approach, such as Generalized Watershed Loading Functions (GLWF), based on surface erosion and the Universal Soil Loss Equation, is often used to calculate sediment budgets where erosion in a watershed is uniform, deterministic, and linked closely to the volume of storm water runoff over areas of bare soil. However, low road density, absence of tracts of bare soil, and dominance of stochastic landslide activity precluded the ability to accurately model the system with a classical soil loss model. In addition, the intensive field survey approach allowed the project team to take advantage of the unique opportunity to survey a fluvial terrace that had formed behind a debris dam that was in place on an unmanaged tributary in the watershed from 1906 to the mid-1950s. This survey was used to determine the amount of material stored in the temporary lake over a 50-year period for comparison to the sedimentation rate calculated for the rest of the watershed.

2. BACKGROUND

Bolinas Lagoon is an estuarine lagoon approximately one by three miles in size, located 12 miles northwest of San Francisco Bay, and south of Point Reyes (Figure 2-1) (MCOSD 1996). The lagoon's watershed covers an area close to 17 square miles. Bolinas Ridge, which runs northwest to southeast at about 2,000 feet above mean sea level (MSL), serves as the eastern boundary of the watershed. On the west side of the watershed is the Point Reyes Peninsula. The San Andreas Fault runs directly through the lagoon itself along its northwest-southeast axis (MCOSD 1996).

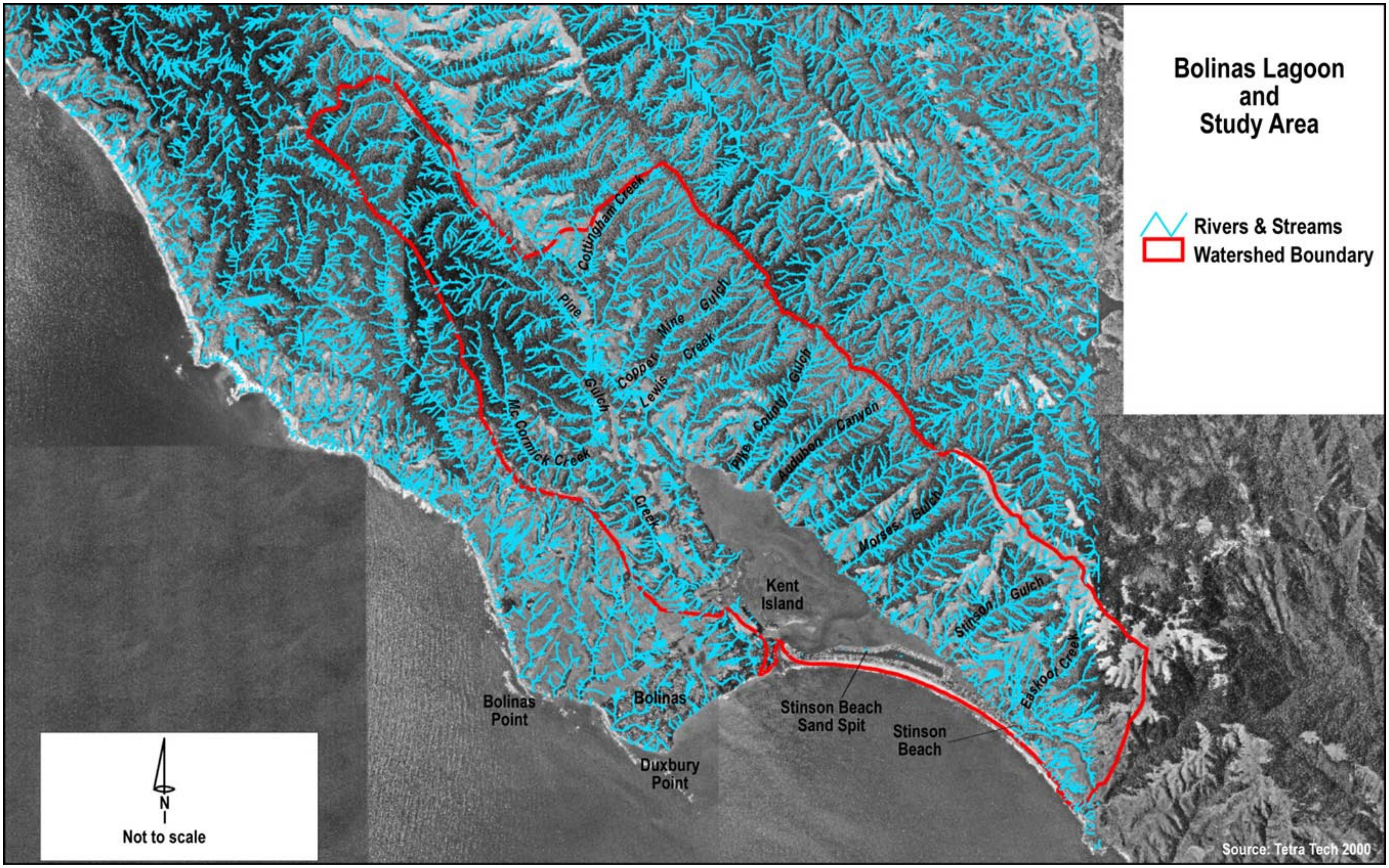
One major tributary and a number of minor tributary streams feed into Bolinas Lagoon. Pine Gulch Creek drains the west side of the watershed and feeds into the lagoon at a point north of the unincorporated town of Bolinas. At the mouth of Pine Gulch Creek is an extensive delta that supports a wide assortment of bird life. Several smaller creeks drain into the east side of the lagoon from Bolinas Ridge.

2.1. History of Bolinas Lagoon

The Bolinas Lagoon was formed as a result of tectonic movements along the San Andreas Rift Valley more than 7,700 years ago (Atwater 1978). A sand spit developed, isolating the lagoon waters from the larger Bolinas Bay. While there have been reports over the past 150 years that Bolinas Lagoon has progressed from a deep water embayment to a shallow lagoon, evidence from sediment cores indicate that it was never a deep water embayment (Bergquist 1978). Rather, Bolinas Lagoon remained in equilibrium over the past 7,700 years as predominantly intertidal mudflats or shallow subtidal areas (Williams and Cuffe 1994).

The evidence that Bolinas Lagoon was always fairly shallow is contradicted by Munro-Fraser's early account (1880) indicating that the Bolinas Lagoon was originally a deep-water embayment where, "when vessels first began to sail into the port, a schooner drawing ten feet of water could pass over the bar with ease at any stage of the tide." It is not clear what exact time period Munro-Fraser is referring to, but it could not have been much earlier than the 1830s when the Spanish first settled in the area (Van Kirk 2001).

Figure 2-1. Map of the Bolinas Lagoon Watershed



Beginning in 1849, the slopes of the Bolinas watershed were a source for timber, particularly redwood for the San Francisco area. Mills reportedly generated nearly 15 million board feet of lumber during the 1849 to 1858 logging boom (Munro-Fraser 1880). Within only 5 to 20 years from Munro-Fraser's initial description of the bar at the entrance to Bolinas Lagoon being at least 10 feet deep (i.e., by 1854) the depth of the entry bar of the lagoon was measured as only one foot deep at low tide (Rowntree 1973).

Lands harvested of timber along the steep slopes on the Bolinas Ridge were converted to cattle grazing or agricultural uses when logging activities ceased. Several mining operations were also active in the area by 1863 (Compas 1997), including a copper ore mine (Mason 1973).

The land-use practices of the late nineteenth century, including logging, mining, and ranching, are assumed to have increased the rate of sedimentation in Bolinas Lagoon. The 1849 to 1858 logging boom in particular has been pointed out as the cause for the accelerated filling of the lagoon during the mid-nineteenth century (Rowntree 1973; Ritter 1973; Bergquist 1978). Munro-Fraser, however, attributed the filling in of Bolinas Lagoon to early farming in the area, not the timber boom of the 1849 to 1858 time period (Van Kirk 2001).

It is unclear what the configuration of Bolinas Lagoon was prior to settlement or if it changed much during the nineteenth century. However, there is little evidence that the lagoon became deeper after the 1906 earthquake caused the floor of the lagoon to subside (Gilbert 1907). There is also photographic evidence that the lagoon changed between 1906 and 1977; Bergquist (1979) noted 8 primary changes in his comparison of 1906 and 1977 photographs:

1. An increase in exposed tidal flat areas since 1907
2. Enlargement of Kent Island, especially the northeast part
3. Sediment accumulation and marsh overgrowth of the nearshore areas south of Pine Gulch Creek delta
4. Advancement (progradation) of Pine Gulch Creek delta
5. Man's destruction of the washover fans north of the spit
6. Dune growth along the axis of the spit
7. Lateral erosion of Picleweed Island

8. Cliff recession at Duxbury Point

The effects of land use changes on sedimentation rates and lagoon configuration are difficult to link over short time periods. While increased sediment rates have been reported for various periods and there is anecdotal evidence of corresponding changes in lagoon depth, there are conflicting opinions over when rates have been highest. This disagreement arises in part because sediment routing through the watershed is affected by factors that are difficult to measure. For instance, a debris dam, which formed during the 1906 earthquake, led to the deposition of 50 years worth of sediment in a temporary lake on McCormick Creek. After the debris dam breached in a 1955 storm the deposited sediments began releasing as the stream cut down through the deposit forming the terrace that exists today. Such situations make predicting the time from the initial mobilization of material from a specific landslide or road failure to its deposition in the lagoon difficult.

2.2. Hydrology and Groundwater

2.2.1. Surface Water Drainage

The watershed of Bolinas Lagoon (Figure 2-1) covers 16.7 square miles. Average annual rainfall in the watershed ranges from about 22 to 50 inches, depending on elevation. Most of the precipitation occurs from November through April.

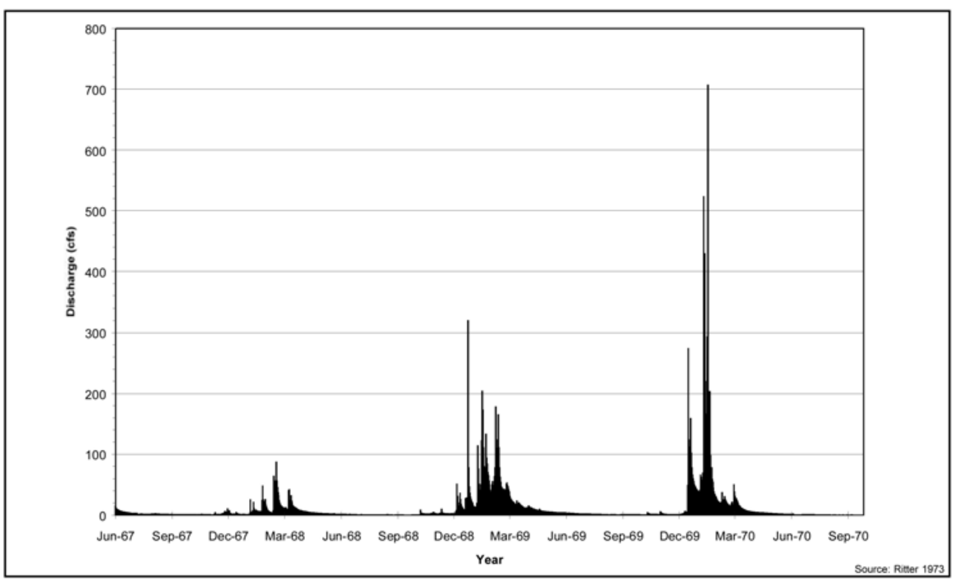
Pine Gulch Creek, the principal drainage to the lagoon, is a perennial (year-round) stream. Most of the drainage area of Pine Gulch Creek lies on the west side of the San Andreas Fault and is underlain by Monterey Formation geology. The drainage area of Pine Gulch Creek is approximately eight square miles (5,120 acres), representing about 50 percent of the Bolinas Lagoon watershed. Pine Gulch Creek and the drainage of Copper Mine Gulch originally followed the trace of the older western boundary of San Andreas Fault, and they continue to follow this course even after lateral movement on the younger 1906 trace shifted their channels northward. Pine Gulch Creek joins McCormick Creek, flows through Paradise Valley west of Horseshoe Hill, and enters Bolinas Lagoon about midway between the head of the lagoon and Kent Island. Pine Gulch Creek discharges on the west side of the lagoon and represents a major source of sediment inflow to the lagoon in wet years.

Easkoot Creek, the second largest sub-basin in the watershed, drains an area roughly 1.7 square miles (1,062 acres) on the south end of the lagoon. This is roughly 10 percent of the total calculated watershed area (Fong 2000b). The drainage areas of the next two largest streams on the east side of the San Andreas

Fault, Morses Creek and Audubon Creek, are 0.70 square miles, and 0.46 square miles, respectively. The remainder of the watershed drains the east side of the San Andreas Fault, which is underlain by Franciscan geology. The streams are steeper on the east side than on the west side of the fault and flow intermittently. Numerous steep, straight, perennial and intermittent streams drain the approximately 1.5-mile long slope from the ridge top to Bolinas Lagoon. The four northern-most of the east side drainages (i.e., Cottingham Gulch, McCurdy Gulch, Cronin Gulch, and Copper Mine Gulch) drain to Pine Gulch Creek. These four streams are culverted under Highway 1; the culverts at Cottingham and McCurdy gulches serve as barriers to fish passage.

Figure 2-2 shows historical flows measured at a stream monitoring station at Pine Gulch Creek operated by the U.S. Geological Survey (USGS) between June 1967 and September 1970. Although the data shown in the figure represent only a brief period of time, it can be seen that flows varied in magnitude over a wide range during the period. The total annual discharge from Pine Gulch Creek from October 1, 1967 to the end of September 1968 (i.e., the 1968 water year) was 3,670 acre-feet. During the following water year, the total discharge was 12,110 acre-feet. The total inflow during the 1970 water year was 14,080 acre-feet. The total annual discharge from Morses Creek in 1968 and 1969 was just 159 acre-feet and 813 acre-feet, respectively (Ritter 1973).[1]

Figure 2-2. Average Daily Flows in Pine Gulch Creek (1967-1970)



[1] Recent data on annual discharges from Pine Gulch Creek exist and will be incorporated into the Administrative Draft EIS/EIR.

2.2.2. Circulation and Tidal Flows

Elevation Datums

Historical changes in water depth and land elevation figure prominently in the discussion of sedimentation and hydraulics in Bolinas Lagoon. It is important to keep in mind that a number of different elevation datums have been used in studies of the lagoon. The most commonly used land elevation datum in the U.S. is the National Geodetic Vertical Datum (NGVD) of 1929. This is the land datum typically used on USGS topographic maps, and is the datum used to calculate habitats in the lagoon. It is commonly referred to as mean sea level, because it was based on the average of the mean tide levels at selected locations. It has been replaced, for some applications, by the more precise North American Vertical Datum (NAVD) of 1988. Navigational charts, however, typically reference mean lower low water (MLLW), which is the average of the lowest daily tidal stands. The shoreline on USGS topographic maps and on navigational charts typically represents MLLW, and underwater depths are typically reported as depths below MLLW. The relationship between tidal averages and land elevation datums varies locally, and tidal averages reported in different historical documents may vary widely from each other. Since bathymetric data, or soundings, are typically reported relative to tidal averages, such as MLLW, this variability makes it difficult to accurately interpret historical water depth information.

Table 2-1 presents the relation between the NGVD and NAVD land elevation datums and the respective tidal averages at gages at the Presidio in San Francisco Bay and at Point Reyes. In this report, if not otherwise noted, elevations above and below water are referenced to the 1929 NGVD, and the term mean sea level (MSL) is assumed to be equivalent to NGVD. A detailed discussion of elevation and tidal references that have historically been used as the basis for depths and elevations reported for Bolinas Lagoon is presented in Bergquist's (1978) study of the depositional history of Bolinas Lagoon.

Table 2-1. Comparison of Tidal Averages and Land Elevation Datums (1929 NGVD and 1988 NAVD)

Description	SF Presidio Elevation relative to NGVD (ft)	Bolinas Bay NGVD (estimated)	Pt. Reyes, Drakes Bay relative to NGVD (ft)
Highest Observed Water Level	5.74		5.82
Mean Higher High Water (MHHW)	2.70		2.92
Mean High Water (MHW)	2.10		2.26
Mean Tide Level (MTL)	0.05		0.30
Mean Sea Level (MSL)	0.00	0.3877	0.00
National Geodetic Vertical Datum (NGVD)	0.00	0.3877	0.00
Mean Low Water (MLW)	-2.00		-1.67
North American Vertical Datum-1988 (NAVD)	-2.99		-2.61
Mean Lower Low Water (MLLW)	-3.13		-2.85
Lowest Observed Water Level	-5.80		-5.33

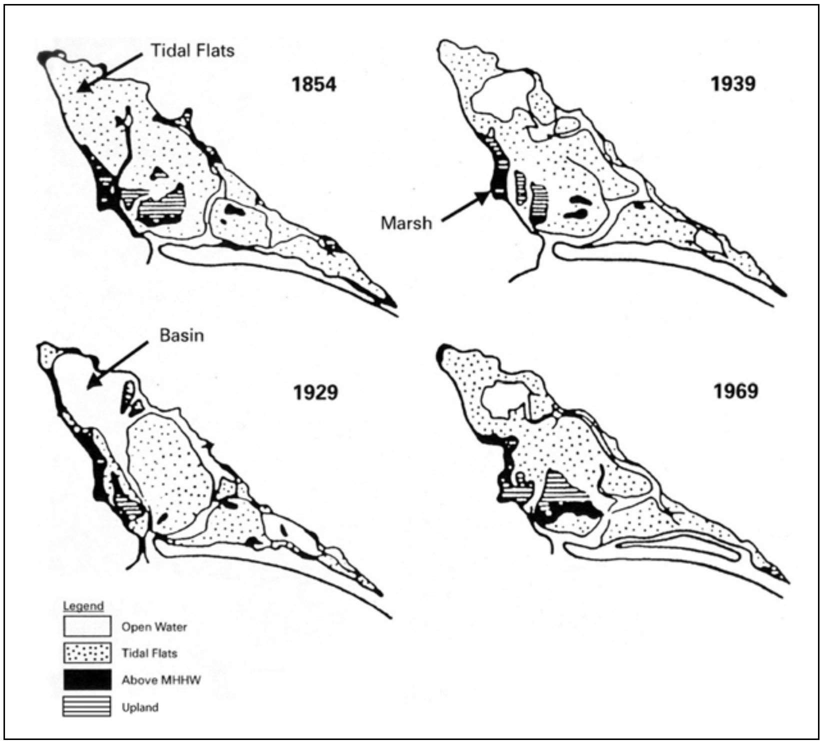
Source: Bergquist 1978

Lagoon Configuration and Bathymetry

Bolinas Lagoon covers an area of about 1,100 acres at mean high water (MHW). There are two main channels within the lagoon: Bolinas Channel and the East Channel (also called the Main Channel). Bolinas Channel extends between Bolinas and Kent Island. The East Channel follows a course eastward between the channel inlet and Kent Island and then turns north and generally hugs the east shore of the lagoon toward the Upper Basin. The Upper Basin lies north of the delta of Pine Gulch Creek. Sediment deposition on the delta apparently prevents the Upper Basin from draining via the Bolinas Channel.

Figure 2-3 shows the evolution of Bolinas Lagoon between 1854 and 1969, and Figure 2-4 shows the current configuration of the lagoon (Rowntree 1973). The lagoon morphology has been influenced by a number of geologic and hydrologic features; it is likely that the most important factors are: changes in sea level, uplift, and subsidence related to movement on the San Andreas Fault; erosion and sediment transport in the watershed; and wave and tidal action. Superimposed on these natural processes are human actions that influence the shape of the lagoon, including dredging and filling, and shoreline erosion protection. These processes occur at different rates, with different cycles of periodicity, and with different degrees of predictability. The ways in which these processes overlap determines the shape and depth of the lagoon. During the past 5,000 years sea level has been rising at an average rate of about one-half foot per century. Rising sea levels invaded the rift valley of the San Andreas Fault, forming a deep tidal inlet. As it did so, a sand spit formed in the shallow waters across the mouth of the inlet. The rift valley is a zone in which the land tends to subside due to movement along the San Andreas Fault. The subsidence occurs episodically. The 1906 earthquake, for example, caused the lagoon east of the active trace of the fault to subside about one foot. Based on evidence from sediment cores, the combination of subsidence and sea level rise was approximately equal to the rate at which sediment accumulated in the lagoon until about 1849 (Berquist 1978).

Figure 2-3. Historic Change in Configuration of Bolinas Lagoon (1854-1969)



Source: Rowntree (1973)

In addition to natural processes that played a role in the configuration of the lagoon, human activities are also suspected to have helped shape the lagoon (Ritter 1973). Munro-Fraser (1880) estimated that about 15,000,000 board feet of lumber was cut in the immediate vicinity of Bolinas between 1849 and 1858. Munro-Fraser also noted that the same ships that could pass into Bolinas port in the mid-1800s were unable to do so by 1880 due to decreasing water depth. In addition, decreasing water depth caused by siltation forced shipbuilders in the bay to move their operations three times before being discontinued entirely in the late 1870s (Munro-Fraser 1880). Quantitative data indicates that the bay, which had a high volume of 210 million cubic feet before 1849, decreased to a low volume of 90 million cubic feet by 1906 (Bergquist and Wahrhaftig 1993).

Despite the fact that historical evidence indicates that human logging activity corresponds with a decrease in total water volume of the lagoon, the direct cause of the sedimentation in the late 1800s has not been firmly established.

Figure 2-4. Current Configuration of Bolinas Lagoon

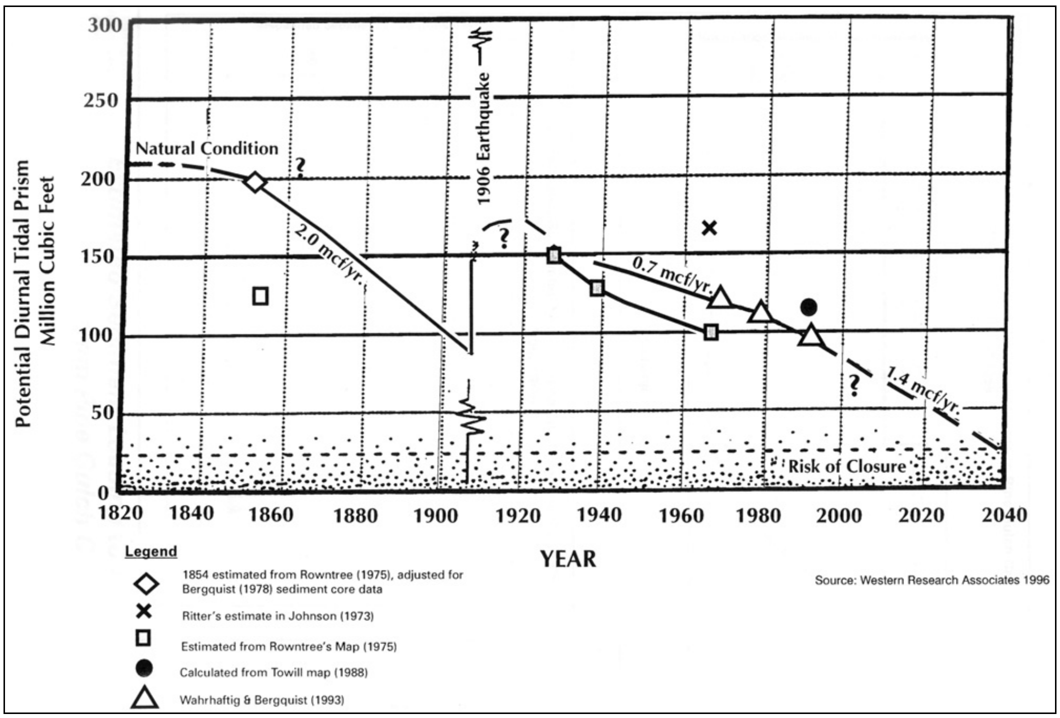
Note: Slight color differences seen on this figure are the result of splicing multiple aerial photographs.

Sediment Deposition and Tidal Prism Change

The size of the tidal prism is an important factor in maintaining sufficient tidal exchange to support many of the existing functions of the lagoon and preserve the dynamic equilibrium of the lagoon configuration, including sediment removal and keeping the inlet channel open.

Figure 2-5 shows the change in the tidal prism since the early 1800s. Prior to 1849, when European settlement of the watershed began in earnest, the tidal prism is believed to have been relatively stable, at about 210 million cubic feet. After 1849 it decreased at a rate of about 2 million cubic feet per year (cf/yr) and reached a low point of about 90 million cubic feet in 1906. Subsidence from the 1906 earthquake abruptly increased the tidal prism to about 175 million cubic feet. Sedimentation continued, however. From the 1930s to the 1960s sedimentation resulted in the loss of tidal prism at a rate of about 0.7 million cf/yr. Since the 1960s, the rate of loss is believed to have doubled to about 1.4 million cf/yr. Bergquist and Wahrhaftig (1993) estimated that the tidal prism was 96 million cubic feet in 1988. In 1993, a causeway and dump were removed from the southern end of the lagoon. This directly increased the tidal prism by 248,000 cubic feet and led to an estimated increase in tidal prism of 435,000 cubic feet because of increased tidal circulation (MCOSD 1996).

Figure 2-5. Estimated Change in Tidal Prism of Bolinas Lagoon Over Time



A USGS study conducted between 1967 and 1970 (Ritter 1973) found that more sediment was carried out of the lagoon on outgoing tides (ebbtides) than was carried in by incoming tides (floodtides). However, the variability in the daily observations was high, suggesting that even if the measured values are highly accurate, the long-term sediment balance in the lagoon is difficult to predict. The rate of discharge of sediment from the lagoon on ebb tides was estimated at approximately 123,000 cubic yards per year (cy/yr) (Ritter 1973).

Other sources of sediment inflow to the lagoon estimated in the USGS study included inflows from streams (primarily Pine Gulch Creek), wind-blown sand, and shore erosion. The total inflow of sediment from all streams was estimated to average about 4,083 cubic yards per year. Nearly all of this sediment comes from

Pine Gulch Creek. By contrast, the sediment load from Morses Creek averages about 28 cy/yr (Ritter 1973). Average rates may be misleading, however. The USGS study showed that the rate of sediment inflow varies considerably with the rate of discharge. For the 1968 water year, when stream discharge was relatively low, the total annual suspended sediment inflow from Pine Gulch Creek was estimated to be about 318 cubic yards. In 1969, the suspended sediment load was 6,292 cubic yards. Nearly half of the sediment inflow in 1969 (about 2,822 cubic yards) was carried by runoff from one storm occurring on December 28, 1969, when the daily discharge was 320 cubic feet per second (cfs).

What happens to sediment when it enters Bolinas Lagoon from Pine Gulch Creek depends mainly on the tidal elevation and the rate of stream discharge. The tidal elevation determines the location of the mouth of Pine Gulch Creek. At lower tidal stands, the creek discharges further along its delta, and more of the sediment load is deposited toward the east side of the lagoon. When the tide is high, the sediment enters the lagoon to the west and disperses over a wider portion of the delta. Higher stream flows not only carry more sediment but also larger sized sediment particles. The larger sediment particles are more likely to remain in the lagoon, while fine-grained particles remain suspended and can be carried out of the lagoon on ebb tides.

Other sources of sediment loading to the lagoon are probably not as significant as tidal inflow and stream inflow. The USGS study concluded that erosion from the lagoon-side of the spit adjacent to Seadrift lagoon, which was built in the early 1960's, contributes an average of about 1,250 cubic yards of sediment per year, and wind-blown sand accounts for about 31,000 cubic yards of sediment annually. The estimated quantity of wind-blown sand entering the lagoon is nearly 10 times the average rate of sediment estimated to enter the lagoon from streams. According to the USGS, however:

> *That value probably is high because houses and fences may interrupt sand movements. Also, the general absence of drifting sand on access roads suggests that sand movement may not be great. However, local residents affirm that substantial quantities of sand are moved across the spit by winds (Ritter 1973).*

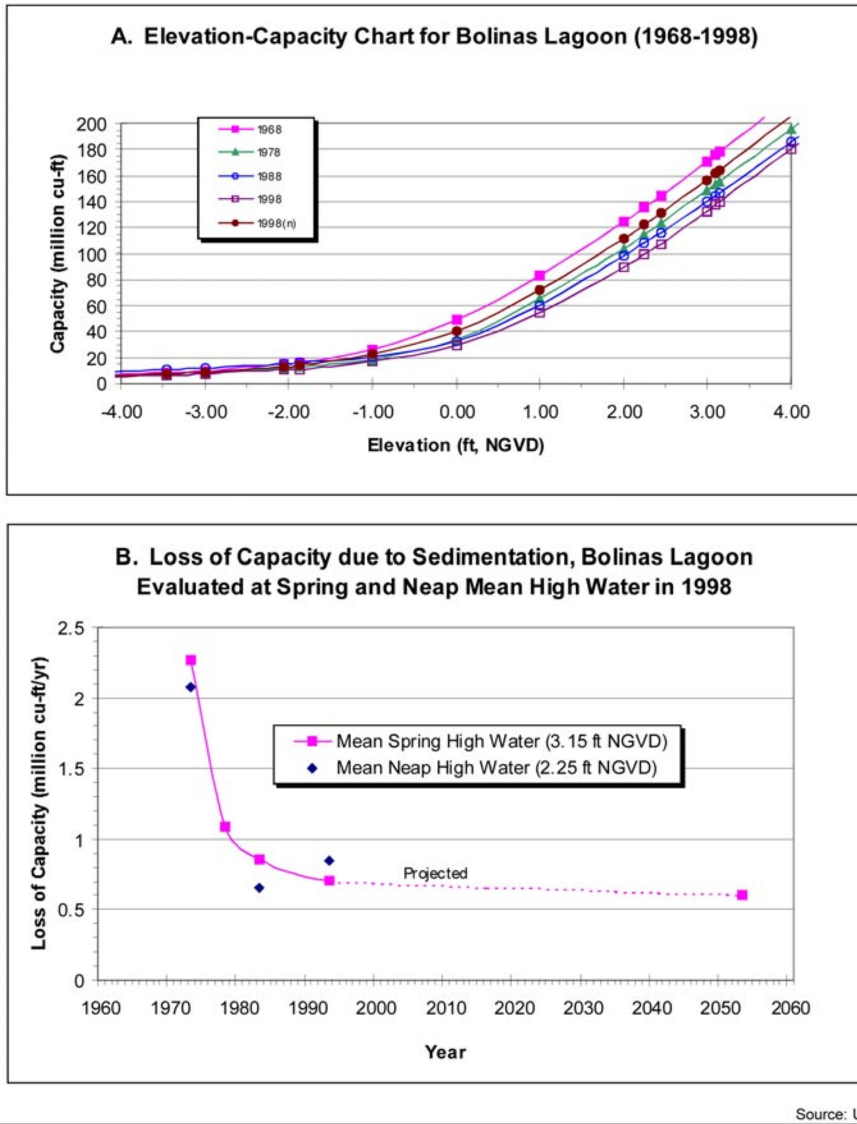
Based on these observations, and estimates by other methods, it was concluded that the rate of sediment accumulation during the period from about 1939 to 1969 was about 25,800 cubic yards per year. Extrapolating these results to the future, it was concluded that the lagoon would fill to the elevation of mean sea level within 90 to 160 years (Ritter 1973). However, as noted above, this prediction is sensitive to errors in measurement and assumptions about the rates at which sediment enters the lagoon.

USACE (1999) evaluated annual sediment infilling rates and changes in lagoon volume based on bathymetric surveys conducted in 1968, 1978, 1988, and 1998[2]. The results of this analysis are shown on Figure 2-6, which shows the change in volume of the lagoon over time. Figure 2-6A shows the change in volume with elevation, and Figure 2-6B shows the average annual rate of loss of volume plotted at the midpoint between each survey date (1973, 1983, and 1993) for elevations corresponding to the typical spring and neap high tide elevations[3]. The figure indicates that the volume of the tidal prism declined dramatically between 1968 and 1978, and the rate of tidal prism loss slowed between 1978 and 1998. The tidal prism decreased 18 million cubic feet between 1968 and 1978, 10 million cubic feet between 1978 and 1988, and 4 million cubic feet between 1988 and 1998 (USACE 1999). The USACE estimates of tidal prism for 1968 and 1988 are very close to the values calculated by Bergquist and Warhaftif (1993) in a separate study based on the same data. The USACE estimate of tidal prism for 1998 is 88.9 million cubic feet, indicating a tidal prism loss of 31 million cubic feet since 1968.

[2] The bathymetric survey data for 1968 and 1988 used in the USACE 1999 report is the same as was used in the Bergquist and Warhaftig 1993 study.

[3] Spring tide is the tide cycle with the greatest difference between high and low tides during a lunar month; the neap tide is the tide cycle with the least difference between high and low tides. The typical spring and neap tides were defined as the 1998 average spring and neap tides and were calculated to be 3.15 feet NGVD and 2.25 feet NGVD, respectively.

Figure 2-6. Change in Tidal Prism based on Bathymetric Data 1968 to 1998



Tidal Exchange and Channel Inlet Size

The entrance channel to the lagoon is an opening in the sand spit that is formed when water rushes in and out on flood and ebb tides; water elevation in the sea and that inside the lagoon move towards equilibrium. The size of the entrance channel is related to the size of the tidal prism and the rate at which the sand spit is built up. The rate at which the sand spit beach is built up is a function of wave power and the availability of sediment. If there is no shortage of sediment, then it is simply a function of wave power. As the tide changes, the elevation inside the lagoon always lags somewhat behind the water elevation of the sea outside the lagoon. It is this difference in elevations that creates tidal inflow and outflow.

There is a dynamic relationship between several factors that results in a particular channel entrance configuration. The smaller the channel opening, the faster the water must move through the entrance channel to equilibrate the elevations. The greater the velocity of the water through the entrance channel, the more sediment scouring can occur. The smaller the tidal prism, the less water needs to be moved through the entrance channel during a tidal cycle, and the lower the velocity will be through a channel of a given size. At some point, if the tidal prism decreases enough, the sand spit will build up enough to close the inlet channel (Williams and Cuffe 1994). Williams and Cuffe (1994) estimated that inlet closure could occur in about 50 years. The USACE (1999) arrived at similar results, concluding that it was possible that the lagoon would close as early as 2033 or sometime beyond 2058, depending on a range of conditions. Historically, however, the ratio of tidal prism to wave power has been large enough that the inlet channel does not close.

Tidal exchange is much more important, overall, in keeping the inlet channel open, than is freshwater flow out of the lagoon; although at times freshwater outflow may be significant (Ritter 1973). For example, during Ritter's study of Bolinas Lagoon in 1968 and 1969 he calculated that maximum daily combined inflow of freshwater from the watershed was approximately 500 cfs, while the maximum flow measured for the tide was 4,000 cfs (with a minimum of 700 cfs). Based on these discharge measurements Ritter concluded that tidal flow far exceeded freshwater in-flow most of the time and that freshwater in-flow was minor compared to the volume of saltwater in the lagoon (Ritter 1973).

Hydrodynamics

The highest tidal current velocities occur in tidal channels and velocities tend to decrease with distance from the inlet channel. Ritter (1973) concluded that except in the Upper Basin and the extreme southeastern portion of the lagoon, nearly every part of the lagoon is subjected to tidal currents strong enough to transport sediment particles of the size most prevalent in the lagoon (silt-size particles). However, more energy is required to erode particles once they have been deposited than is needed to transport particles once they are suspended. Most of the erosion in the lagoon takes place in the tidal channels, which remain inundated longest and where the velocities are highest. Only very fine-grained sediments tend to be deposited in the Upper Basin and southeastern area, where current velocities are lowest.

The pattern of distribution of current velocities and the magnitudes of the velocities vary depending on the height of the tides and on the tidal difference. At higher stands, the flow that passes through the inlet channel is distributed over a wider area of lagoon, so that velocities tend to be lower at higher stands. However, as the tide rises, the inlet channel widens, allowing more water to enter. Floodtide inflows initially follow the courses of tidal channels and then become less constrained by the channels as the tide rises. During ebbtides, the currents initially move as sheet flow over the tidal flats and gradually become channelized as the tide ebbs. Wind-generated wave action can resuspend sediments in shallow areas, and the ebbtide currents then move the resuspended sediment toward the channels, where it is transported out of the lagoon.

2.3. Geology, Soils, and Seismicity

2.3.1. Geology and Geomorphology

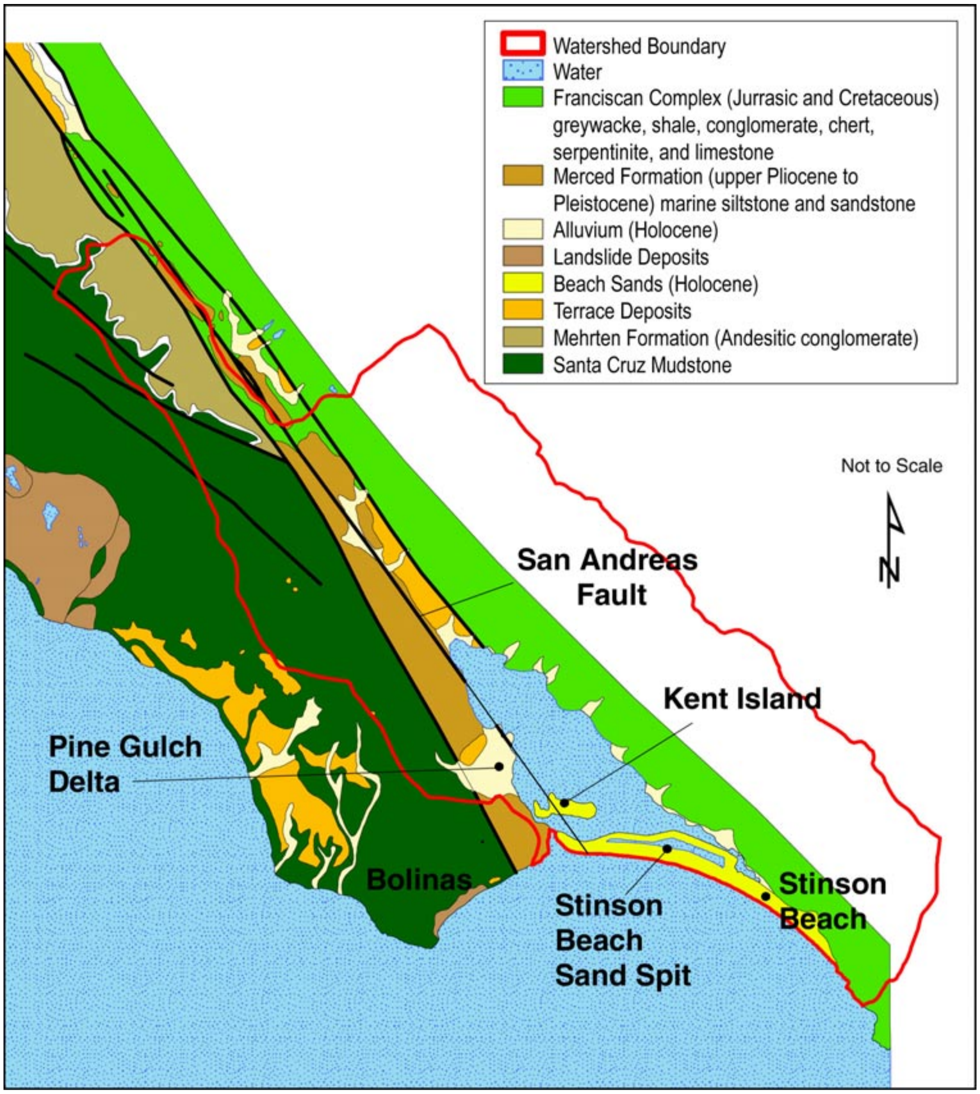
Geology

Figure 2-7 is a regional geologic map showing the study area in relation to geologic features. One of the most important geologic features affecting the formation of the lagoon is the San Andreas Fault, which runs along the Pacific Coast from near the Gulf of California to Cape Mendocino. The fault zone is about 1.25 miles wide at the mouth of the lagoon and narrows to about 1,500 feet wide along the Rift Zone between Bolinas Lagoon and Tomales Bay.

On the west side of the lagoon the basement rocks are granite similar to that of southern California, and are overlain by younger sedimentary rocks. The basement rocks on the east side of the San Andreas Fault consist of an assemblage of oceanic crustal rocks similar to those that underlie most of Marin County and the San Francisco Bay Area. Together, these basement rocks are known as the Franciscan Complex. Franciscan geology is exposed in the study area, but in some places they are also overlain by younger sedimentary deposits.

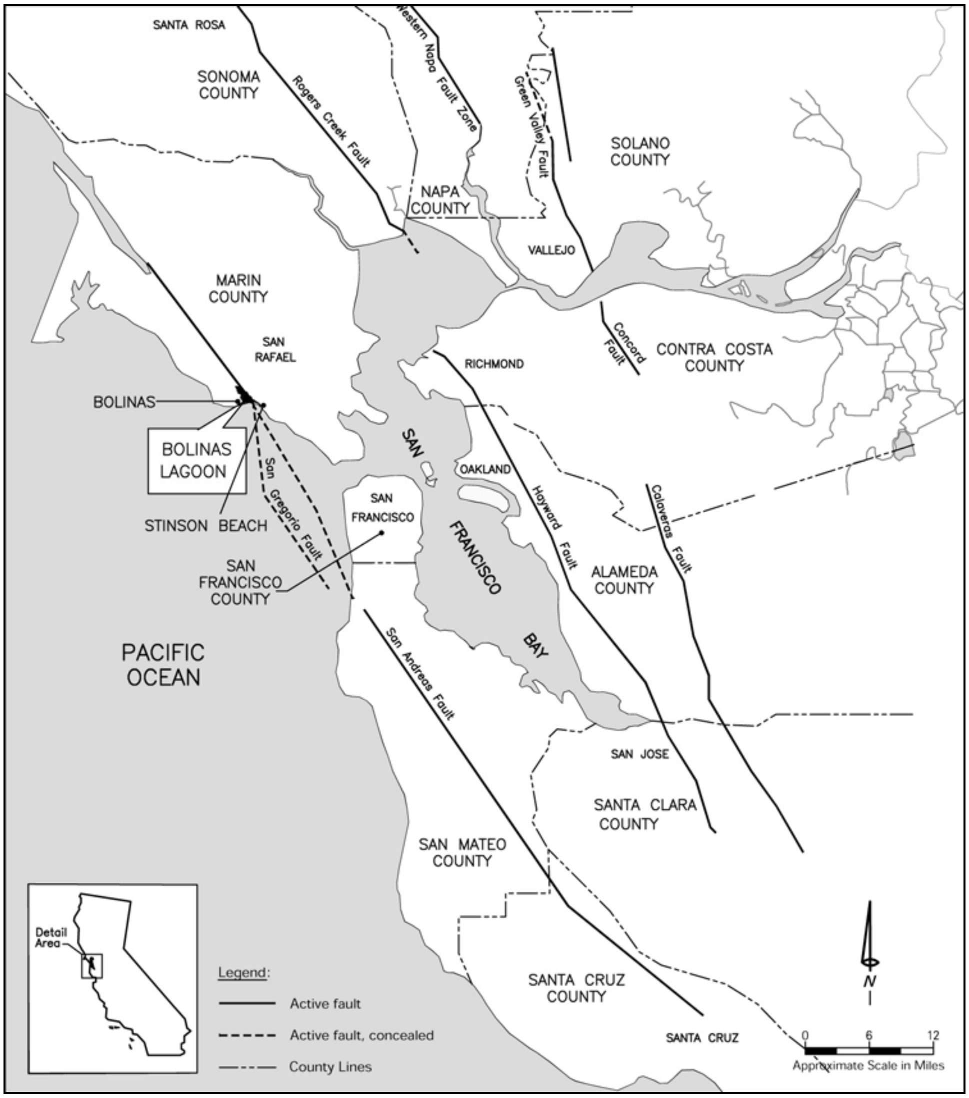
The lagoon itself occupies a graben, a geological structure resulting from subsidence of the land that lies between traces of the San Andreas Fault. The most westerly trace, which marks the western edge of the San Andreas Fault Zone, is also the oldest. The San Andreas Fault forms the eastern edge of the Fault Zone. The 1906 Trace of San Andreas Fault, that ruptured in the 1906 earthquake, lies about midway between these two (Figure 2-8) (Wagner 1977; Bergquist 1979).

Figure 2-7. Geology of the Bolinas Lagoon Area



The oldest exposed rocks on the Bolinas Peninsula are less than 26 million years old and belong to the Monterey Formation. The Monterey Formation is composed of siltstone and light-colored silica-rich shale. The rock is highly fractured and crumbles easily. The bedding in these rocks is tilted down to the west at an angle of about 40 to 60 degrees. As a result, steep unstable slopes tend to form on the eastern uptilted side of the peninsula, and unstable cliffs form where wave action erodes the material at the foot of the slopes. The south-facing cliffs of the Bolinas peninsula are estimated to be retreating at an average rate of about 0.3 to 0.6 meters (1 to 2 feet) per year (Wagner 1977).

Figure 2-8. Principal Regional Faults in the San Francisco Bay Area



Overlying the Monterey Formation on the east side of the older trace of the San Andreas Fault are massive blue siltstones, clays, buff-colored sandstone, and gravels of the Merced Formation. The Merced Formation is more than 90 meters (292 feet) thick in the study area and forms cliffs along the west side of Bolinas Lagoon. The bedding in the Merced Formation slopes down to the east at an angle of between 5 and 35 degrees. The deposits are not well consolidated and erode easily, making them susceptible to debris-flow landslides (Wagner 1977). The cliffs between Brighton Avenue and Wharf Road, on the Bolinas peninsula opposite the Stinson Beach sand spit, are estimated to be retreating at a rate of about 0.5 meters (1.6 feet) per year (Wagner 1977).

Filling depressions in the Monterey Formation on the Mesa are relatively thin unconsolidated deposits of silt, sand, and gravel derived mainly from erosion of the Monterey Formation. In some areas, these terrace deposits contain boulders of Franciscan rocks that must have originated from the slopes east of the San Andreas Fault. The terrace deposits were formed during the last Ice Age (less than about 2 million years ago) when the Mesa was partially submerged below sea level.

At about the same time the terrace deposits were formed, stream gravels derived mainly from Franciscan geology, but also containing Monterey and Merced formation material, were being deposited. These older stream gravels, in a sandy matrix, have been named the "older alluvium" and are common in former streambeds within, or immediately adjacent to, the San Andreas Fault Zone. These deposits are easily eroded.

The east side of the San Andreas Fault Zone is underlain by rocks that are quite distinct from those on the west side. While the rocks on the east side of the fault share some general characteristics, they represent a variety of materials that were scraped onto the North American continental plate as it slid beneath the Pacific plate near the end of the age of dinosaurs, more than 65 million years ago. In the study area, the Franciscan rocks consist of melange, a chaotic mixture of sandstone, greenstone, chert, and other rocks in a sheared clayey matrix (Clark et al. 1991; Wagner 1977). The matrix is weak and erodable and subject to slope failure. Because the slopes east of the San Andreas Fault Zone tend to be steep, they are prone to landsliding in the study area.

Recent unconsolidated deposits in the study area consist of landslide deposits, alluvium, beach sand, and Bay Mud. The Stinson Beach sand spit, which is about 3 kilometers (1.9 miles) long and nearly connects the Bolinas Peninsula to the mainland, is composed of beach sand deposits. In the mid-1960s, the lagoon side of the spit was dredged in order to extend the land upon which houses were later constructed. Between this extension and the original spit, Seadrift Lagoon, an artificial lagoon, was created (Bergquist 1978). A narrow opening in the sand spit at the foot of the Bolinas Peninsula, about 50 meters (163 feet) wide, allows water to flow in and out of the lagoon with changing tides. Kent Island, located just inside the lagoon from the mouth, is a tidal delta composed of beach sand deposits and formed from changing tides that move sand in and out of the inlet.

Wagner (1977) described the deposits within Bolinas Lagoon as Bay Mud. Bay Mud is a mixture of silt, clay, sand, shells, and organic material of recent age. It is water-saturated and poorly-consolidated, with the consistency of jelly. Ritter found that the median grain size of lagoon sediment and the sediment on beaches along the Stinson Beach sand spit is in the fine sand range. A larger proportion of silts and clays were found in the extremities of the lagoon than in the center of the lagoon, while the coarsest sediment was found near the mouths of some of the east shore streams on the east shore. Based on circulation studies using a dye tracer, Ritter concluded that the southeast extremity of the lagoon, the upper basin (north of the Pine Gulch Creek delta), and the tidal flat north of Kent Island are areas of net sediment deposition in the lagoon. Elsewhere, he concluded that current velocities are sufficient to transport and to resuspend sediment.

Seismicity

The U.S. Geological Survey (USGS) estimates that there is a 70 percent probability of at least one magnitude 6.7 or greater earthquake, capable of causing widespread damage, striking the San Francisco Bay region before 2030. For the North Coast South segment of the San Andreas Fault (the segment that crosses Bolinas Lagoon), the probability of a magnitude 6.7 quake is estimated to be 12 percent in the next 30 years (Working Group 1999). Figure 2-8 shows active faults in the greater San Francisco Bay area.

The 1906 earthquake is likely to have been associated with both vertical and horizontal displacement. Vertical displacement along the 1906 trace of the fault was estimated to be about 30 to 35 centimeters (12 to 14 inches) (Bergquist 1978). Horizontal displacements in the area, measured after the earthquake, ranged from about 3.7 meters (12 feet) near Bolinas Lagoon to about 6.1 meters (19.8 feet) near Point Reyes Station (Wagner 1977). Another such quake could cause both significant increases in landslide activity and mass wasting but could also lower the floor of the lagoon and significantly increase the tidal prism.

Slope Stability, Bearing Capacity, and Liquefaction Potential

The Franciscan melange east of the San Andreas Fault is locally variable in stability. Landsliding is common on steep slopes, but large blocks of rock occur in places within the melange and can locally increase its stability.

On the Bolinas peninsula the principal stability problem is undercutting and collapse of cliffs underlain by Monterey shale. The slopes adjacent to the floodplain of Pine Gulch Creek are classified in the two least stable slope categories. This includes areas in which the slopes are near the stability limits of the underlying materials, or areas in which active downslope movement (landslides or slope creep) is occurring.

Unstable deposits may underlie level areas classified as stable slopes as well. Areas on the floodplain and delta of Pine Gulch Creek, which are underlain by loose, sandy materials with a high water table, may be vulnerable to liquefaction in an earthquake.

2.3.2. Soils and Erosion

Soils on Bolinas Ridge are generally thin, derived from the Franciscan melange, and easily eroded when disturbed or exposed to rainfall. Soils derived from the Monterey Formation, on the west side of the San Andreas Fault, are much less stable and much more easily eroded (Ritter 1973).

Soils on land adjacent to the Bolinas Lagoon, including most of the Bolinas peninsula and most of the watershed on the eastern side of Bolinas Lagoon belong to the Cronkhite-Dipsea-Centissima group. These include deep to moderately deep soils on steep slopes. The soils are generally described as moderately well drained (Kashiwagi 1985). Soils on the central ridge of the Bolinas Peninsula, west of Pine Gulch Creek, belong to the Palomarin-Wittenber group. These are shallow, well drained soils on moderately steep upland slopes. Soils on upland portions of the watersheds of most of the creeks that drain the east side of the San Andreas Fault (north of Morses Creek) belong to the Maymen-Maymen group, which are described as shallow to moderately deep, excessively-drained soils on steep slopes. Many of the soils in upland areas are characterized by a high degree of susceptibility to erosion. Erosion increases when the vegetation cover is reduced, such as from grazing or logging. Soil erosion also increases where slopes fail or are cut and filled.

2.4. Vegetation

As is to be expected, vegetation within the watershed varies as a function of soil, elevation, aspect, and historic land use. In several areas within the lagoon and along its border, exposed sand substrate has created sandbars and beaches, but upland areas are well vegetated with very few areas of bare soil with high erosive potential. Proceeding inland from the margins of the lagoon, the watershed consists of freshwater streams draining steep canyons. The streams are bordered by coniferous and mixed evergreen forest. Proceeding up the canyons toward the ridges, the vegetation cover transitions from forest to coastal scrub, chaparral, and annual prairie/grassland.

Freshwater Marsh and Riparian Areas

Many freshwater creeks drain the 17-square mile watershed of Bolinas Lagoon. Where the streams enter the lagoon, the mix of fresh and salt water supports brackish marsh, with species such as cattails and bulrush (MCOSD 1996).

Riparian habitat is increasing along the margins of the lagoon. The creek deltas are expanding into the lagoon due to large annual sediment loads carried out of the channelized eastern tributaries. The expanding marshlands are creating suitable substrate for riparian vegetation to establish on the landward margins (MCOSD 1996). The montane riparian vegetation typically includes red alder (*Alnus rubra*) and willow (*Salix* spp.) (MCOSD 1996; Mayer and Laudenslayer 1988).

Upland Habitat - Forest, Scrub, and Grassland

Mixed evergreen forests extend up the canyons, gulches, and ridges of the lagoon watershed, grading into coastal scrub and annual/perennial grasslands on more exposed slopes. Some chaparral is present, although it occurs more commonly inland. In the shady canyon areas, coast redwood (*Sequoia sempervirens*) forests have reestablished themselves by sprouting from the stumps left from logging operations (Gustafson 1968). Coast live oak (*Quercus agrifolia*), Douglas fir (*Pseudotsuga menziesii*), and California bay (*Umbellularia californica*) make up the mixed evergreen woods on the ridges and canyon slopes (Rowntree 1973). The main species found in the coastal scrub include *Baccharis* sp. and California sagebrush (*Artemesia californica*) (Szychowski 1999).

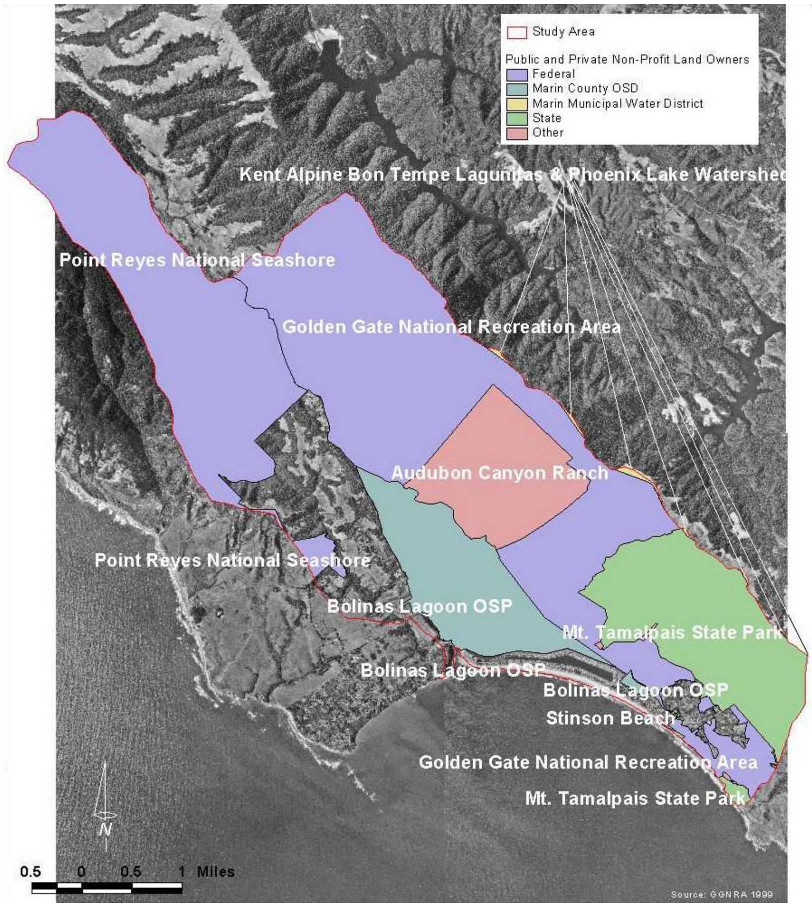
2.5. Land Use

This section discusses land ownership, the types of land use surrounding Bolinas Lagoon, and regional and local land use plans and policies. The types of land use surrounding the lagoon have been divided into three broad categories that describe the type of development and activity that occur in the area: public, research and education, and urban land uses. The predominant use of the land within the watershed is for recreational purposes.

2.5.1. Land Ownership

The land within the Bolinas Lagoon watershed covers approximately 10,700 acres within Marin County. Figure 2-9 shows the distribution on land ownership and jurisdiction within the Bolinas Lagoon watershed. Sixty six percent of this land is publicly owned and 34 percent is privately held. Most of the acreage administered by government agencies is undeveloped open space property, as is the 1,014 acres owned by the Audobon Canyon Ranch. In total, approximately 75 percent of the Bolinas Lagoon watershed is set aside for conservation purposes. The privately held acreage is mostly located low in the watershed on gently sloping areas that have low erosion hazard and are devoted to residential and agricultural uses.

Figure 2-9. Land Use and Ownership in Bolinas Watershed



2.5.2. Public Land Use

Public land within the watershed is managed by federal agencies, including the National Park Service, and by state agencies, including the California Department of Parks and Recreation.

Federal Land

A total of approximately 4,121 acres are part of the Golden Gate National Recreation Area (GGNRA) and 2,647 acres make up Point Reyes National Seashore (PRNS). Land within the Olema Valley portion of the GGNRA makes up most of the watershed east of Bolinas Lagoon. The property includes forested canyons, tree-lined ridges, open grassy slopes, and historic farm buildings. The Olema Valley property is zoned as Natural Space, for which the management emphasis is on the conservation of natural resources and processes and the accommodation of uses that do not adversely affect these resources and processes (NPS 1992). This land is largely undeveloped and provides numerous hiking and biking trails. GGNRA also manages three properties on the west side of the lagoon that occupy a combined area of approximately 45 acres (Fong 2000a).

Property within the PRNS covers most of the watershed west of Bolinas Lagoon. This property is used for purposes similar to those of Olema Valley, including hiking and mountain biking.

Stinson Beach is managed for typical beach activities, including swimming and sunbathing. The beach also provides barbecue and picnic facilities.

State Land

A small portion of Mount Tamalpais State Park is present at the southern tip of the Bolinas Lagoon watershed between McKinnon Gulch and Stinson Gulch above Stinson Beach. Approximately 1,572 acres of the park fall within the watershed.

Local Government Land

Marin County Open Space District owns Bolinas Lagoon itself as well as a small parcel immediately adjacent to the west side of the lagoon north of the community of Bolinas. A small area below the high water line of the lagoon was used as an unofficial dumpsite by Bolinas residents in the 1950s and 1960s. Refuse was dumped, burned, and bulldozed into the mud on the edge of the lagoon (Camiccia 2001).

The Marin Municipal Water District holds land on the west side of the lagoon. Although not landowners themselves, the unincorporated Marin County communities of Bolinas and Stinson Beach are both within the watershed. Land use within the two communities is primarily residential.

Private Land Ownership

The Audubon Canyon Ranch, an environment, research, and education organization, is the largest private landowner, with 1,014 acres in the eastern portion of the watershed. The remaining private lands, which cover approximately 2,636 acres, are owned by individuals and are located throughout the watershed, but primarily in the communities of Bolinas, Stinson Beach, and Seadrift.

2.5.3. Research and Education Land Use

While much of the public lands discussed above have research and education as a component of their management strategy, Audubon Canyon Ranch's Bolinas Lagoon Preserve is managed primarily for research and education activities.

2.5.4. Urban Land Use

Bolinas

The unincorporated town of Bolinas (population 1,555) is located between Bolinas Lagoon and the Pacific Ocean. The portion of Bolinas within the watershed is zoned for single-family residential, residential commercial, open space, and agriculture.

Stinson Beach

The Stinson Beach community (population 630) is located primarily southeast of the lagoon, but also includes the Stinson Beach sand spit (ABAG 1990). Additional areas are zoned for retail, residential, commercial, open space, and agriculture.

Seadrift

Seadrift is a series of subdivisions occupying the northern third of the Stinson Beach sand spit on the southern edge of Bolinas Lagoon, and includes the eastern Dipsea Road fill area. Located in the center of Seadrift is a 45-acre human-made lagoon, also privately owned. No commercial activity currently occurs at Seadrift (Kamieniecki 2000).

2.5.5. Parks

Bolinas Lagoon Open Space Preserve

Managed by the Marin County Open Space District, the 1,100-acre Bolinas Lagoon Open Space Preserve encompasses the area of the lagoon itself. Ownership of the lagoon tidelands was transferred to Marin County from the California State Lands Commission in 1972 and was originally managed by the Marin County Parks Department. Management of the lagoon was transferred to Marin County Open Space District in 1988 (Bramham 2000). The lagoon is part of a larger protected natural habitat which includes Gulf of the Farallones National Marine Sanctuary, PRNS, Central California Coast Biosphere Reserve, Mount Tamalpais State Park, and the GGNRA. The lagoon is recognized as a Ramsar wetland site of international significance[4].

Golden Gate National Recreation Area

GGNRA is a multi-parcel unit of the National Park Service, covering 76,500 acres in three counties. Among the properties under its jurisdiction is the section of the Bolinas Lagoon watershed on the east side of Highway 1, running from a point approximately 2 miles north of the lagoon to its border with Mount Tamalpais State Park on the south edge of the watershed.

Mesa Park

Mesa Park is a twelve-acre park located on Mesa Road in Bolinas. The land was originally privately owned and was acquired by the Bolinas Community Public Utility District (BPUD) (Buchanan 2001a) in the late 1970s. Mesa Park is now jointly owned by the BPUD and the Bolinas-Stinson Union School District, and managed by the appointed Mesa Park Board of Commissioners (Buchanan 2001b).

Mount Tamalpais State Park

Part of the upper section of the Easkoot Creek watershed runs through Mount Tamalpais State Park. The park includes 6,300 acres of redwood groves and oak woodlands with a spectacular view from the 2,571-foot peak (California State Parks 1999).

Point Reyes National Seashore

PRNS is an independent unit of the National Park System, covering nearly the entire Point Reyes peninsula. Part of the park extends into the Bolinas watershed, on the west side of Highway 1 (NPS 1999).

Stinson Beach Park

Stinson Beach Park was originally a county park, but by 1977 it was transferred to the federal government. It is now administered by GGNRA. The park covers approximately 50 acres, including 0.6 miles of beach (Giambastiani 1999).

[4] For more information on Ramsar designations see http://www.ramsar.org.

Upton Beach

Upton Beach is an approximately 1.5 mile public beach that is bordered by Seadrift Beach and by the GGNRA. The beach has been managed by Marin County since 1932, and is zoned for recreational use only. To date, there has been no recreational development at Upton Beach (Jauch 2000).

2.6. Synthesis of Previous Bolinas Lagoon Sediment Studies

Numerous studies of sediment deposition rates in Bolinas Lagoon have been conducted using different methods and yielding different results. Three different estimates exist for the average rate of sediment deposition to Bolinas Lagoon during the Holocene period. In addition there are conflicting estimates regarding when the greatest rate of sediment deposition occurred, in the nineteenth or twentieth century. There is further conflict regarding the largest source of sediment: whether it comes from streams draining the watershed, by wind deposition, or through transport by tidal action (Table 2-2).

2.6.1. Holocene Period Deposition Rate Estimates

Warhaftig

Warhaftig (1970) made an estimate of the rate of filling of the Lagoon over the Holocene (last 8,000 years) by reconstructing the longitudinal profile of Pine Gulch Creek's original outlet. Warhaftig found evidence that 10,000 years ago the outlet of Pine Gulch Creek was nine miles south of Duxbury Point and 120 feet below current sea level. From this information he determined the depth of Bolinas Lagoon prior to the rise in sea level and determined the rate of sediment in-filling for the lagoon. Warhaftig estimated the lagoon filling rate at 0.25 to 1.0 feet per 100 years for the past 5,000 years; a volumetric rate of 4,000 to 18,000 cy/yr.

USGS

In 1971 USGS conducted an acoustic survey to determine the original surface of the lagoon bottom prior to Holocene era sediment infilling (Rowntree 1973). The results indicated the pre-Holocene lagoon bottom was approximately 105 feet lower than the current level, giving an average deposition rate of 1.3 feet per 100 years over the past 8,000 years, or 23,000 cy/yr.

Bergquist

Bergquist (1978) used sediment core samples to arrive at his estimate of deposition rates over the past 6,500 years: 3-4 mm/year or 16,000 cy/yr. This long-term average rate of sediment deposition is equivalent to the 'background' rate of sedimentation. Bergquist determined that this estimate of the 'background' rate of sedimentation was approximately the same as the sedimentation rate for the 1906 to 1978 time period, indicating that recent deposition rates are similar to long-term average rates.

Table 2-2. Summary of Estimated Annual Deposition Rates to Bolinas Lagoon

Author, Year	Time Period	Portion of Budget Represented	Annual Deposition Volume (cubic yards)	Range (cubic yards)	Deposition Rate (tons/sq km/yr)	Method Used	Notes
Ritter, 1973	1968-1969	Aeolian	31,000		n/a	Bagnold-Kadib aeolian transport equation	Rowntree has much criticism for this estimate
Tetra Tech, 2001	1951-2001	Fluvial	10,000		275	Rapid evaluation of sediment budget (Reid and Dunne 1996)	Based on field observations made within the watershed.
Rowntree, 1973	1939-1968	Fluvial	4,000		112	Adjusted data from Ritter's estimates by including an estimate of bedload on eastside streams and logging of Sweet Ranch.	
Rowntree, 1973	1939-1969	Fluvial	17,000		498	Estimate based on Warhaftig's assignment of relative percentages of 47% for tidal contribution versus 53% for fluvial contribution to the Lagoon.	The 47% value for tidal deposition uses the 15,500 cubic yard value estimated by Rowntree.
Ritter, 1973	mid-1800's logging related	Fluvial	19,920		583	Multiplication of Ritter's fluvial erosion estimate by 5 to account for logging related erosion. Ritter used Burgy's observation of 5 fold increase in SSC on Righetti Ranch stream after logging.	Rowntree disputes this estimate.
Ritter, 1973	1968-1969	Fluvial (whole watershed)	4,083		114	Suspended sediment monitoring at mouth of Pine Gulch, Audubon and Morses Creeks in WY 1968 and 1969 plus bedload for Pine Gulch.	
Ritter, 1973	1968-1969	Fluvial -east side streams	458		13	Suspended sediment monitoring at mouth of Pine Gulch, Audubon and Morses Creeks in WY 1968 and 1971.	Ritter extrapolated SSC data from Audubon and Morses to all east side streams, but did not include bedload for eastside streams
Ritter, 1973	1968-1969	Fluvial -Pine Gulch	3,625	318 - 6,292	101	Suspended sediment and bedload monitoring at mouth of Pine Gulch Creek in WY 1968 and 1969.	On December 28, 1968 a one day total of 2,822 cubic yards of sediment yield was recorded at Pine Gulch
Ritter, 1973	1968-1969	Floodtide	115,000		n/a	Suspended sediment monitoring at mouth of lagoon on two days.	Ritter concluded that tides exported more sediment from the lagoon than they deposited.
Ritter, 1973	1968-1969	Ebbtide	-123,000		n/a	Suspended sediment monitoring at mouth of lagoon on two days.	Ritter concluded that tides exported more sediment from the lagoon than they deposited.

Author, Year	Time Period	Portion of Budget Represented	Annual Deposition Volume (cubic yards)	Range (cubic yards)	Deposition Rate (tons/sq km/yr)	Method Used	Notes
Rowntree, 1973	1859 -1968	Tidal transport of cliff erosion	15,500		n/a	Adjusted data from Ritter and Helley's estimates of cliff erosion north of the Lagoon.	Assuming approximately 1/3 of cliff erosion enters the Lagoon through tidal action.
Helley & Ritter (from Rowntree, cited from Ritter, 1969b)	Recent	Tidal transport of cliff erosion	24,000		n/a	Measurement of seacliff erosion north of the Lagoon and estimate of transport into Lagoon.	Assuming approximately 1/3 of cliff erosion enters the Lagoon through tidal action.
Bergquist, 1978	Holocene	Total	15,787		n/a	sediment cores	
Bergquist, 1978	Logging era (1849-1860)	Total	78,935		n/a	sediment cores	
Bergquist, 1978	Modern (1906-1978)	Total	15,787		n/a	sediment cores	
Bergquist and Warhaftig, 1993	1968-1988	Total	51879*	38,648 - 65,111	n/a	Bathymetric Surveys	* only the range of values was presented in the 1993 report, the average was calculated for this report
US ACE, 1999	pre 1850	Total	16,666		n/a	Bathymetric Surveys	
US ACE, 1999	1968-1978	Total	84,000		n/a	Bathymetric Surveys	increase in sedimentation attributed to logging
US ACE, 1999	1988-1998	Total	26,296		n/a	Bathymetric Surveys	
Warhaftig (from Rowntree thesis), 1973	Holocene	Total	18,000	4,367 - 17,365	n/a	Reconstruction of Lagoon depth based on observation of ancient outlet of Pine Gulch Creek 9 miles south of Duxbury Point.	Warhaftig notes that this could be an overestimate.
McCulloch, USGS. (from Rowntree thesis)	Holocene	total	23,000		n/a	Acoustic sampling of pretransgression surface below Holocene sediements in Lagoon.	results only accurate to between 2 times and one order of magnitude
Ritter (from Rowntree thesis)	modern (1939-1968)	total	25,800	20,800 - 30,900	n/a	USGS resurvey of transects in Bolinas Lagoon	

2.6.2. Logging Effects on Maximum Sedimentation Rates

The two highest estimates of sediment deposition rates are nearly the same (80,000 cy/yr) and correspond to the eras in which logging occurred in the Bolinas watershed. However, the estimated deposition rate for the 1968 to 1978 logging era by the USACE (1999) conflicts with estimates of sediment deposition rates for that same period by Bergquist (1978).

USACE

By comparing the 1939 and 1968 bathymetric surveys of the lagoon, Ritter (1973) estimated that approximately 25,800 cy/yr were being deposited in Bolinas Lagoon. The USACE (1999) estimated that sediment deposition rates increased to 84,000 cy/yr between 1968 and 1978 and then decreased to 26,000 cy/yr between 1988 and 1998 (USACE 1999). These estimates were based on bathymetric survey data that was collected every ten years from 1968 to 1998 and analyzed by the USACE for their 1999 report (currently being revised). The USACE attributed the 58,000 cy/yr increase in sedimentation during the 1968 to1978 time period to two logging operations, covering 510 acres, present at the time in the Pine Gulch Creek watershed.

It has not been determined what portion of the increase in sedimentation was the result of the two logging operations. For comparison, Redwood Creek near Orick, California, which has a similar geologic type and was logged much more intensively than Pine Gulch Creek, has one of the highest sediment production rates in California at 5,845 tons/sq mi/yr.

Based on field observations and the comparison to Redwood Creek, it is unlikely that the observed increase in sedimentation in Bolinas Lagoon during the 1968 to 1978 time period was due entirely to the Pine Gulch Creek logging operations.

Bergquist

Bergquist estimated that sediment deposition rates were 13-16 mm/year or 84,000 cy/yr during the first cycle of logging in the watershed (1849 to1858). These rates are three to four times higher than he estimated for the long term average rate and for 1906-1976 time period. He also reported an increase in sediment grain size from what appeared to be chips or sawdust from redwoods (Bergquist 1978).

Contrary to the USACE (1999) report, Bergquist (1978) did not detect any increase in sedimentation during the 1968 to 1976 time period. He concluded that sediment deposition rates were the same during the 1906 to 1976 time period as they were for the pre-1849 time period. Bergquist characterized the 1906 to 1976 time period as, “a time of fine-grained sedimentation with no indicators of major sedimentary changes.”

However, estimates of sediment deposition included in the Bergquist and Warhaftig (1993) report indicate that sediment deposition rates were well above background (i.e., pre-1849) in the twentieth century. In contrast to Bergquist’s (1978) earlier characterization of sedimentation in the twentieth century having, “no indicators of major sedimentary changes,” he states in the 1993 report that results from the bathymetry studies, “suggest a 1.5 to 2.5-fold increase in the rate of sedimentation between 1939 and 1988.”

The two reports (Bergquist 1978 and Bergquist and Warhaftig 1993) use different methods to arrive at their results; the 1978 report relied on sediment cores, while the 1993 report used existing bathymetric survey data from 1968 and 1988. This partly explains the difference in the results, but does not resolve which estimate is more likely to be correct.

Results regarding sedimentation rates and tidal prism volumes from the Bergquist and Warhaftig 1993 report are similar to those reported by the USACE in their 1999 report. However, Bergquist and Warhaftig (1993) chose not to use the 1978 survey data in their analysis and characterized it as, “essentially useless for calculation of sedimentation or tidal prism.” Because of its exclusion of spot altitudes, the contour intervals on the maps were too coarse (2-foot intervals), resulting in no contours being displayed for the area below high tide. It is not clear if this is the same 1978 data set that USACE used in its 1999 report.

Nor is it clear why the dramatic increase in sedimentation rates observed by USACE (1999) and Bergquist and Warhaftig (1993) using bathymetric surveys were not detected by Bergquist’s (1978) sediment core analysis. Possible answers include: 1) errors exist for either the bathymetry (e.g., the 1978 data) or sediment core data; or 2) one of the methods does not yield accurate results. It seems that either Bergquist’s sediment core work yields an underestimate of sedimentation rates this century or the bathymetry data used by USACE (1999) and Bergquist and Warhaftig (1993) yields overestimates of the rates of sedimentation.

Munro-Fraser Lumber Export Estimate

Munro-Fraser (1880) reported that 15 million board feet (MMBF) of lumber was exported from Bolinas Lagoon between 1849 and 1858. A conservative estimate of timber volume for old growth redwood stands is 100,000 board feet per acre.

Thus, 150 acres could produce the 15 MMBF of lumber reported by Munro-Fraser. However, utilization rates and sawmill efficiency were lower during the mid-nineteenth century, so we employ more conservative yield estimates, suggesting that no more than 500-1000 acres would have been required to produce the reported 15 MMBF.

Based on field observation of old cut stumps throughout most of the watershed, it is likely that Munro-Fraser's estimate of lumber production was low. Other factors, such as grazing, may have contributed to the reported increases in sedimentation. Furthermore, it is possible that cordwood production caused increased erosion in the watershed; Van Kirk (2001) reports that over 500,000 cords of wood were exported from Bolinas Lagoon in the 1870s; therefore occurring after the time period for which Bergquist estimates that increases in sedimentation occurred. It does not seem likely that the volume of sediment reported by Bergquist could have been produced from only 500-1000 acres of logging. However, a combination of logging, cordwood production, mining, grazing and wild fires could have been responsible for the increase in sediment deposition reported by Bergquist (Van Kirk 2001).

2.7. Rates and Sources of Sediment Deposition in the Twentieth Century

There are multiple estimates of sediment deposition rates in Bolinas Lagoon for the twentieth century. Bergquist (1978) estimated the 1906 to 1978 deposition rate at 16,000 cy/yr. Using bathymetry survey data Bergquist and Warhaftig (1993) estimated that the deposition rate for 1968 to 1988 was between 38,648 to 65,111 cy/yr. Ritter estimated that the rate from 1939 to 1968 was 25,800 cy/yr. USACE estimated that the deposition rate from 1968 to 1978 was 84,000 cy/yr, but dropped to 26,296 cy/yr for the 1988 to 1998 period. The preceding estimates of sediment deposition are all based on bathymetry survey data, except for Bergquist's 1978 estimate, which is based on sediment core data. The estimates of deposition rates for the twentieth century are all within the same order of magnitude, but vary widely within the order. In summary, previous studies indicate that twentieth century sediment deposition rates in Bolinas Lagoon range from 15,000 to 84,000 cy/yr (Table 2-1). The USACE (1999) estimate of 26,296 cy/yr for the 1988 to 1998 time period is the most recent available.

Sources

Three possible sources of sediment to the Bolinas Lagoon are:

1. Transport from within the watershed

2. Transport by tidal action
3. Transport by wind

Ritter (1973) reported that wind and tidal action were the two biggest potential sources of sediment transport. Using the Bagnold-Kadib aeolian transport equation, he estimated wind deposits of 31,000 cy/yr into Bolinas Lagoon. Rowntree questions Ritter's estimate due to:

1. Errors in the equation were reported by the equation's author, Kadib.
2. The logical source of wind driven material would be the Stinson Beach sand spit, however, the spit is mostly stabilized with structures. Regardless, the artificial lagoon would trap most wind transported sediment.
3. The dominant mineralogy in the lagoon is shale (Monterey Formation), not the quartz sands found at Stinson Beach.
4. Since the sand spit is south of the lagoon, south winds are required to move the sand into the lagoon. However, south winds are most often associated with wet storms which actually result in compaction of sand and transport inhibition (Rowntree 1973).

If Rowntree's vigorous critique of Ritter's wind transport theory is accurate, it is unlikely that wind is the dominant sediment source for Bolinas Lagoon. This leaves watershed and tidal transport as the most likely remaining sources.

Ritter (1973) measured suspended and bedload tidal transport of sediment into and out of the lagoon (at the mouth) in 1968 and 1969. He found that an average of 115,000 cy/yr was transported into the lagoon on floodtide and 123,000 cy/yr was transported out of the lagoon on ebbtide. Thus Ritter calculated that there was a net export of sediment out of the lagoon from tidal action of 8,000 cy/yr. Although Ritter noted that his measurements were made during calm periods as opposed to during winter storms when larger volumes of sediment are likely to be moved (i.e., creating a different net outcome).

Ritter, Warhaftig, and Rowntree all made estimates of tidal transport of material into the lagoon from the eroding cliffs north of the mouth of the lagoon. The estimates ranged from 15,000 to 24,000 cy/yr (Table 2-2). It is unknown how much of the transported cliff material was actually deposited in the lagoon rather than re-suspended and transported back out of the lagoon. Tidal transport of sediment and patterns of circulation and redistribution within the lagoon are not the primary focus of this report. However, these dynamics may have a significant influence on the lagoon's overall sediment budget. Given the volumes of tidal sediment transport observed by Ritter on calm days, it is possible that this process dominates the lagoon's sediment budget, overshadowing contributions from within the watershed.

2.8. Previous Estimates of Sediment Production from the Watershed

Of these previous studies only Ritter and Rowntree made estimates of the quantity of sediment delivered to the lagoon from streams within the watershed.

Ritter

Ritter (1973) measured discharge and suspended sediment concentration in Pine Gulch, Morses, and Audubon creeks during 1968 and 1969. Bedload transport was measured in Pine Gulch Creek and estimated for the two eastside streams. From these data, Ritter determined that the total sediment contribution from streams in the watershed was 4,100 cy/yr (114 tons/sq.km/yr): 3,600 cubic yards from Pine Gulch and 500 cubic yards from all of the eastside streams combined (Table 2-2).

Rowntree

Rowntree (1973) made an estimate of the quantity of sediment produced by streams in the watershed using a formula developed by Warhaftig (1970). Warhaftig's formula was based on the abundance of different mineral types in the lagoon sediments in relation to the mineral composition and spatial extent of each of the three geologic types found in the watershed. Using Warhaftig's formula, Rowntree estimated that 17,000 cy/yr were delivered to the lagoon via streams in the watershed.

Comparison

The estimates of both Ritter and Rowntree are in different orders of magnitude, which makes reconciliation difficult. Ritter's estimate is based on actual data from stream discharge, which gives it some validity, although his sample size is small (only two years of data). Rowntree's estimate, by contrast, is based on a formula developed by Warhaftig (1970), which predicts that 53 percent of lagoon sediment comes from within a watershed and 47 percent comes from tidal transport of eroded cliff material. Rowntree estimated that 15,500 cy/yr of cliff material were transported into the lagoon, leaving the remaining 17,500 cy/yr (53 percent) originating from within the watershed. It is not clear which of the two estimates of sediment deposition originating from the watershed is more accurate.

3. METHODS

The first step in constructing this partial sediment budget for the watershed is to identify the processes mobilizing sediment (Lehre 1982, Reid and Dunne 1996). Two reconnaissance field trips were conducted to characterize these processes within the Bolinas Lagoon watershed. Local residents were also interviewed. Furthermore, all available aerial photographs and previous sediment studies were reviewed. Based on these methods, we determined that the dominant erosion processes in the watershed were:

- Landslides (shallow landslides, rotational slumps, and earth flows)
- Gullying
- Bank erosion
- Soil creep
- Road-related erosion (road failure, road-triggered slides, and in-channel roads)

Based on this preliminary understanding of the watershed a methodology was developed to quantify the various inputs of sediment into the stream network. The process or rates of sediment transport through the stream network were not determined due to the complexity and uncertainty associated with the procedures and limited project scope (Reid and Dunne 1996).

What can be said, however, is that the stream network acts as an averaging function, integrating the sedimentation rate over time. Because of the natural conditions present in the watershed, the stream is never starved for sediment; what is deposited in one reach will be regained in another. Therefore, sedimentation is limited by stream power, or capacity to move sediment, and not by the availability of material. Thus, by assuming that all mobilized material is eventually delivered to the lagoon over long periods of time, one can develop an annual average rate of sediment delivery that, over the long term, will not be affected by delayed or accelerated routing of sediment through the system.

Due to the dense forest canopy covering most of the Bolinas Lagoon watershed and the small size of landslides (average area of 130 sq m), few landslides were visible on historical aerial photographs. Other researchers have also commented that observing landslides in forested areas in Marin County on aerial photographs was difficult and yielded uncertain results (Lehre pers. comm. 2001, Ellen and Wieczorek 1988). Consequently, our sediment input budget was based on a combination of field observations for easily observed processes (landslides, road-related erosion) and literature values for more complex processes (bank erosion, soil creep, road cut bank erosion).

Surface erosion from roads and large areas of unvegetated soil is not a major erosion process in the Bolinas Lagoon watershed due to the sparse presence of exposed bare soil. Field work consisted of stream, hillslope, and road surveys for sediment sources. Figure 3-1 shows the survey locations within the watershed. The input-only sediment budget was estimated for the past 50 years (1951 to 2001), representing the time period when erosion scars are still evident in the field.

3.1. Stream Surveys – Landslide Inventory

To determine distinct erosion patterns by geology and stream size, surveyed stream segments were stratified over the Franciscan, Monterey, and Merced geologic units and first through fourth order streams. Channel segments ranged from 0.1 to 0.5 kilometers (km), with a total of 7 km of stream channel surveyed; this constitutes approximately 5 percent of the total stream network in the watershed. The volume and approximate age for each erosional feature (shallow landslide, earth flow, slump, gully) observed along a measured length of channel was estimated. The volume of each feature was estimated by measuring the average width, depth, and length of the erosional scarp. Figure 3-2 shows typical data collection at two separate mass wasting sites. The proportion of sediment delivered to the channel was determined by estimating the size of the scarp and the amount of sediment remaining on the slope. The age of each feature was estimated in ranges of less than 10, 10 to 20, 20 to 30, 30 to 40, or 40 to 50 years. Where trees were present in scarps, ages were estimated by coring trees (Figure 3-3) and counting growth rings or whorls. Scarps with bare soil or sparse vegetation were generally considered less than 10 years old. When accessing streams and roads, upslope and midslope areas were surveyed for erosion sources. In general, most erosion sources were found adjacent to streams or related to roads.

3.2. Road Surveys

Road survey methods were similar to stream survey methods. Estimates of the volume, age, and percent delivery to the nearest channel were made for each erosional feature (landslide, fill or cutbank failure, gully, surface erosion). The USGS 7.5-minute topographic maps, which were used as base maps for all field work, only show primary paved roads and some unpaved roads such as McCurdy Trail. Most of the unpaved roads shown on the map and a sample of the paved roads were surveyed as part of the study, giving a total of 8.4 km of road surveys

(Figure 3-1). There is no record or map of abandoned logging or ranch roads, nor are they visible on the historic aerial photographs. Consequently, un-mapped roads in the watershed were surveyed as encountered during stream and hillslope surveys.

Figure 3-1. Map of Field Survey Locations in the Bolinas Lagoon Watershed

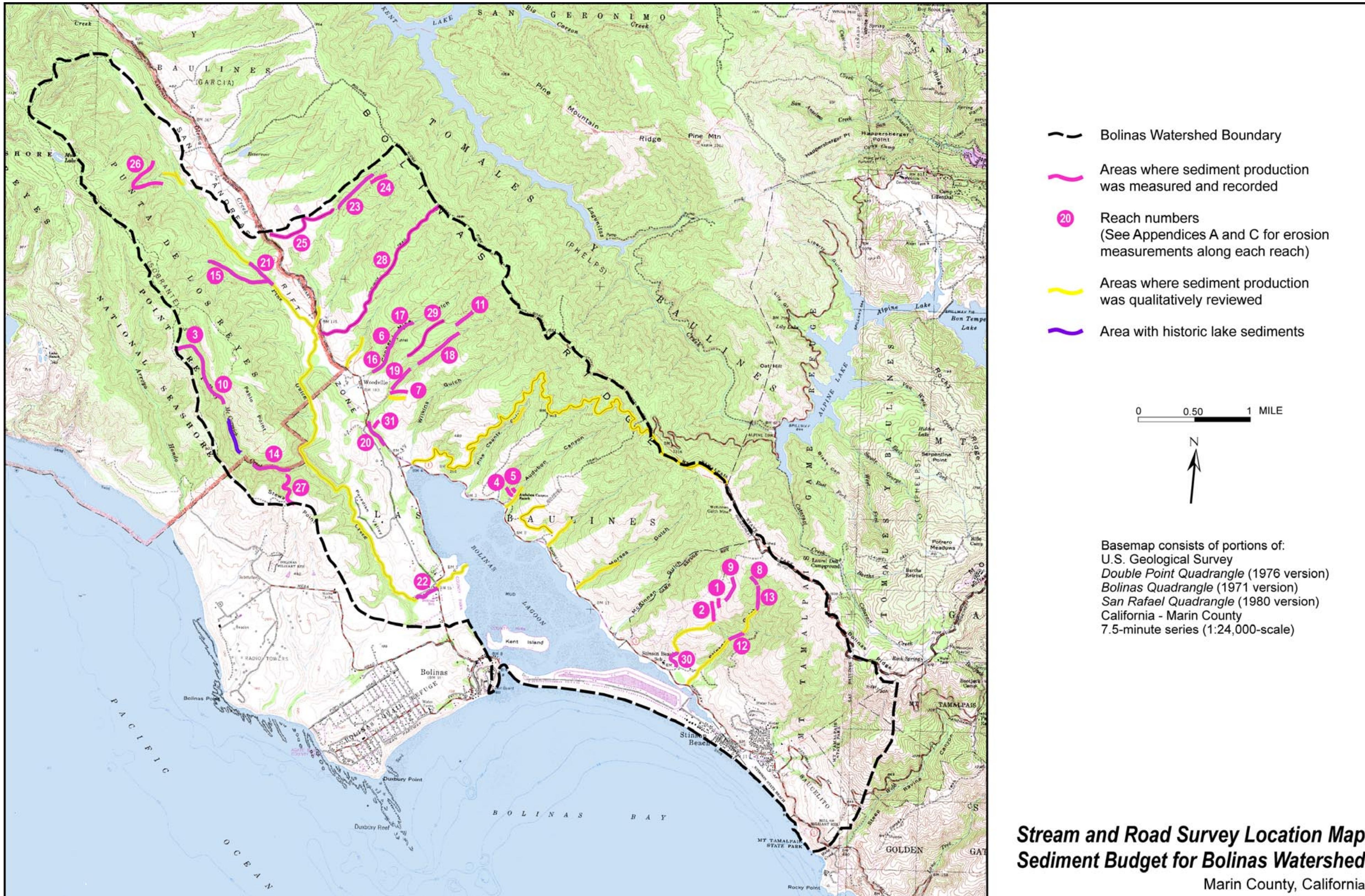


Figure 3-2. Streamside Landslide Earthflow on the Mainstem of Pine Gulch Creek

Figure 3-3. Example of Tree Coring Technique on Tributary to Pine Gulch Creek

4. CALCULATIONS AND RESULTS

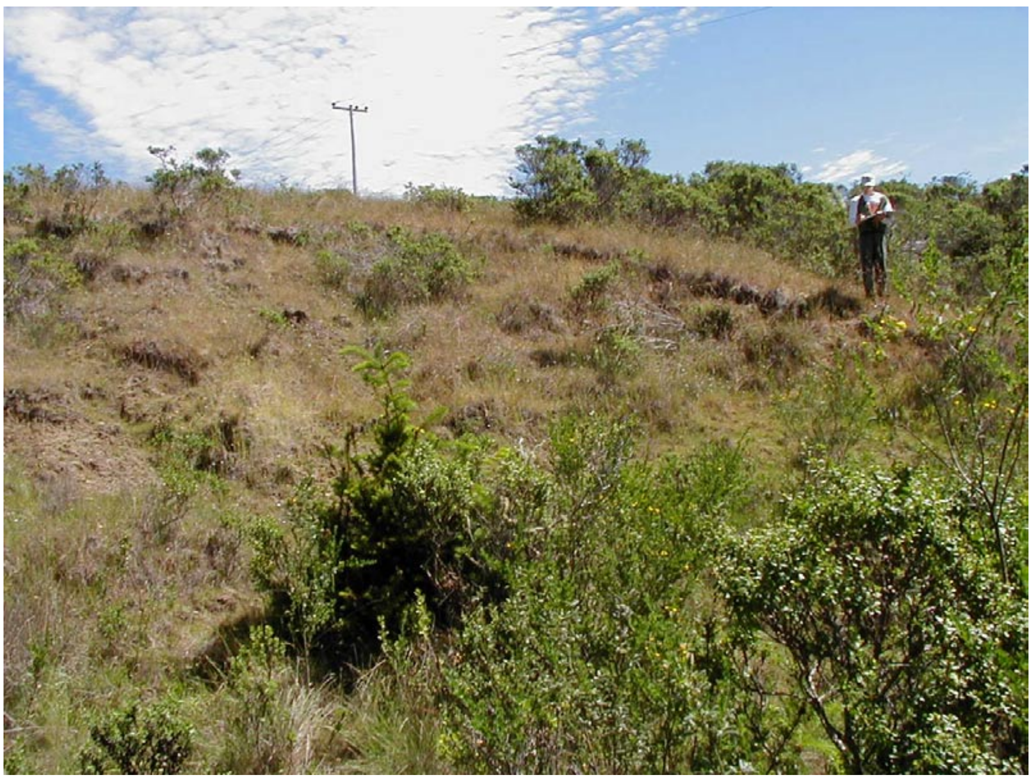
4.1. Mass Wasting

Of the 79 erosional features inventoried during the Bolinas Lagoon watershed stream surveys, 86 percent were shallow streamside landslides (Figure 4-1), 5 percent were rotational slides or slumps, 5 percent were earth flows (Figure 4-2), and 4 percent were gullies. A summary of the percent contribution of each mass wasting process is presented in Figure 4-3. Appendix A summarizes the landslide inventory data collected during field surveys. Streamside landslides, typically less than one meter in depth, generally occurred along confined channels and failed along shallow planar shear surfaces. Slumps (i.e., failures along rotational surfaces) were generally greater than 1.5 m in depth. Observed earthflows were large fluid-like mass movement of hillslopes and natural gullies were associated with either erosion at the base of earth flows or head cutting in low order channels.

Figure 4-1. Streamside Landslide on Copper Mine Gulch

Prior to calculating a landslide rate for the 50-year period, frequency-magnitude histograms of the inventoried slides were plotted by decade to determine the ability of field surveys to detect older slides (Figure 4-4). Assuming the relative frequency distribution of landslide sizes is similar over time, the plots indicate that small landslides older than 20 years were under-detected. The 10 and 20-year periods show similar distributions, but the 30-, 40-, and 50-year periods depart from the expected distribution. Confidence in the ability to detect older large slides (>400 tons) is high due to the visible lateral and head scarp and conspicuous even age tree stands within the scarp. In order to recreate the distribution for undetected older smaller slides, the best-fit regression equation from the 10-year period landslide distribution was applied to all decades based on the number of observed 400-ton landslides for each decade (Figure 4-4). Appendix B summarizes the corrections to the landslide distributions.

Figure 4-2. Unstable Section of Earthflow Delivering Sediment to Lower Lewis Creek



Using the corrected distributions for each decade, a landslide rate of 233 tons/sq km/yr was calculated by summing the total landslide mass (22,080 tons), dividing by the budget period (50 years) and the length of stream surveyed (7.2 km), and multiplying by the stream density for the watershed (3.8 km/sq km).

$$\text{Landslide Rate (tons/sq km/yr)} = \frac{\text{Stream Density (km/sq km)} \times \text{Total Landslide Mass (tons)}}{\text{Budget Period (yrs)} \times \text{Stream Survey Length (km)}}$$

Landslide rates appeared to vary by both underlying geology and stream order (size). A trend of larger slides adjacent to higher order streams was observed

(Figure 4-5). Higher landslide rates in basins originating from the Monterey and Merced formations were also noted, compared to those in the Franciscan Complex (Figure 4-6). While the data collected shows significant differences in landslide rates from one stream order or geology to another, the limited sample size (5 percent of the stream network) did not allow for application of those rates exclusively within their own regions with great statistical confidence. Therefore the more conservative approach of applying an average rate across the entire watershed was used.

Figure 4-3. Percent of Mass Wasting by Process

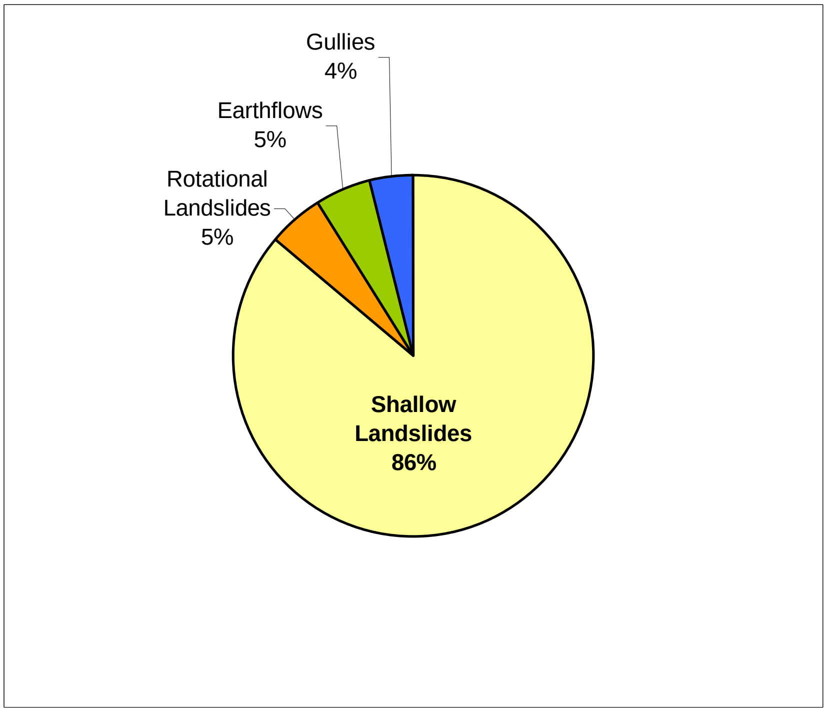


Figure 4-4. Landslide Frequency-Magnitude Histograms Based on Field Data (left) and Adjusted Histograms (right)

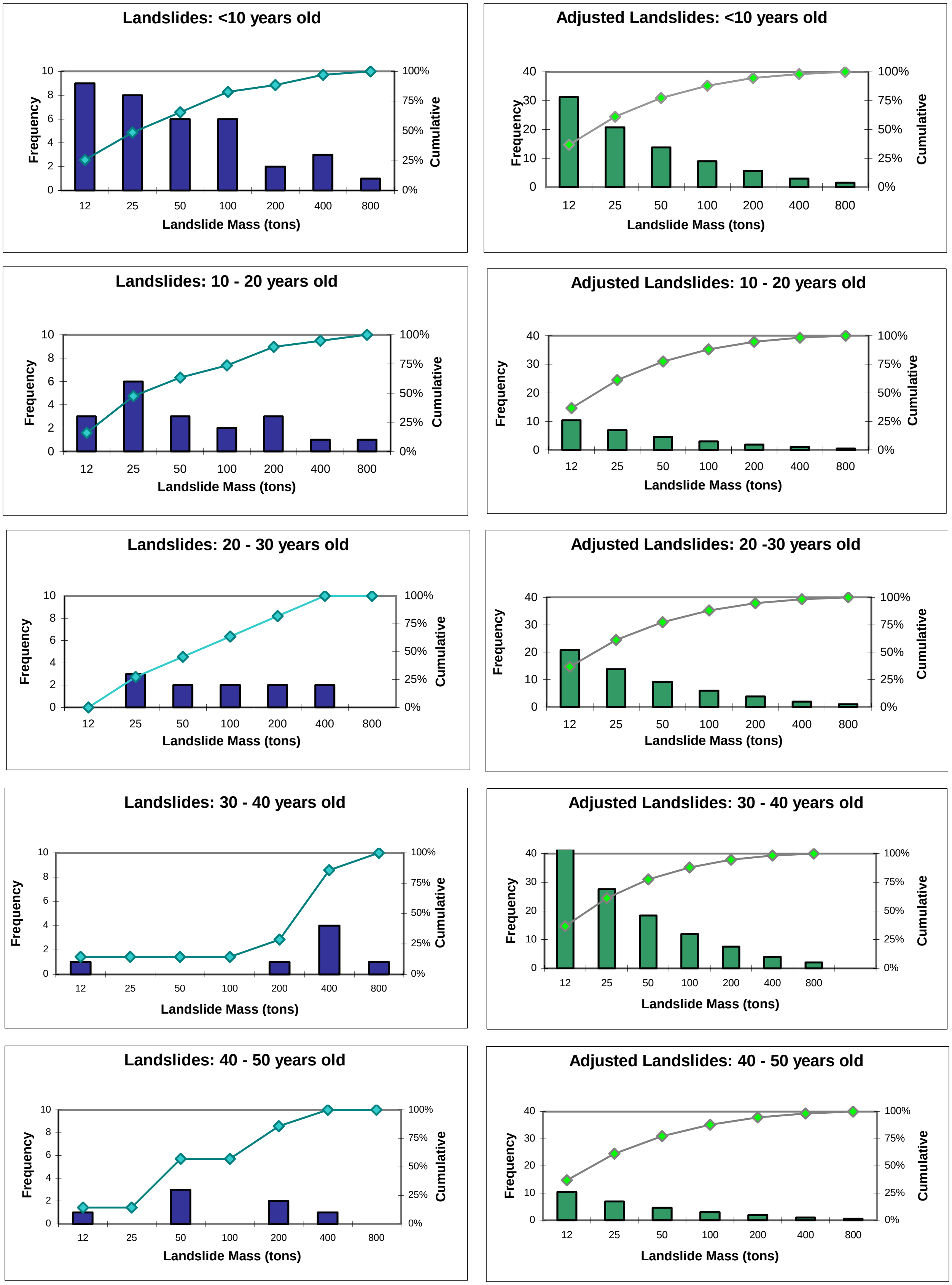


Figure 4-5. Observed Landslide Input Rates by Stream Order

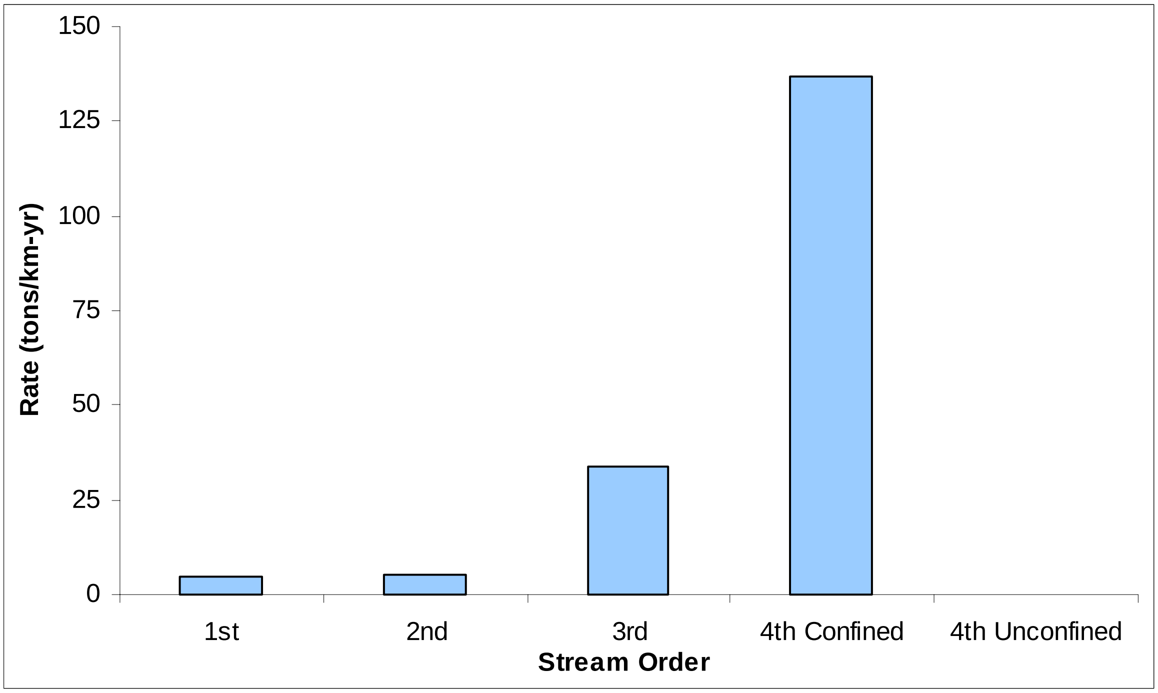
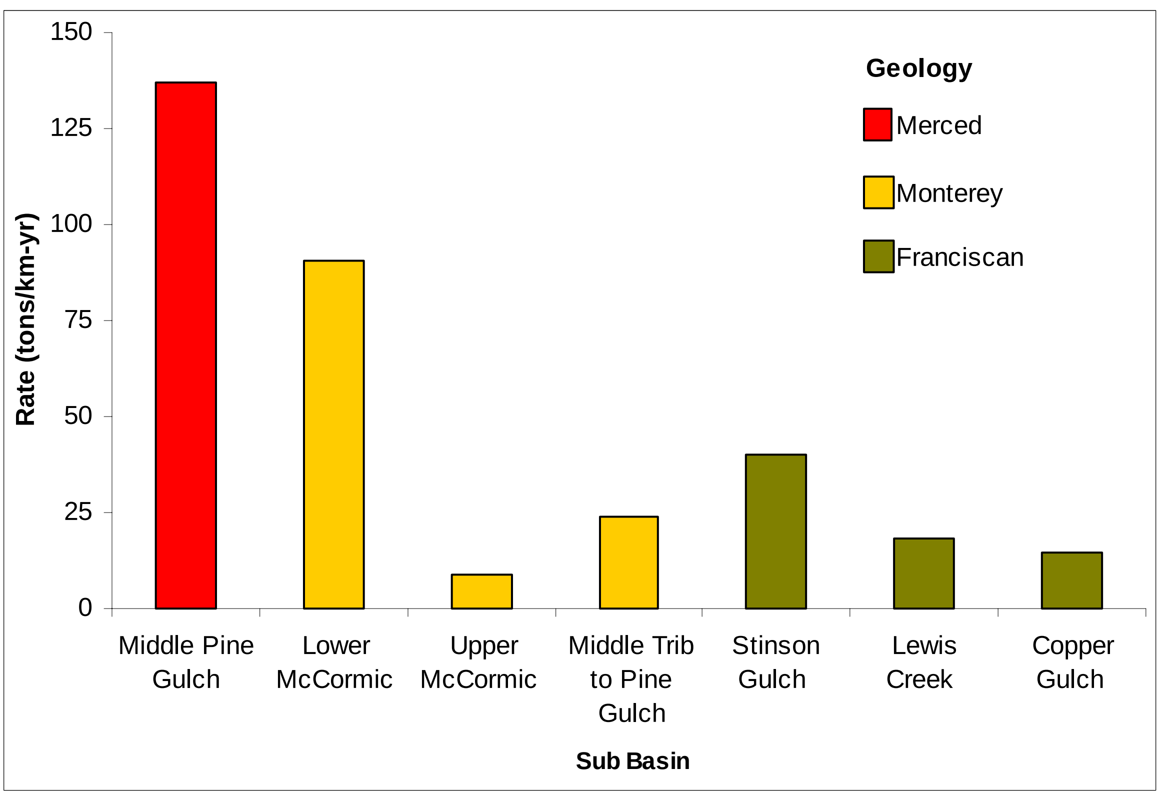


Figure 4-6. Observed Landslide Input Rates by Geology



4.2. Bank Erosion and Soil Creep

Due to time limitations, bank erosion and soil creep rates could not be quantitatively measured using erosion pins or repeated cross sectional surveys. Nor could rates be estimated using wood budgeting techniques as there were very few trees recruited to low order channels by bank erosion. Down trees on slopes adjacent to low order streams were often recruited by what appeared to be a combination of very loose soils on steep slopes (extreme soil creep).

Since field estimates were not possible, bank erosion and soil creep rates calculated in nearby Lone Tree Creek (Lehre 1982) were used as a surrogate. Applying the Lone Tree Creek bank erosion rate of 0.011 cubic meters per meter per year (average bank height of 2.5 meters) to the Bolinas drainage density for third and fourth order streams (1.1 km/sq km) yields a bank erosion rate of 18.5 tons/sq km/yr. Applying the Lone Tree Creek soil creep rate of 0.0003 cubic meters per meter per year (average colluvium depth of 0.4 meters) to the Bolinas drainage density for first and second order streams (2.8 km/sq km) yields a soil creep rate of 2.6 tons/sq km/yr for the Bolinas watershed.

4.3. Lake Sediment Budget Check

A fluvial terrace that had formed behind a former landslide dam on McCormick Creek was evaluated during the course of the field surveys. The landslide reportedly dammed the creek during the 1906 earthquake, forming a small lake. The dam eventually breached during a 1955 storm event (P. Martinelli, pers. comm., 2001). The terrace formed as McCormick Creek cut down through the accumulated lake sediments. The scarp from the landslide was massive (approximately 1,000 square meters). The terrace, which formed in a confined section of the channel upstream of the landslide deposit, was approximately 5 to 20 meters wide and 370 meters long. This 50-year sediment storage record for the McCormick Creek basin provides a check of our sediment budget estimate.

To estimate the volume of lake sediment, cross sections of the terrace were roughly surveyed at 100-foot intervals using a measuring tape and stadia rod (Figure 4-7). At each cross section, the slope of the valley wall was measured with a clinometer to estimate the cross-sectional channel shape prior to the dam. Assuming a flat surface from the left bank terrace to the right bank terrace, cross-sectional areas were calculated using WinXSPro (U.S. Forest Service 1997) and multiplied by the distance between cross sections to give a volume of sediment. The volumes were summed for the length of the terrace to give a total volume of stored lake sediment.

Figure 4-7. Field Measuring of Sediment Volume Accumulated in the Temporary Lake on McCormick Creek

The mass of sediment remaining in the reservoir (13,050 tons) was divided by 0.77 to account for a 77 percent trapping efficiency of small reservoirs (Dendy and Cooper 1984 as cited in Reid and Dunne 1996), and divided by the budget period (50 years, 1906-1956) and drainage area (1.8 sq km) to give an estimated sediment input rate of 189 tons/sq km/yr. Since the drainage area above the former landslide dam contains old growth Douglas fir and lacks indication of current or previous land management, the calculated rate most likely reflects natural processes only.

The sediment deposition rate calculated for the former lake on McCormick Creek may represent a background sediment deposition rate for the Bolinas Lagoon watershed. However, the background sediment deposition rate for the lake occurred during a different time period (1906-1955) than our current 50-year sediment budget (1951-2001), accounting for some difference between the calculated rates. The sediment deposition rate calculated for the lake is within 26 percent of our current input estimate (254 tons/sq km/yr) for natural inputs of sediment to the channel, including landslides (233 tons/sq km/yr), soil creep (2.6 tons/sq km/yr), and bank erosion (18.5 tons/sq km/yr).

4.4. Roads

Since a complete survey of all roads within the watershed was beyond the scope of work for this project, a sample of roads were surveyed and the resulting data was extrapolated to roads in the rest of the watershed. This task was complex because of the abundance of non-mapped roads and small sample size. The road network was divided into paved and unpaved roads.

4.4.1. Paved Roads

For paved roads the two dominant processes observed were cutbank erosion and gullying at culvert outlets.

Cutbanks

It was not possible to estimate cutbank erosion in the field since road maintenance activities routinely remove the apron of sediment accumulating at the base of cut banks. Consequently, we used a cutbank erosion rate of 7.6 tons/sq km/yr developed by Raines (1991). The cutbank erosion rate was applied to sections of Highway 1 and Bolinas-Fairfax Road that had cut banks (7.6 km), and then divided by the watershed area (43 sq km) yielding a cutbank erosion rate of 2.3 tons/sq km/yr.

Gullying

The contribution of gullying below culverts were estimated using measurements below two culverts on a section of Highway 1 south of Dogtown (Figure 4-8). This linear rate of erosion (790 tons/km) was applied to other paved roads constructed on hillslopes in the watershed, including the “13 turns” section of Highway 1, as well as the entire length of the Bolinas-Fairfax Road (8.2 km total). The total was then divided by the watershed area and budget period, yielding a culvert gullying rate of 3 tons/sq km/yr.

4.4.2. Dirt Roads

We observed different rates of erosion on dirt roads based on location. The four distinct locations for roads were mid-slope, ridge, inner gorge and in-channel. A further distinction was made between maintained and abandoned roads. There were fewer maintained dirt roads in the watershed than there were abandoned roads. Most of the maintained roads were on ridges or on gentle terrain in grassy areas with little connection to the channel network. Most of the abandoned roads were located in channels or in the inner-gorge (i.e., next to the stream). Sections of maintained and abandoned roads were surveyed in each of the locations and the erosion rates associated with each were determined. Estimates of erosion were limited to the past fifty years to correlate with the time period of this sediment budget.

Figure 4-8. Example of Gully From Paved Roads; (Broken Culvert at Highway 1 South of Dogtown)

Abandoned Logging Roads

Two logging operations are documented in the past fifty years of the watershed's history: Righetti Ranch and Sweet Ranch. Portions of both operations were surveyed and estimates of the road related erosion were made from each (Figure 4-9) The estimates were then extrapolated to the portions of the operations not surveyed. Righetti Ranch (90 acres, 0.36 sq km) yielded a road erosion rate of 340 tons/sq km/yr, or 2.8 tons/sq km/yr when prorated (0.36 sq km/43 sq km * 340 tons/sq km/yr) over the entire watershed. Sweet Ranch (400 acres, 1.7 sq km) yielded a road erosion rate of 48 tons/sq km/yr for the ranch area only, or 1.9 tons/sq km/yr when prorated (1.7 sq km/43 sq km * 48 tons/sq km/yr) over the entire watershed.

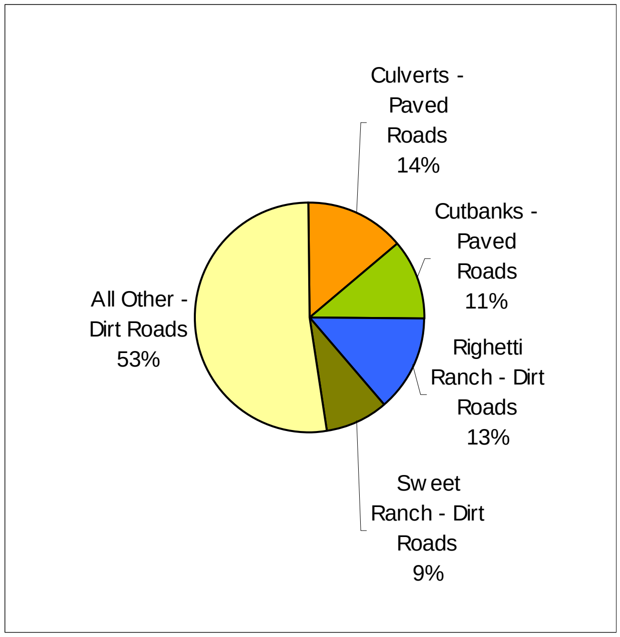
Figure 4-9. Abandoned Inner-Gorge Road at Righetti Ranch. (Note conifer trees growing on road prism and lack of visible surface erosion.)

Abandoned Non-Logging Roads

Abandoned dirt roads also contributed erosion over the past 50 years to areas outside the Righetti and Sweet Ranch logging operations. While some of these access roads were built by ranchers during this century, others were likely constructed during logging and/or mining during the late 1800s. Based on field observations, 2 km/sq km of these un-mapped roads were estimated to be present throughout the watershed.

Based on observations of road-related erosion along tributaries to Pine Gulch, a road-related erosion rate of 11 tons/sq km/yr was determined. Combining all the road-related erosion rates from different processes (Figure 4-10) yields a total rate of 21 tons/sq km/yr. Appendix C summarizes the road survey field data.

Figure 4-10. Percentage of Road-Related Erosion by Process or Source



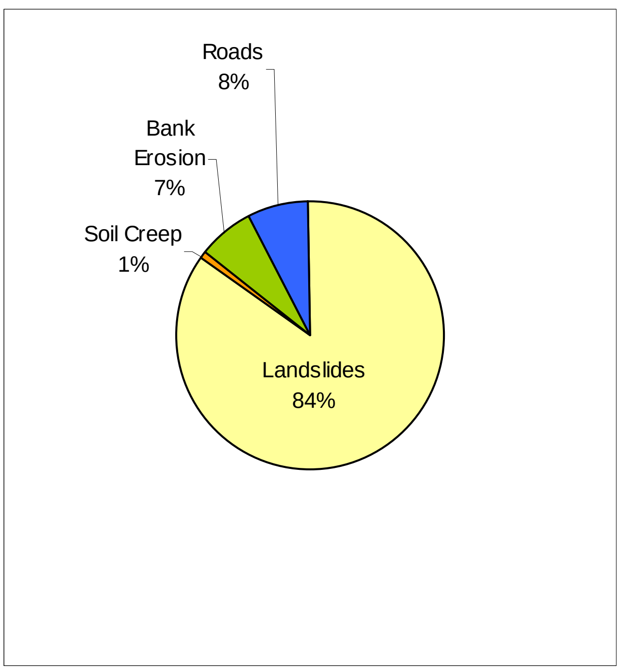
5. DISCUSSION

Sediment budgets provide rough approximations of erosion rates, but are very useful in comparing relative inputs of sediments from different sources. A comparison of all sources of sediment to streams (Figure 5-1; Table 5-1) shows that, of the entire budget (275 tons/sq km/yr), natural landslides contribute the vast majority of sediment (84 percent), followed by road-related erosion (8 percent), bank erosion (7 percent), and soil creep (1 percent). The estimated erosion rate (275 tons/sq km/yr) and accuracy of the estimate has implications for proposed dredging, while the relatively low contribution of management related sources (8 percent road-related erosion) indicates that there are few controllable sources of sediment within the watershed. These two issues are discussed in detail in the following sections, along with other management related sources of sediment in the Bolinas Lagoon watershed.

Table 5-1. Bolinas Watershed Fifty-Year Input Sediment Budget

Sediment Budget Component	Tons/sq km/yr	Tons/yr	Percent of Total
Landslides	233	10,000	84
Bank Erosion	18.5	800	7
Soil Creep	2.6	110	1
Roads	21	900	8
Totals:	**275**	**11,800**	**100**

Figure 5-1. Percentage of Input Sediment Budget by Process



5.1. Implications for Proposed Dredging and Accuracy of Budget

The proposed volume to be dredged from the Bolinas Lagoon by the U.S. Army Corps of Engineers is 1,600,000 cubic yards (USACE 2000). If the watershed were the only source of sediment for the lagoon it would take 135 years for the lagoon to re-fill to its current sediment level following the proposed dredging, using the calculated sediment input rate of 11,800 cy/yr. This estimated input rate (275 tons/sq km/yr) appears reasonable since it is of the same order of magnitude as:

- The only previous Bolinas watershed-based estimate of 114 tons/sq km/yr (Ritter 1973).
- The 184 tons/sq km/yr rate based on former lake sediments in McCormick Creek (see section 5.3).
- The long-term (100 year) slide mobilization rate of 187 tons/sq km/yr and sediment discharge rate of 237 tons/sq km/yr for nearby Lone Tree Creek (Lehre 1982).

However, this calculation is somewhat misleading for three reasons: First, the watershed is not the only source of sediment to the lagoon; second, it is not clear how much of the sediment that is delivered to the lagoon remains in the lagoon as opposed to that exported on the tides, and; third, the *average annual sediment input* calculated is a mathematical artifact rather than a realistic representation of sediment transport dynamics.

Although an average annual rate is reported here, sediment delivery to the lagoon is highly episodic. The majority of sediment is generated and transported during infrequent large storm events. For example, Ritter (1973) found that 87 percent of the sediment discharged from Pine Gulch Creek during 1968 occurred on one day. In a 35-year sediment budget for the Van Duzen River watershed in northern California, Kelsey (1980) estimated that up to 20 percent of the sediment input to channels occurred during one storm event in 1964. For the budget period of 1951-2001, it is likely that a high proportion of sediment was generated and transported to the lagoon during recent historic storm events (e.g., January 1982 storm [See Ellen and Wieczorek 1988]). It should also be noted that recent cosmogenic dating of long-term (10,000 years) erosion rates indicates that short-term (50-year) budgets can be under-estimated by 10 to 17 times because the short time frame is less likely to include such extreme events (Kirchner et al. 2001).

The implications of the dynamic nature of sediment transport for management are as follows: A prolonged drought may result in negligible sediment input or transport to the lagoon and conversely, three 100-year magnitude storm events in a single decade could deliver all 1.6 million cubic yards in a ten-year period. Therefore, the decision to dredge and schedule for future dredging cannot be based exclusively on the *average sediment input rate* calculated for this watershed.

The estimate of sediment inputs from this watershed study should be viewed as evidence that there are very few controllable sediment sources in the watershed. The current rate of sediment production from the watershed is mainly a function of natural instability and is unlikely to be significantly reduced through upland watershed restoration activities such as road removal[5]. Most of the sediment sources created by past management activities have already delivered their sediment load to the channel network and are no longer controllable. However, restoration of natural function (e.g., access to floodplain, channel adjustment, breaching, etc.) to lowland areas such as lower Pine Gulch Creek and Seadrift may decrease sediment deposition in the lagoon or increase sediment export.

Furthermore, based on calculations from Ritter, the tidal exchange transports hundreds of thousands of cubic yards of sediment per year both in and out of the lagoon (Table 2-2). Therefore, tidal transport of sediment has the potential to overshadow the contribution of the watershed; the watershed itself only contributes tens of thousands of cubic yards per year. Although Ritter calculated a net export of sediment from tidal exchange, this sediment source merits further study based on the potential volumes involved, especially during large storms not included in Ritter's calculations (Ritter 1973).

5.2. Management Related Sediment Sources

The limited amount of agriculture in Paradise Valley and lower Pine Gulch Creek does not appear to be contributing significant erosion to the lagoon. No other land uses were observed that could generate erosion. Therefore, the only source of management-related erosion appears to be from roads.

In the Bolinas Lagoon watershed, road-related erosion only contributes 8 percent of the total sediment budget (Figure 5-1). Erosion from roads can be a significant component of a sediment budget in actively managed landscapes. For example,

[5] Although road removal and upgrade activities may not significantly reduce sediment loading to Bolinas Lagoon, these restoration activities have the potential to benefit fish habitat in localized areas by reducing direct sediment inputs to stream reaches of particularly high value to salmonids.

road-related erosion was estimated at 29 percent of the total sediment budget in the South Fork of the Eel River in Northern California (USEPA 1999). The bulk of this erosion is attributed to an extensive network of dirt roads that are still intensively used for rural homes, ranches, and commercial logging. The network of actively used dirt roads is much smaller in the Bolinas Lagoon watershed because there is no timber harvest activity or ranching, and rural housing is minimal. Accordingly, the proportion of the sediment budget attributed to roads is much lower in the Bolinas Lagoon watershed.

Of the road-related sediment sources in the Bolinas watershed (Figure 4-10), contributions of logging roads in Righetti and Sweet Ranches, as well as paved road-related erosion (gullying below culverts, cut bank erosion), will likely decrease in the future. The majority of these observed sources have already failed or gullied and are unlikely to contribute much more sediment in the future. Of the small network of actively used dirt roads in the Bolinas Lagoon watershed, most are located in areas that have low erosion potential. For example, the dirt roads serving Paradise Valley are located on the valley floor, well away from the main channel. Recreation trails and fire roads, such as the McCurdy Trail, commonly follow the ridgeline where erosion is unlikely to reach a channel. One of the few other actively used dirt roads in the watershed is the National Park Service access road to the former Righetti Ranch area. This road is mainly on gentle topography, yielding very little erosion.

The majority of field-observed road-related erosion came from abandoned roads located in the active channel or inner gorge near the channel. Remnants of roads were observed in the active channel of Copper Mine Gulch, upper Lewis Gulch, and Cottingham Gulch. Remnants of inner gorge roads were also observed on the Righetti and Sweet Ranch logging sites and McCormick Creek. Most of the road prism had already washed out for roads constructed in the active channel and numerous fill and cutbank failures were found on the inner gorge roads (Figure 5-2). This is because some of the largest storms on record occurred after these roads were constructed and vulnerable sections washed out and were not repaired. Surface erosion on abandoned roads is minimal because the road surfaces have largely revegetated and stabilized naturally (Figure 5-3). Abandoned mid-slope roads were not found to produce significant erosion; field observation did not reveal evidence of fill failures or diversion gullies.

Figure 5-2. Example of Road Constructed in Active Channel of Lewis Gulch, Which has been Largely Washed Away. Remaining Section of Road Prism is Visible on Left Side of Photo.

It would be difficult and expensive to decommission what is left of these abandoned roads using heavy equipment. Furthermore, decommissioning these roads may not reduce erosion significantly because most of the vulnerable sections of road have already washed away. Access with heavy equipment to these sites would be difficult since major portions of the roads are gone and ten to twelve-inch diameter trees have regenerated on the portions of the road that remain.

Some erosion from the main paved roads in the watershed was observed (Highway 1 and the Bolinas-Fairfax Road), however, it was difficult to extrapolate these findings with our small sample size. Two large gullies were observed at the outfall of two cross drain culverts on Highway 1 at the grade south of Dogtown, above Lewis Gulch. The gullies were caused by the discharge of water from these culverts onto a hillside where water had never been concentrated in such volumes before. This erosion rate was extrapolated to other mid-slope paved roads in the watershed including the section of Highway 1 known as “13 turns” as well as most of the Bolinas-Fairfax Road. This estimate is likely to be high.

Figure 5-3. Typically Maintained Park Service Dirt Road below Righetti Ranch. (Note gentle topography and lack of visible erosion.)

5.3. Other Possible Management Related Sources of Sediment

5.3.1. Easkoot Creek

The original discharge location of Easkoot Creek is the subject of some debate within the Bolinas community. The general opinion is that Easkoot Creek historically emptied into the ocean but was manipulated at some point in the past to flow into the south end of the lagoon (Van Kirk 2001). If true, the relocation of the outlet into the lagoon rather than the ocean could have added a significant quantity of sediment to the south end of the lagoon. Van Kirk investigated this question through review of historical maps and interviews with local long time residents. She determined that Easkoot Creek has been in roughly the same location since at least 1897. Van Kirk found an account of the creek leaving its channel and emptying directly into the ocean once in the 1930s. Thus, prior to installation of the road and parking lot at Stinson Beach it was possible for Easkoot Creek to leave its channel and breach the sand spit during high discharge events and empty directly into the ocean. Under normal conditions, however, it flowed behind the sand spit into the south end of the lagoon in its current location.

5.3.2. Pine Gulch Creek

The channelization of lower Pine Gulch Creek from Paradise Valley to the mouth of the creek is likely to have altered sediment dynamics in the watershed. Prior to channelization, Pine Gulch Creek would have had access to its floodplain and could have deposited a portion of its sediment load on the floodplain. It is also likely that Pine Gulch Creek had numerous main channels through this lower floodplain over time, suggesting its outlet was not always in one place. By constraining the creek to one course and eliminating sediment deposition on the floodplain, all sediment transported by Pine Gulch Creek is concentrated in the current delta location causing the increase in size observed by previous studies (Rowntree 1973, Bergquist 1978).

5.3.3. Other Channelized Creeks

In addition to Pine Gulch Creek all of the other creeks that drain directly to Bolinas Lagoon have been channelized to some extent through culverts under Highway 1. These creeks include Copper Mine, Lewis, Wilkins, Pike County, Garden Club, Audubon, Morses, McKinnan and Stinson Gulch. These creeks are no longer free to 'jump' out of their low-flow channels during high flow events to dissipate energy and deposit sediment on their floodplains. Photographs show a tractor digging out the low-flow channel of Audubon Canyon during a storm to get the creek back in its channel in order to prevent the destruction of buildings on the floodplain (DeNevers, pers. comm., 2001). We also observed evidence of an intensive channelization effort on lower Stinson Gulch.

The low gradient sections of these creeks with floodplains are much shorter than Pine Gulch Creek, so the amount of sediment that could be stored on these floodplains is lower, but could be cumulatively significant when considering all of the creeks together. Total loss of floodplain storage capacity was not calculated in this report.

5.3.4. Stinson Beach Sand Spit

Another major modification to Bolinas Lagoon that has the potential to alter sediment dynamics is the stabilization of the Stinson Beach sand spit (MCOSD 1996). Construction of the Seadrift housing development, seawall, and artificial lagoon precludes the possibility of the breaching of the sand spit during large storms. Review of G.K. Gilbert's photographs of the sand spit prior to stabilization in 1907 shows evidence of the ocean washing over the spit (Bergquist 1978). Van Kirk (2001) interviewed a woman name Mildred Sadler who commented that, "during many winters the ocean would cut through the sand

and pour into Bolinas Lagoon, cutting the spit off from the land." There is also an account that dredging and filling of 56 acres in the southeastern portion of the lagoon in 1960 reduced tidal circulation in that portion of the lagoon (Van Kirk 2001). Maintenance of the ability of the spit to breach may have been an important component of tidal exchange and sediment transport dynamics within the lagoon historically.

6. CONCLUSIONS

Bolinas Lagoon was never a deep embayment, although it may be shallower now than it was 150 years ago. This is supported by:

1. Observations from Van Kirk's History report describe the lagoon as shallow and muddy in the late nineteenth century.
2. Historic map comparisons show changes in the lagoon over time (Rowntree 1973).
3. Vertical distribution of fauna recovered in sediment bores indicates that Bolinas Lagoon was never a deep-water embayment, but always a shallow lagoon (Bergquist 1978).
4. Comparison of 1907 and 1976 photos sets of the lagoon show aggradation at Pine Gulch Creek, enlargement of Kent Island, and an overall increase in tidal flat exposed at low tide (Bergquist 1978).

Photo 6-1 shows that this remains true today as shallow water and deposited sediment can be seen from neighboring Bolinas Ridge.

Figure 6-1. View of Bolinas Lagoon from the Ridge North of Mt. Tamalpias.

Although historic land management activities increased erosion rates in the past, current land management is minimal; 75 percent of the watershed is in protected or parkland status. The majority of private lands are located low in the watershed on flat or gently sloping areas, where erosion hazards are relatively low. There are no logging operations, ranches, or rural subdivisions on steep slopes; off-road vehicle use, hillside vineyards, and major agriculture are not present in the area; and the last major fire was in 1945. Current erosion rates appear close to background rates as indicated by: (1) comparison to reservoir calculations downstream of uncut forest in McCormick Creek, and (2) the small percentage of management related erosion observed in watershed (8 percent).

Early activity in the watershed may have caused a dramatic increase in sediment deposition rates, although Munro-Fraser's (1880) and Bergquist's (1978) attribution of sources differs (farming verus logging). The observation of cut stumps and 80 to 100 year old trees in Pine Gulch Creek, Copper Mine, Lewis, Audubon, and Volunteer Canyons suggests timber harvest was widespread 100 to 150 years ago. Fire scars observed on old stumps and mature trees indicate fires burned through the Bolinas Lagoon watershed multiple times in the past 150 years. In addition, historic pictures from the turn of the century show burned forests in the background.

The most likely scenario for the dramatic increase in sediment deposition rates in the late nineteenth century reported by Bergquist (1978), is that wide scale timber harvest for lumber was followed by harvesting for firewood, which was furthermore concurrent with mining and ranching operations in the watershed. Either concurrent with or after these activities ceased, fire burned through a large portion of the watershed and likely resulted in wide-scale erosion during the first significant storm following the fires (Van Kirk 2001). Early logging methods included downhill yarding of trees and transportation of timber in and across stream channels (including road building in the active channel); such activities caused severe erosion and increased erosion potential for decades following the period of activity.

Results from USACE (1999) and Bergquist and Warhaftig (1993) indicating that twentieth century sediment deposition rates in Bolinas Lagoon were elevated over background (pre-1850) rates are not supported by sediment core data from Bergquist (1978). It is not clear if the sediment core or the bathymetry-based studies are more accurate. However, it is clear that the dramatic increase in sedimentation reported by the USACE between 1968 and 1978 could not have come entirely from the logging operations on the Sweet and Righetti Ranches; the combined acreage (510 acres) was not sufficient to produce such an increase.

According to our watershed sediment input budget current erosion rates are near background (pre-1850) levels within the watershed. However, several alterations in the lower watershed *could be* contributing to increased sediment deposition or decreased sediment export out of Bolinas Lagoon:

1. The channelization of lower Pine Gulch Creek and the other smaller creeks that discharge directly to the lagoon causes transportation of fine sediment to the lagoon rather than deposition on the floodplains.
2. The Stinson Beach sand spit is no longer able to breach during large rain events because of the Seadrift development.
3. Easkoot Creek is no longer able to discharge directly to the ocean during large storm events because of the Stinson Beach parking lot location.
4. Construction of the artificial lagoon at Seadrift may have altered tidal circulation patterns in the lagoon.

Given the volumes of tidal sediment transport observed by Ritter (1973) on calm days (115,000 cy/yr), it is possible that this process dominates the sediment budget of the lagoon and has the potential to overshadow contributions from within the watershed (9,800 cy/yr).

It is therefore unlikely that efforts to reduce erosion within the watershed will have a significant effect on sedimentation rates in the lagoon[6]. Not only is most of the sediment entering the lagoon via the watershed derived from natural mass wasting, but that amount is an order of magnitude lower than the potential volume mobilized by the tide. Finally there is no clear evidence that Bolinas Lagoon was ever a deep-water embayment, thus dredging may not actually 'restore' Bolinas Lagoon to any historic natural condition. These conclusions can help USACE and the Bolinas Lagoon Technical Advisory Committee in decision and policy making. Specifically this information should factor into the discussion of:

1. Whether or not to dredge
2. The scale of dredging if selected

[6] Sediment reduction activities, however, may improve fish habitat in localized areas within the stream network.

3. The amount of additional resources to be committed to mitigations within the watershed

The Bolinas Lagoon serves its neighboring communities in a variety of ways, not the least of which are recreational, natural, cultural, economic, and aesthetic. It will continue to do so for many years in one form or another. The decision before the leaders of those communities today is to what extent is anthropogenic intervention required to preserve the balance between natural and human uses. It has been the objective of this study to provide insights that will aid in the decision making process and enable those involved to select actions capable of both preserving benefits and reducing impacts.

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8. APPENDIX A. SUMMARY OF STREAM SURVEY DATA

					DIMENSIONS OF LANDSLIDES					
Reach	Basin	Geology	Stream Order	Survey Distance (km)	Length (yd)	Width (yd)	Depth (yd)	Proportion Delivered	Tons*	Age (yr)
1	Stinson Gulch	Franciscan	1	0.12					0	
2	Stinson Gulch	Franciscan	1	0.24	66	2	1	1	158	15
3	Upper McCormick	Monterey	1	0.24	2	2	1	1	5	5
4	Garden Club	Franciscan	1	0.15	4	12	0.5	0.8	23	15
5	Garden Club	Franciscan	1	0.15	15	12	0.5	0.8	86	15
					6	6	0.5	0.8	17	15
					4	5	0.5	0.8	10	15
6	Upper Copper Gulch	Franciscan	1	0.14					0	
7	Middle Lewis	Franciscan	1	0.20					0	
8	Stinson Gulch	Franciscan	2	0.12					0	
9	Stinson Gulch	Franciscan	2	0.37	6	5	1	1	36	15
					10	8	1	0.6	58	5
10	Upper McCormick	Monterey	2	0.82	9	2	0.5	0.9	10	5
					10	6	0.5	0.5	18	5
					10	3	0.5	0.5	9	5
					10	1	0.5	0.4	2	5
					18	18	1	0.15	58	25
					10	8	0.5	0.3	14	5
					14	14	1	0.15	35	25
					6	2	1	0.2	3	5
					15	15	1	1	270	35
					8	1.5	1	1	14	5
					10	10	0.5	0.5	30	5
11	Upper Lewis Tributary	Franciscan	2	0.29					0	
12	Stinson Gulch	Franciscan	3	0.24	30	30	1	1	1080	15
					12	10	0.5	1	72	5
					20	15	1	1	360	25

*Reach numbers correspond to Stream and Road Survey Location Map (Figure 3-1)

DIMENSIONS OF LANDSLIDES										
Reach	**Basin**	**Geology**	**Stream Order**	**Survey Distance (km)**	**Length (yd)**	**Width (yd)**	**Depth (yd)**	**Proportion Delivered**	**Tons***	**Age (yr)**
13	Stinson Gulch	Franciscan	3	0.34	12	12	0.5	1	86	15
					10	10	0.5	1	60	5
					32	20	1.5	0.8	922	5
					18	4	0.5	1	43	5
14	Lower McCormick	Monterey	3	0.40	12	14	0.5	1	101	25
					30	18	1	0.6	389	35
					8	5	0.5	0.9	22	15
					30	10	1	0.7	252	15
					40	15	0.5	0.8	288	35
					13	7	0.5	1	55	5
					5	2	0.5	0.7	4	15
					12	10	2	0.15	43	5
					6	2	0.5	0.15	1	5
					32	16	1	0.8	492	35
					13	17	0.5	0.9	119	15
15	Tributary to Pine Gulch	Monterey	3	0.46	10	6	1	0.8	58	5
					15	15	1	0.5	135	45
					22	18	1	0.3	143	45
					4	4	0.5	0.8	8	5
					6	6	0.5	0.8	17	5
					18	8	1	0.2	35	45
					18	8	1	0.2	35	45
					25	15	1	0.1	45	5
					10	6	0.5	0.2	7	5
					20	10	1	0.2	48	45
					10	5	1	0.2	12	35
					10	5	1	0.2	12	45

*Reach numbers correspond to Stream and Road Survey Location Map (Figure 3-1)

DIMENSIONS OF LANDSLIDES										
Reach*	Basin	Geology	Stream Order	Survey Distance (km)	Length (yd)	Width (yd)	Depth (yd)	Proportion Delivered	Tons*	Age (yr)
16	Lower Copper Gulch	Franciscan	3	0.46	6	7	0.5	0.8	20	25
17	Upper Copper Gulch	Franciscan	3	0.58	25	18	1	0.7	378	5
					12	8	0.5	0.8	46	5
					30	18	0.5	0.8	259	30
					15	12	1	0.75	162	15
18	Middle Lewis	Franciscan	3	0.61	4	10	1	0.9	43	15
					18	8	1	0.4	69	25
					25	15	0.5	0.8	180	5
19	Middle Lewis	Franciscan	3	0.49	8	12	2	0.8	184	35
					8	3	0.5	0.9	13	5
20	Lower Lewis	Franciscan	3	0.30	6	2	0.5	0.6	4	5
					8	3	1	0.6	17	5
					13	6	1	0.8	75	5
					10	2	1	0.6	14	5
					6	8	0.5	0.7	20	5
					6	10	0.5	0.7	25	15
					5	5	1	0.7	21	15
					5	5	1	0.7	21	15
					1.5	12	1	0.9	19	15
					8	2.5	0.5	0.9	11	15
21	Pine Gulch	Merced	4	0.24	8	5	1	0.7	34	25.0
					10	4	0.5	0.8	19	25
					10	4	0.5	0.8	19	25
					12	20	1	0.8	230	5
					8	4	1	0.8	31	5
					28	10	0.5	0.8	134	25
					12	25	1.5	0.6	324	5
					15	15	2	0.7	378	35
					20	20	1	0.7	336	45
					12	15	1.5	0.5	162	5

*Reach numbers correspond to Stream and Road Survey Location Map (Figure 3-1)

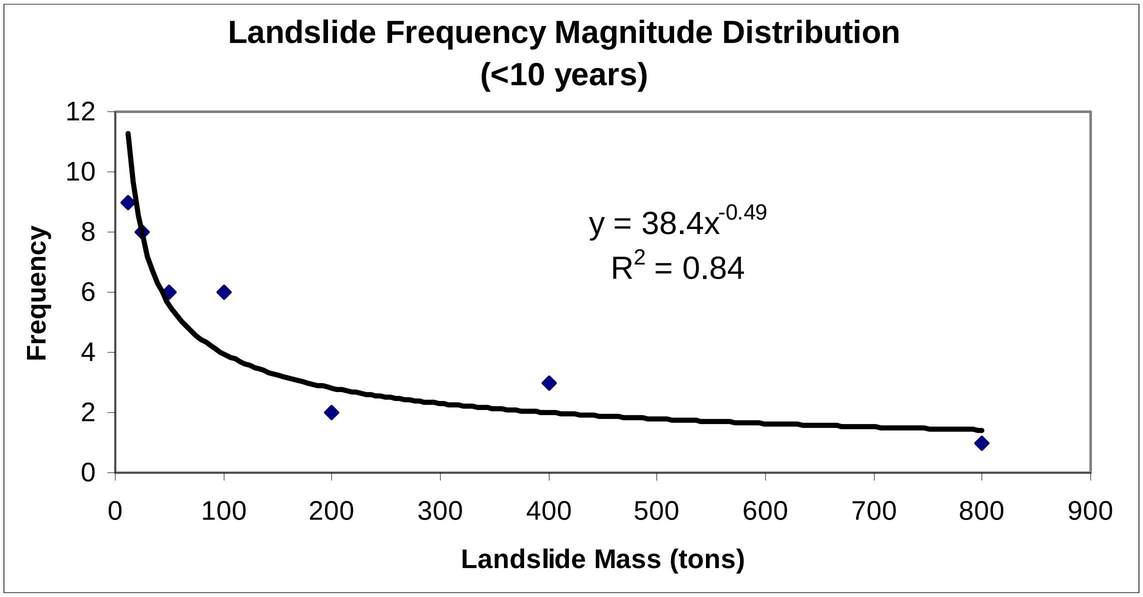
DIMENSIONS OF LANDSLIDES

Reach	Basin	Geology	Stream Order	Survey Distance (km)	Length (yd)	Width (yd)	Depth (yd)	Proportion Delivered	Tons*	Age (yr)
22	Pine Gulch Flood Plain	Merced	4	0.24	20	15	1	0.5	180	15
31	Tributary to Lower Lewis		1	0.20	20	15	1	0.5	180	15

Note: density conversion factor of 1.2 ton/yd^3

9. APPENDIX B. CORRECTED LANDSLIDE FREQUENCY AND MASS DISTRIBUTIONS

Figure B-1. Best Fit Regression Equation



Based on regression equation, the distributions are adjusted as follows to determine the corrected mass:

Bin (tons)	Increase
12	10.4* (observed frequency of 400 ton bin) * (12 tons)
25	6.9* (observed frequency of 400 ton bin) * (25 tons)
50	4.6* (observed frequency of 400 ton bin) * (50 tons)
100	3* (observed frequency of 400 ton bin) * (100 tons)
200	1.9* (observed frequency of 400 ton bin) * (200 tons)
400	1* (observed frequency of 400 ton bin) * (400 tons)
800	0.5* (observed frequency of 400 ton bin) * (800 tons)

9.1. Period	Bin (tons)	Observed Frequency	Adjusted Frequency	Adjusted Mass (tons)
10 yr	12	9	31.2	374
	25	8	20.7	518
	50	6	13.8	690
	100	6	9.0	900
	200	2	5.7	1140
	400	3	3.0	1200
	800	1	1.5	1200

Period	Bin (tons)	Observed Frequency	Adjusted Frequency	Adjusted Mass (tons)
20 yr	12	3	10	125
	25	6	7	173
	50	3	5	230
	100	2	3	300
	200	3	2	380
	400	1	1.0	400
	800	1	0.5	400
30 yr	12	0	20.8	250
	25	3	13.8	345
	50	2	9.2	460
	100	2	6.0	600
	200	2	3.8	760
	400	2	2.0	800
	800	0	1.0	800
40 yr	12	1	41.6	499
	25	0	27.6	690
	50	0	18.4	920
	100	0	12.0	1200
	200	1	7.6	1520
	400	4	4.0	1600
	800	1	2.0	1600
50 yr	12	1	10.4	125
	25	0	6.9	173
	50	3	4.6	230
	100	0	3.0	300
	200	2	1.9	380
	400	1	1.0	400
	800	0	0.5	400

10. APPENDIX C.
SUMMARY OF ROAD SURVEY DATA

Survey Segment	Basin	Survey Distance (km)	Length (yd)	Width (yd)	Depth (yd)	Proportion Delivered	Tons*	Age (yr)
	Paved Roads with Culverts							
20	Lower Lewis Culverts	0.61	28	2	3	0.9	181	15
			20	2	1	0.9	43	15
			25	2	3	0.9	162	15
			22	2	2	0.9	95	10
	1960-70 Logging Roads							
23	Cottingham	0.49	533	2.5	1	0.7	1120	20
24	(Righetti Ranch)	0.26	283	2.5	3	0.6	1530	20
25		1.13	6	4	2	0.9	52	20
26	Tributary to Upper Pine Gulch	1.13	8	1.5	1.5	0.9	19	25
	(Sweet Ranch)		8	3	1	0.9	26	25
			20	12	1	0.9	259	25
			5	6	1	0.8	29	25
			20	2	2	0.6	58	25
	Old Logging Roads							
27	Lower McCormick	0.76	15	15	0.5	0.8	108	35
			15	8	2	0.4	115	25
15	Tributary to Middle Pine Gulch	0.46	10	6	1	0.8	58	5
			25	15	1	0.1	45	5
	Ridge Dirt Roads							
28	McCurdy Trail	2.74					0	
29	Lewis/Cottingham Ridge	0.82					0	
30	Lower Stinson	1.00					0	

* density conversion factor of 1.2 ton/cubic yard

Note: Survey segment numbers correspond to Stream and Road Survey Location Map (Figure 3-1)