Bolinas Lagoon Ecosystem Restoration Feasibility Project

Final Public Reports

II Projecting the Future of Bolinas Lagoon

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PROJECTING THE FUTURE EVOLUTION OF BOLINAS LAGOON

Final Public Draft

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with

WRA, Inc.

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GLOSSARY OF TERMS

Aggradation	vertical expansion of a geomorphic feature
Alluvium	material, such as sand, silt or clay, deposited on land by streams
Alluvial fan	the fanlike deposit of a stream where it issues from a gorge upon a plain or of a tributary stream near or at its junction with its main stream
Anthropogenic	of or pertaining to humans
Bedload	sediment transported by water close to or on the bottom by rolling, sliding or bouncing
Brackish	a mixture of fresh and salty water
Delta	a body of alluvium having a surface that is nearly flat and fan shaped; deposited at or near the mouth of a river or stream where it enters a body of relatively quiet water, generally a sea or lake
El Nino	a major warming of the equatorial waters in the Pacific Ocean; El Nino events usually occur every 3 to 7 years, and are characterized by shifts in "normal" weather patterns
Episodic	occurring, appearing, or changing at usually irregular intervals
Estuary	an embayment of the coast in which fresh river water entering at its head mixes with the relatively saline ocean water
Fluvial	of or pertaining to rivers; produced by river action, as a fluvial plain
Geomorphic	the form and process of landforms
Holocene	a period of time covering the past 10,000 years
Hypersaline	very high salinity
Incision	erosion and down-cutting of channels by low sediment-high energy discharges
Intertidal	pertaining to the elevations between those of MHHW and MLLW; undergo wetting and drying consistent with tidal propagation
Lagoon	a shallow body of water, separated from the sea by a sand-spit; lagoons may be continuously, occasionally or periodically connected to the ocean
Littoral	of or related to the littoral zone; the relatively narrow portion of a coast affected by wave energy and longshore currents
Morphology	characterization of form and process
Neap tides	the tides resulting when the sun and moon are at right angles to each other, characterized by a reduced tidal range
Prograde	lateral expansion of a geomorphic feature
Sedimentary	formed by or from deposits of sediment
Spring tides	tides resulting when the gravitational forces exerted on the earth by the sun and moon are acting in the same direction
Subtidal	pertaining to the elevations consistently below MLLW
Suspended load	volume of sediment transported in suspension by water; moves at a velocity slightly lower than that of water without many intermittent stages of deposition
Supratidal	pertaining to the elevations consistently below MHHW
Tectonics	describing the forces that cause the movements and deformation of Earth’s crust on a large scale

Tidal damping	attenuation (reduction) of the tidal range
Tidal prism	the volume of water between the high-tide surface and the low-tide surface of an embayment, estuary or creek
Suspended load	term relating sediment to river flow; consists of small particles generally in suspension and not found on the bottom even during low energy intervals

1. INTRODUCTION

Bolinas Lagoon, located approximately 15 miles northwest of San Francisco, provides an important estuarine environment for a rich variety of bird, fish, plant, and wildlife species (Figure 1-1). The Marin County Open Space District (MCOSD) manages the approximately 1,200-acre lagoon, although portions of the site are within the Gulf of the Farallones National Marine Sanctuary and much of its watershed is within the Point Reyes National Seashore and the Golden Gate National Recreation Area.

The U.S. Army Corps of Engineers (USACE), in cooperation with the MCOSD, began developing the Bolinas Lagoon Ecosystem Restoration Project (ERP) in 1998 in response to noticeable siltation in the lagoon over the past few decades. In June 2002, the USACE released draft versions of the joint environmental impact statement / environmental impact report (EIS/EIR) and feasibility study (FS) which proposed to dredge approximately 1.4 million cubic yards (CY) of sediment from the lagoon. In response to concerns voiced during the public comment period, MCOSD decided to reformulate the ERP in order to develop a scientifically sound plan with greater support from the community and regulatory agencies.

MCOSD contracted Philip Williams & Associates, Ltd. (PWA) and Wetlands Research Associates (WRA) to develop a 50-year projection of the evolution of Bolinas Lagoon and its habitats. In the next steps of the planning process, projected hydrologic and ecologic functions of the lagoon can be assessed against selected management objectives in order to provide a basis for a decision as to whether or not restoration actions are required. The study is the first step of the ERP reformulation.

The following sections describe various elements of the PWA and WRA analyses. Section 2 summarizes key findings and conclusions. Sections 3 and 4 present, respectively, past and existing lagoon conditions and rates of geomorphic changes. Section 5 presents projected future lagoon conditions. The description of future conditions includes a “snapshot’ of conditions at Year 50 as well as a discussion of the trends beyond 50 years; important natural processes will continue to change the character of the lagoon over time scales much longer than the 50-year planning horizon. Section 6 discusses human-induced changes to the lagoon, and Section 7 presents a rationale for monitoring and adaptive management.

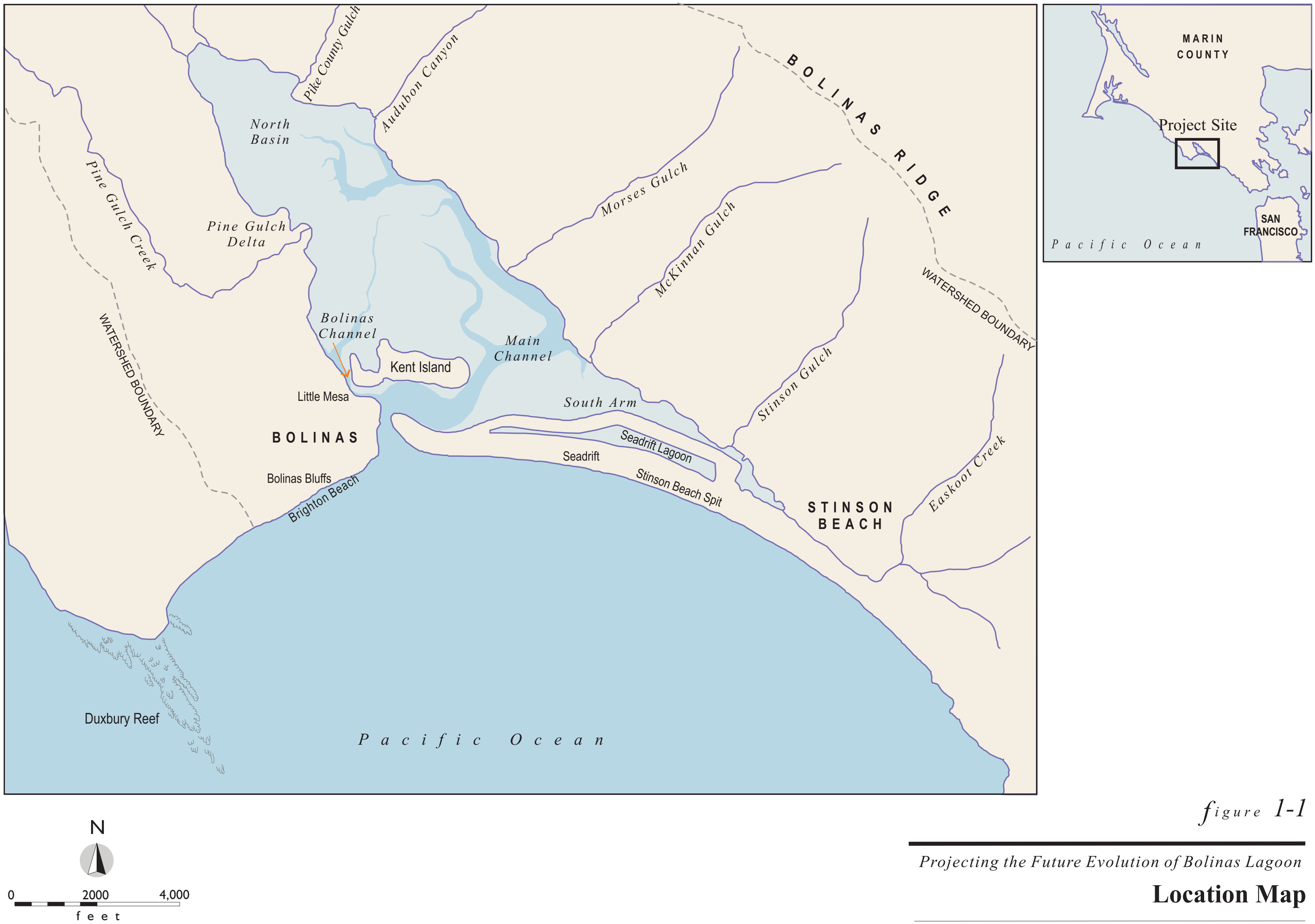

figure 1-1

Projecting the Future Evolution of Bolinas Lagoon

Location Map

PWA Ref. # 1686.02

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2. FINDINGS AND CONCLUSIONS

The subsections below present a summary of our key findings and a list of specific conclusions regarding the physical evolution and ecological functions of Bolinas Lagoon.

2.1 SUMMARY OF KEY FINDINGS

Bolinas Lagoon has persisted as a tidally dominated estuarine landform for the past several thousand years, although its shape and volume have varied over time in response to large earthquakes and gradual changes in sea level and sediment transport processes. Although the lagoon tends to evolve toward a dynamic equilibrium form that balances erosive and depositional forces, large earthquakes along the San Andreas Fault punctuate its evolutionary trajectory every few hundred years. These earthquakes drop the bottom of the lagoon floor by vertical displacement and compaction of unconsolidated sediment and result in a nearly instantaneous increase in lagoon volume (or ‘tidal prism’), modifications to the channel system, and shifts in habitat distribution. After large earthquakes, the delivery of ‘littoral’ sediment is enhanced due to strong flood tide currents and an increase in the amount of bluff-eroded silt deposited in newly formed subtidal sinks.

Evidence from recent sediment core analyses has confirmed that logging and grazing during the 1800s increased the rate of watershed derived sediments to the lagoon. These data also show that following the last major earthquake of 1906, beach sands and silt eroded from the ocean bluffs account for the majority of the sediment accumulated in the lagoon. This change in sediment delivery is consistent with our understanding of the lagoon’s relatively small supply of sediment from the watershed, and the ability for tidal currents to disperse beach sands and silt far into the lagoon interior. It is also clear that sediment delivery varies year to year; the majority of watershed delivery occurs during infrequent rainstorms, and intense coastal storms may transport large amounts of beach sand through the inlet.

We project that over the next 50 years, in the absence of another large earthquake, sediment accumulation will continue to outpace sea level rise and result in a continued reduction in tidal prism. However, the future rate of tidal prism loss will diminish as erosive forces of locally generated wind waves limit further mudflat accretion and the ability of tidal currents to disperse sand far into the lagoon interior as the tidal prism reduces. We project these changes will reduce the tidal prism of Bolinas Lagoon by approximately 1 million cubic yards over the next 50 years, from about 3.5 MCY to 2.5 MCY. Although the tidal prism is projected to decline over this time, the inlet is expected to maintain an open connection to the ocean, except possibly under extreme combinations of strong El Nino storms and weak neap tides. Beyond 50 years, we project the lagoon will move slowly toward a dynamic equilibrium that balances sea level rise and net sedimentation and results in a tidal prism of approximately 2 MCY.

Over the last century there have been significant habitat changes in response to the 1906 earthquake and subsequent adjustments to lagoon form, with commensurate effects on wildlife populations. Habitat shifts will continue as Bolinas Lagoon continues to evolve toward a new dynamic equilibrium. We project the area of salt marsh and high mudflats to increase, with a concurrent decline in low mudflats and subtidal shallows. Although shifts in the relative distribution of habitats are projected over the next 50 years, major changes to species abundance and diversity and ecological function are not expected. If inlet closure did occur, rapid changes to estuarine conditions would reduce species diversity since fewer plants and animals could tolerate these large and sudden modifications.

A number of human-induced or 'anthropogenic' activities have resulted in direct changes to the habitat distribution and tidal prism of Bolinas Lagoon. Overall, the combined effects of direct and indirect anthropogenic modifications to Bolinas Lagoon have reduced its tidal prism.

Our projections of future conditions are based on rates of sediment delivery averaged over several decades, which include large pulses of littoral and watershed material during infrequent but intense rainstorms and coastal storms. Therefore, the illustrations of future lagoon habitats and tidal prism are approximations of future conditions and not intended to be exact predictions.

2.2 SPECIFIC CONCLUSIONS

<u>General conclusions regarding physical and ecological functions at Bolinas Lagoon:</u>

1. Bolinas Lagoon was formed following the last ice age and has persisted as an intertidal lagoon for at least the past 7,000 years. During this time, the particular shape or 'morphology' of the lagoon has responded to earthquakes, waves, tsunamis, tides, sea level rise, and changing land use in the watershed.

2. At any given time, the lagoon morphology is evolving towards a dynamic equilibrium in response to both slowly varying and sudden episodic changes in sedimentation processes. Large earthquakes along the San Andreas Fault punctuate the evolutionary trajectory of Bolinas Lagoon. These events occur on the order of once every several hundred years, and when they occur, seismically-induced compaction results in a nearly instantaneous increase in tidal prism as tectonic subsidence and compaction drops the elevation of intertidal marsh and mudflats.

3. Sediment transport processes shape lagoon morphology, which is the primary determinant in creating the different types of aquatic habitats. The elevation of the lagoon bottom relative to the tides determines the distribution of mudflats, channels, marsh, and open water habitats. The abundance and diversity of plant and wildlife species inhabiting the lagoon depend on this habitat distribution.

4. Abundance and diversity of plant and wildlife species also depends on the exchange of energy, sediment, and nutrients with the ocean. Lagoon morphology affects these estuarine processes by controlling the movement of water through the inlet, or 'tidal exchange', and circulation patterns within the lagoon.

5. Prior to the significant settlement in the mid-1800s, the elevation and area of mudflats, sandflats and marshes of Bolinas Lagoon appears to have been close to dynamic equilibrium with sedimentation balanced by sea level rise and wind-wave erosion. In this state, the lagoon had a tidal prism – the volume of water moving in and out of the lagoon during the tidal cycle – of approximately 3.7 million cubic yards (MCY). This volume of water was sufficient to keep the inlet open under the most extreme combinations of wave and tidal conditions.

6. Over the last two centuries, human activities such as grazing, logging, elimination of floodplain sedimentation through creek channelization, placement of fill, and land development have altered the physical processes that affect lagoon morphology. Natural processes such as climatic variability, sea level rise, and earthquakes have also affected lagoon morphology over the past two centuries.

7. Logging and other land use changes in the watershed during the mid to late 19th century increased sediment delivery to the North Basin of Bolinas Lagoon. From 1850 to the 1906 earthquake, sediment accumulation rates were particularly high at the northern head of the lagoon (near the former embarcaderos used during the harvesting of lumber) and near the mouth of Pine Gulch Creek (which drained the Briones ranch). We estimate that these watershed disturbances reduced the tidal prism by about 0.5 MCY to approximately 3.2 MCY.

<u>Past and Existing Conditions:</u>

8. The 1906 earthquake along the San Andreas Fault resulted in significant subsidence and compaction of sediments, particularly submerged unconsolidated silt and clay. This down-drop of the lagoon floor converted much of the marsh and intertidal mudflats to subtidal shallows. We estimate that the earthquake-induced subsidence increased the tidal prism of Bolinas Lagoon by approximately 3.5 MCY to about 6.7 MCY.

9. The effects of both natural processes and man-induced changes to physical processes have resulted in net sedimentation and a reduction of tidal prism from about 6.7 MCY immediately after the 1906 quake to approximately 3.5 MCY today.

10. Analysis of sediment cores collected in Bolinas Lagoon reveal that sediment accumulation has averaged approximately 43,000 CY/yr between 1906 and 2004. Over the same period of time, sea level rise has partially offset net sedimentation, resulting in an average rate of tidal prism loss of approximately 34,000 CY/yr. The rate of tidal prism loss was greater during the decades immediately after the 1906 earthquake, but results from bathymetric surveys suggest that it has slowed to about 25,000 CY/yr during the late 20th century.

11. Sediment deposited within the lagoon originates from two sources: ‘littoral’ beach sands and silt from eroded bluffs, which are transported into the lagoon during flood tides; and ‘alluvial’ gravel, sand and mud washed into the lagoon from the watershed by creek flows. The importance of these sediment sources varies across Bolinas Lagoon and shape distinct geomorphic ‘units’.

12. Under current conditions, most of the sediment deposited in the lagoon is derived from littoral sources. Of the 43,000 CY/yr of sediment accumulation, approximately 10,000 CY/yr comes from the watershed. The remaining 33,000 CY/yr consists of beach sands and bluff-eroded silt swept into Bolinas Lagoon during flood tides.

13. The rate of littoral sediment delivery is largely determined by the strength of flood tide currents. These currents have the ability to sweep beach sands through the tidal inlet and disperse this material into the interior of the lagoon. The strength and extent of tidal dispersion is in turn controlled by the size of the tidal prism. Bluff-eroded silt is more efficiently transported and less dependent on tidal current velocity.

14. Delivery of littoral sediment substantially increased after the 1906 earthquake due to the sudden down-drop of the lagoon floor east of the fault. This down-drop significantly increased the tidal prism and disturbed the relative balance of sediment inputs and outputs.

15. This increase in tidal prism and modifications to the channel system near the inlet led to higher current velocities, which transported large quantities of beach sand throughout Bolinas Lagoon. Although the tidal prism has diminished from its 1906 value, current velocities during spring tides are still sufficiently strong to disperse fine sand into the lagoon interior.

16. In areas exposed to significant wind action, turbulence from locally generated waves limits the equilibrium elevation of mudflats to slightly below the local mean sea level. Although the Pine Gulch Creek delta and Kent Island have sheltered areas along the eastern side of the lagoon, erosive wind waves continue to shape a portion of the mudflats along the main axis of the lagoon.

17. Although most sediment deposited in the lagoon is derived from marine sources, human-induced increases in the amount of watershed sediment delivery have altered the morphology and habitats of Bolinas Lagoon as well. Through direct impacts and changes to natural sediment dynamics, these ‘anthropogenic’ effects have resulted in more riparian and marsh habitat area, especially along the western shoreline of the lagoon.

18. Channelization along Pine Gulch Creek has eliminated floodplain sedimentation, which under natural conditions stored a substantial amount of stream borne sediment. This change has increased the rate at which gravel and coarse sand are delivered to Bolinas Lagoon, forming a delta at the mouth of Pine Gulch Creek.

19. The Pine Gulch Creek delta is growing in response to delivery of coarse alluvial sediment. Other deltas have formed near the mouths of the steep creeks that drain Bolinas Ridge, although these features are smaller and store less sediment.

20. Extension of Pine Gulch Creek delta has altered the equilibrium form and habitat distribution of Bolinas Lagoon by converting intertidal estuarine habitats to upland riparian woodland. The Pine

Gulch Creek delta and Kent Island act to shelter much of the western shoreline of the lagoon from wind waves, allowing mudflats to convert to salt marsh.

21. Aerial photographs reveal that the 1906 earthquake substantially altered the channel system near the inlet. During the past few decades, sedimentation between the Pine Gulch Creek delta and Kent Island has also filled the head of the Bolinas Channel, thereby reducing the ability of tidal scour to maintain a large channel. The reduction in channel depth has reduced access to fishing and recreational boating along Wharf Road.

22. Although the 1906 earthquake and subsequent changes to the transport of sand into the lagoon account are natural processes, human modifications to the landscape have affected the evolutionary trajectory and ultimate long-term equilibrium form of Bolinas Lagoon. The most substantial alterations to natural conditions include the construction of Seadrift Lagoon and channelization along Pine Gulch Creek, which has produced a large delta near the creek mouth and created conditions conducive to marsh expansion. Since relatively little down-drop occurs to the west of the fault during large earthquakes, tectonics along the San Andreas Fault may also explain the dominance of marsh in this area.

Future Conditions:

23. Changes in the delivery rates of fine and coarse sediment from the watershed and littoral zone will modify various landforms or ‘geomorphic units’ throughout the lagoon. Future changes in tidal prism depend on the cumulative effect of these geomorphic adjustments, sea level rise and the occurrence of large earthquakes. Because large earthquakes on the San Andreas Fault in the region occur every few hundred years but are not predictable, their effects were not considered in establishing the 50-year projection of lagoon morphology.

24. The rate at which beach sands accumulate in Bolinas Lagoon will slow over time as tidal prism diminishes and net sedimentation rates are balanced by sea level rise, forming a new dynamic equilibrium.

25. Accounting for a modest acceleration in sea level rise of 0.4 ft over the next 50 years, and assuming no active intervention or major earthquakes, we anticipate that tidal prism of Bolinas Lagoon will reduce by about 1 MCY to approximately 2.5 MCY over the next 50 years. Depending on how rapidly sea level rises and the balance between wind-wave erosion and deposition over mudflats, this projected 50-year change in tidal prism may vary by ± 0.3 MCY.

26. A tidal prism of 2.5 MCY is sufficient to maintain an open connection to the ocean during typical conditions. However, under extreme combinations of strong El Nino storms and weak neap tides, sand accumulation in the entrance channel could reduce its hydraulic efficiency and induce closure.

27. Over the next 50 years, we expect future sedimentation to increase the extent of high (frequently exposed) mudflats by approximately one-third, as low (frequently submerged) mudflats and subtidal shallows rise in elevation. The rate of vertical rise will diminish as the erosive effects of wind-waves become stronger and mudflats reach an equilibrium elevation in areas where exposure to winds is substantial.

28. Salt marsh will continue to expand most rapidly in the areas between Pine Gulch Creek delta and Kent Island due to sheltering of wind waves and increased trapping of suspended sediments. Additionally, the width of salt marsh fringing the margins of the lagoon will probably increase. Overall, we expect an increase of approximately 20% in the aerial extent of vegetated salt marsh over the next 50 years.

29. Although a shift in the proportion of habitats is expected to occur over 50 years, major changes in species abundance and diversity and ecologic function are not expected. Assuming the inlet remains open, the lagoon will likely support a similar mix and quality of habitats that are present today.

30. One habitat type that has been in decline and may have disappeared based on recent surveys is eelgrass beds – an important habitat for subtidal fish and is used by herring for egg laying. According to previous observations, eelgrass beds were limited to subtidal channels near the mouth of the lagoon, but were not detected in the 2005 survey. The disappearance of eelgrass beds cannot be explained by the data collected during this project.

31. In the absence of a major earthquake along the San Andreas Fault, we expect the loss of tidal prism will continue beyond the next 50 years as Bolinas Lagoon evolves towards a new equilibrium form. The most significant potential long-term changes include expansion of salt marsh in areas sheltered from the erosive effects of wind waves and a continued rise in the mudflat elevation. The ultimate tidal prism of this projected long-term equilibrium form where net sedimentation keeps pace with sea level rise could be close to 2 ± 0.3 MCY — until the next large earthquake.

32. With a tidal prism of about 2 MCY, inlet closure may occur on the order of once every decade. If inlet closure does occur, consequences would include large changes in salinity and nutrients and a significant reduction in energy that currently supports the food web. Under such conditions, the lagoon may become hyper-saline as evaporation increases salinity levels above that of normal seawater. In addition, lagoon water may undergo a rapid decrease in dissolved oxygen and an increase in temperature. Diversity could decline since fewer plants and animals are tolerant to large and sudden modifications.

3. PAST EVOLUTION OF BOLINAS LAGOON

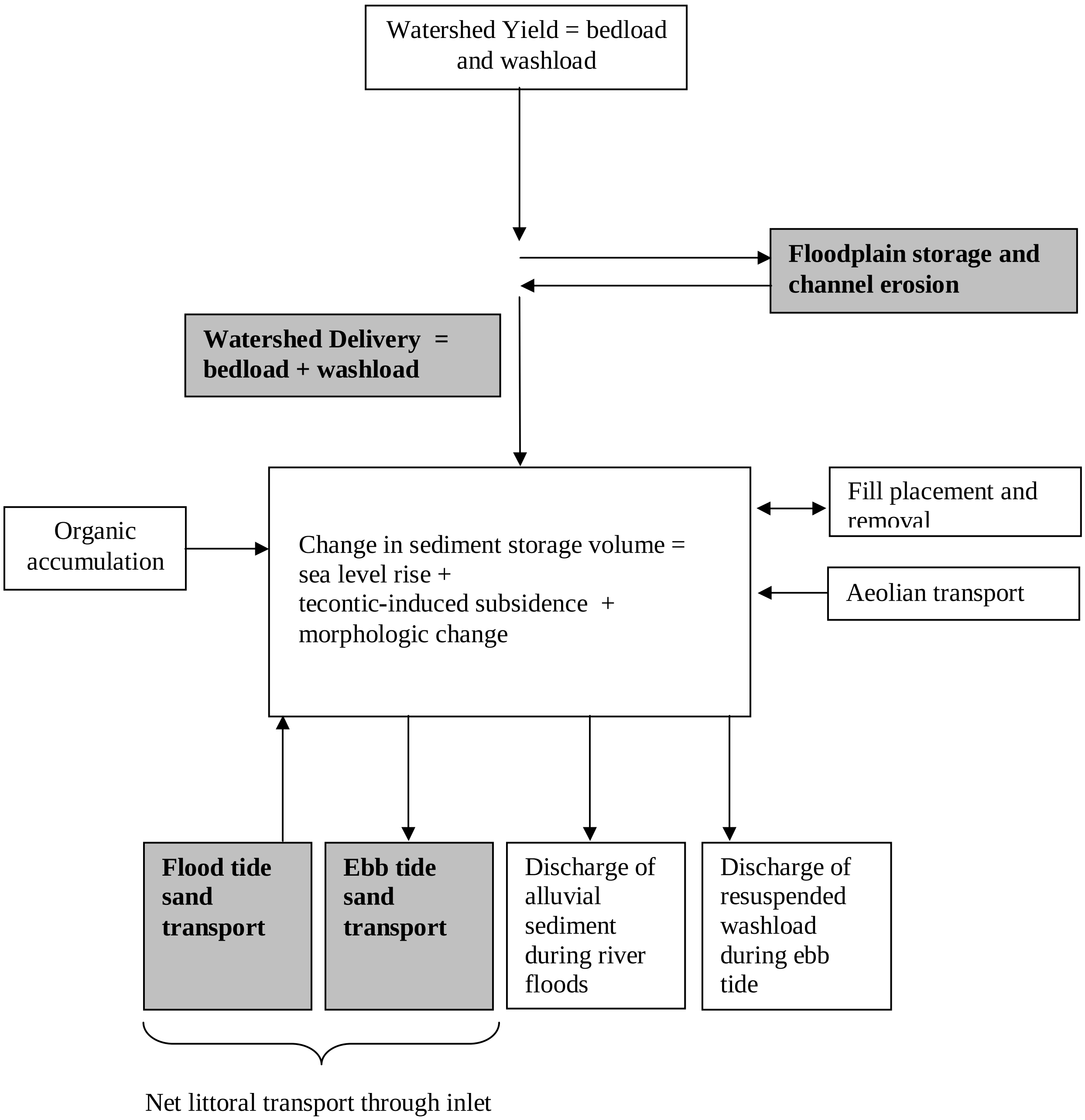
Understanding the evolution of Bolinas Lagoon – over both geologic and historic time – helps to explain more recent changes and also increases our ability to project its future conditions. The following subsections rely primarily on findings from recently completed analyses of sediment cores by UC Berkeley (Byrne and others, 2005). Historic maps and bathymetric surveys collected from 1968-1998 provide supporting evidence and add to the description of lagoon evolution.

The abundance and diversity of plants and wildlife species found in Bolinas Lagoon are largely controlled by the relative size and distribution of habitats within the lagoon and ultimately supported by estuarine processes that shape the physical morphology and hydrologic conditions of the lagoon. Therefore, the following subsections also describe how important ecologic resources respond to changing physical processes.

3.1 SEDIMENT BUDGET, SEDIMENT DYNAMICS AND EQUILIBRIUM FORM

In general, the shape or 'morphology' of Bolinas Lagoon is driven by two interdependent processes: the sediment budget of the lagoon and its internal sediment dynamics. The sediment budget expresses the relative balance between net sediment delivery, sea level rise and tectonic subsidence (Figure 3-1). Sediment dynamics, the movement of sediment within the lagoon, reflects the influence of erosive and depositional processes that redistribute material and shape particular landforms, or 'geomorphic units', within the lagoon . These sediment transport processes may affect the sediment budget by strengthening or weakening pathways of sand and silt movement in and out of the lagoon.

The balance between net sediment delivery and the combined effects of sea level rise and tectonic subsidence, interacting with the balance between erosive and depositional processes, determines an equilibrium form toward which the lagoon continually evolves. Because the interplay between opposing erosive and sedimentary processes undergo continual changes at different time scales, the equilibrium form is dynamic, adjusting to perturbations in physical processes. The lagoon morphology can reach equilibrium when sediment inputs and outputs are in relative balance with sea level rise and subsidence. Large earthquakes along the San Andreas Fault punctuate the evolutionary trajectory of Bolinas Lagoon every few hundred years, possibly before the lagoon morphology ever reaches a dynamic equilibrium state. Once the relative balance of the sediment budget is disturbed by these infrequent high-energy events, erosional and depositional processes gradually adjust as the lagoon seeks a new dynamic equilibrium (Figure 3-2).



Dominant input/output terms in the sediment budget.

f igure **3-1**

Projecting the Future Evolution of Bolinas Lagoon

Sediment Budget Framework

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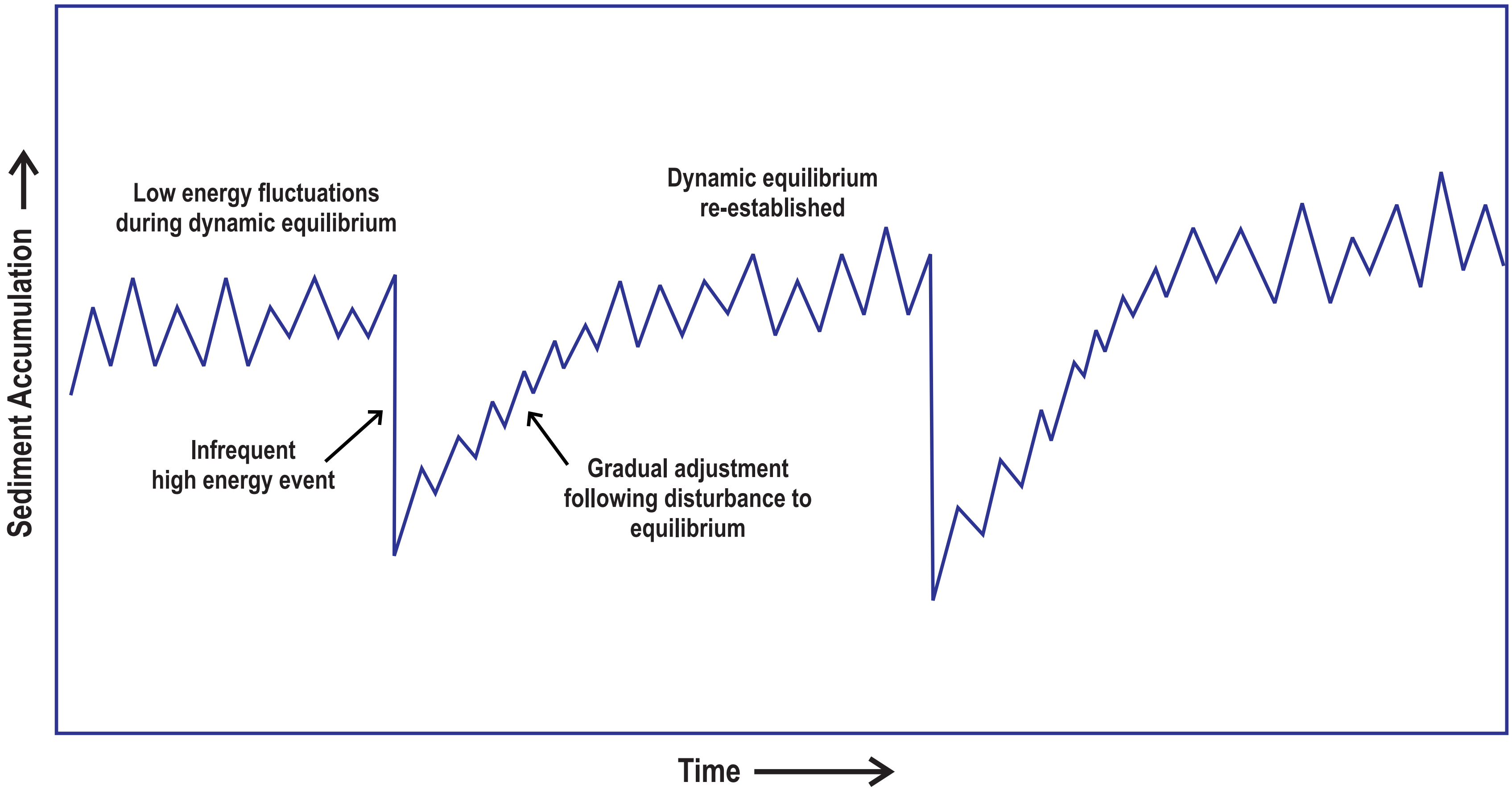

Source: after Woodroffe 2002

figure 3-2

Projecting the Future Evolution of Bolinas Lagoon

Concept of Punctuated Dynamic Equilibrium

PWA Ref# 1686.02-T8

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Large earthquakes along the San Andreas Fault cause sudden down-drops of the lagoon bottom through a combination of two processes: vertical displacement, particularly along the eastern block of the fault; and dynamic compaction of unconsolidated sediment, especially silts and clays that tend to accumulate in low-energy environments. Earthquakes also modify the size and location of channels, and drown marsh plants that occur along margins of the lagoon and on islands within its interior. The resulting changes to the lagoon form alter the sediment budget, and result in a rapid increase in net import of sediment until erosive forces gradually slow the rate of deposition as the lagoon asymptotically approaches a new dynamic equilibrium form. Human alterations in the processes that determine the sediment budget and sediment dynamics of the lagoon inevitably alter the evolutionary trajectory and hence the ultimate equilibrium form of the lagoon.

Because the lagoon is always adjusting to changes that occur both gradually (e.g., sea level rise) and suddenly (e.g., earthquakes), it is not possible to manage for a particular form. Changes to the sediment budget or sediment dynamics, either natural or anthropogenic, will alter the trajectory of lagoon but not hold its form in any one static or steady state condition.

3.2 NATURAL EVOLUTION OF BOLINAS LAGOON

3.2.1 Evolution over Geologic Time and the Role of Large Earthquakes

Millions of years of tectonic activity along San Andreas Fault have created a rift valley that was flooded between 18,000 and 7,000 years ago by rapidly rising sea level and formed Bolinas Bay (Bergquist, 1978). As the rate of sea level rise stabilized, sand transported by wave and tidal action built Stinson Spit, which separated Bolinas Lagoon from Bolinas Bay. Deep sediment cores within the lagoon show it has persisted as a coastal landform for the past several thousand years, during which time Bolinas Lagoon has slowly transgressed landward in response to continued sea level rise (Bergquist, 1978).

Recent study of sediment cores by UC Berkeley (Byrne and others, 2005) contains the most comprehensive set of data regarding the late Holocene evolution of Bolinas Lagoon. Based on radiocarbon dating of shell fragments and the layering of fine-grained silt and clay and coarse-grained sand particles of two cores extracted from the North Basin, Byrne and others (2005) have identified five major earthquakes over the past 1,600 years (ca. 450, 1080, 1220, 1520, and 1906) that resulted in large shifts in the depositional environment of the lagoon. In addition to these earthquakes, the UC Berkeley study revealed the presence of a 1-3 ft thick layer of sand present throughout the North Basin, which is evidence of a high-energy environment in the North Basin sometime between 1600 and 1800. Byrne has attributed this deposit to the January 26, 1700 tsunami that occurred offshore northern California, or more frequent winter storms during the Little Ice Age.

The chronology of these two 'long cores' reveal that the long-term sedimentation rates prior to 1850 varied from 2-4 mm/yr (Byrne and others, 2005), approximately double the estimated late Holocene sea level rise established for San Francisco Bay (*in* Byrne, 2002). These data suggest that repeated tectonic subsidence has been a major determinant in the long-term maintenance of Bolinas Lagoon as a fully tidal system. Indeed, the absence of pollen from freshwater marsh plants in both long cores is evidence that the lagoon mouth has not closed at any time during the last 1,600 years.

3.2.2 Mechanisms of Sediment Delivery

Under natural conditions, sediment deposited within the lagoon comes from two sources: 'littoral' or beach sands and coastal bluff sediments suspended by wave action and carried into the lagoon during flood tides; and 'alluvial' or stream borne sediment eroded from the watershed by rain storms. The relative contribution of littoral and alluvial sources to net sedimentation depends on the amount of material available (the sediment supply) and the ability of tidal currents, ocean waves, internal wind-waves and creek flows to carry sediment into the lagoon (the transport capacity).

Littoral sediments come primarily from longshore transport of beach sand from Stinson Spit and silt eroded from the Bolinas Bluffs (A and B in Figure 3-3). Ocean waves move sand along the shore by rolling and dragging large particles along the bottom, and by stirring up smaller grained sand in the surf zone. These smaller grained beach sands can then be efficiently transported in suspension by longshore currents. Swells from the south-southwest are most effective at transporting sand along the beaches adjacent to the inlet, since Duxbury Reef shelters Bolinas Bay from ocean waves that approach from the northwest (Battalle, 1984). Once mobilized by ocean waves, flood-tide currents sweep a portion of the beach sand that is moving along the shoreline through the inlet into the lagoon. Most of the beach sands imported by flood tide currents are later exported from the lagoon during the subsequent ebb tide (Ritter, 1973), but a portion of these sediments deposit on flood-tide shoals just inside the lagoon. Fine-grained beach sands can be dispersed far into the lagoon if subsequent flood-tide currents along the main channel are sufficiently strong. Wind-blown sand from the flood-tide shoal captured by vegetation builds the supratidal dunes of Kent Island.

In addition to beach sand, the littoral sediments swept into Bolinas Lagoon include silt eroded from the bluffs between the lagoon and Duxbury Point. These steep cliffs consist primarily of mudstone, which is susceptible to rapid landslides when exposed to groundwater seepage and wave attack. Once eroded from the face of the cliffs, ocean waves and tidal currents transport fine-grained silt toward the inlet. Although ocean waves and tidal currents easily transport fine-grained silt eroded from the face of the cliffs, only a fraction of this material makes its way through the inlet and into the lagoon due to complex circulation patterns in Bolinas Bay.

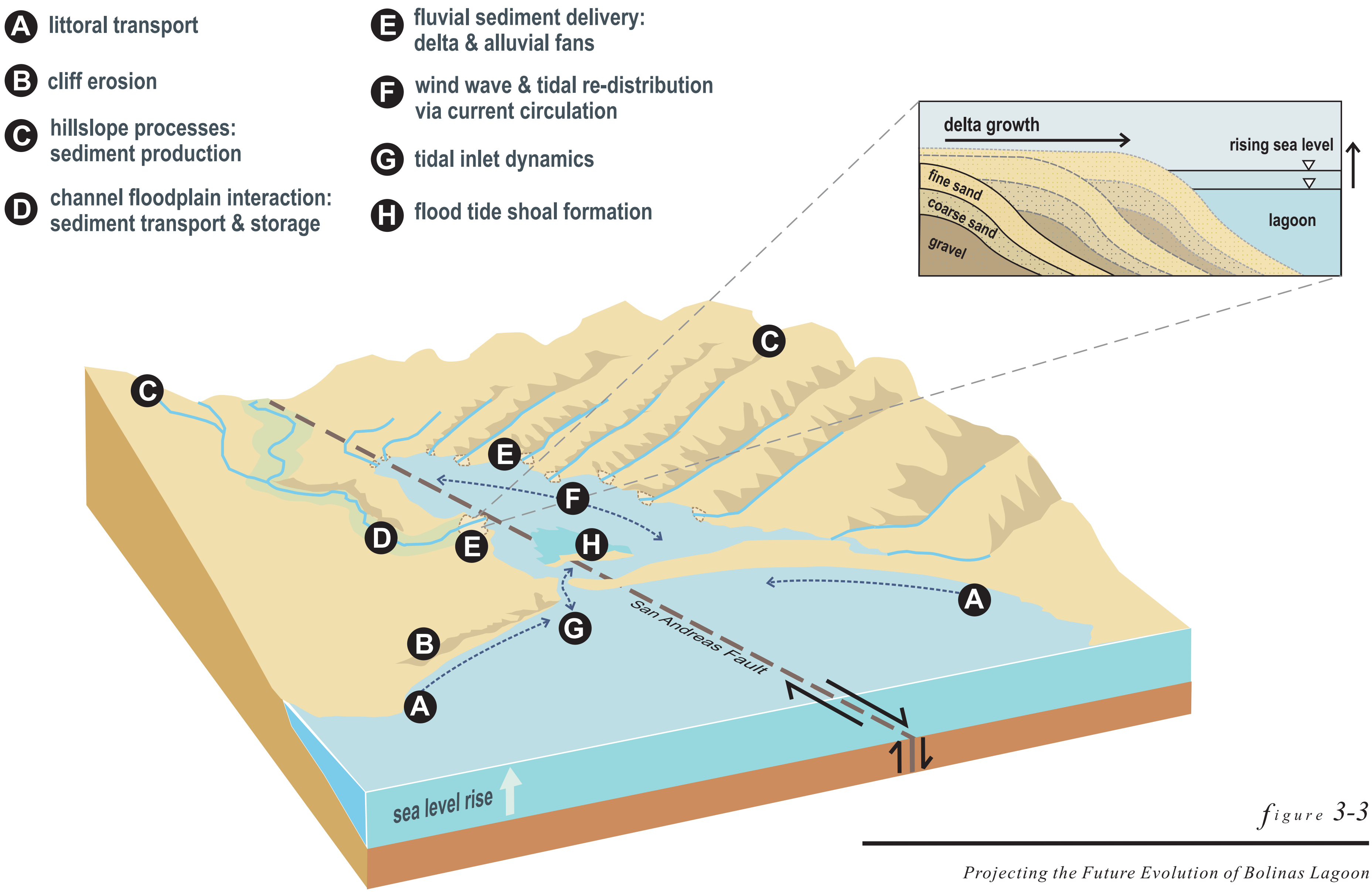

figure 3-3

Projecting the Future Evolution of Bolinas Lagoon

Physical Processes Affecting Bolinas Lagoon

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PWA

Alluvial sediment produced in the watershed due to erosion consists of mud, silts, sands, and gravel (C in Figure 3-3). The coarser material, or 'bedload', moves downstream in response to high winter flood events and is deposited where flow velocities slacken, either on alluvial fans and floodplains upstream, or on deltas where Pine Gulch Creek and smaller tributaries enter Bolinas Lagoon (D and E in Figure 3-3). Since delivery of gravel and coarse sand only occurs during infrequent floods, gravel and coarse sand is deposited on the creek deltas as discrete layers, which are sandwiched between beds of fine material (insert in Figure 3-3). Sedimentation on the supratidal portions of Pine Gulch Creek delta has created riparian habitat, while alluvium deposited at lower elevations are largely responsible for the progradation of salt marsh and mudflats into the interior of Bolinas Lagoon. Due to the steep and naturally eroding watershed, bedload delivery of watershed material is controlled by the frequency and magnitude of peak creek flows and is not limited by the supply of coarse sediment.

In contrast to bedload delivery, the amount of 'suspended' load moved downstream is more dependent on the supply of material, and hence the extent of erosion in the watershed. Because these finer sediments are easily transported by moderate flows and have low settling velocities, much of the suspended load is discharged beyond the delta and directly into Bolinas Lagoon where it is redistributed by wind-wave action and tidal circulation. Unlike bedload delivery, which is almost completely captured within the lagoon, a portion of the suspended load is flushed out of Bolinas Lagoon during ebb tides. The suspended load that remains in the lagoon is redistributed by internal circulation patterns and deposited on mudflats (F in Figure 3-3). In locations sheltered from wind-wave agitation and where tidal currents are weak, sedimentation rates are sufficiently high to sustain vegetated marshplain habitat. Once salt marsh is established, sedimentation rates may increase due to the ability of the vegetation to 'trap' suspended particles, reduce the erosion of previously deposited material and contribute organic material to the marsh plain.

Internally generated wind waves erode material previously deposited on the intertidal mudflats, which can then be redistributed within the lagoon or swept to the ocean by tidal currents (G in Figure 3-3). Under typical conditions, wind waves are sufficient to resuspend finer mud and silt – but not coarser sand and gravel. This produces mudflats in areas exposed to high wind waves that are too low to support salt marsh vegetation. In areas protected from substantial winds, such as the lee side of Kent Island, accumulation of fine mud and silt builds intertidal flats to elevations suitable for colonization of marsh vegetation. Accumulation of beach sand and re-distribution by energetic tidal flows and waves result in relatively dynamic flood tide shoals (H in Figure 3-3).

Redistribution of previously deposited mud and silt also produces a gradient of sediment texture within Bolinas Lagoon, with grain size of intertidal flats generally decreasing with distance from the inlet (Ritter, 1973). (This general trend is sediment texture was also observed in recent field measurements described in Appendix A.) Mudflats in the North Basin and South Arm generally consists of fine-grained sediment, except near the mouths of creeks where alluvial bedload deposits within the lagoon. In the relatively high-energy central portion of the lagoon, wind waves sweep away fine-grained sediments and produce sandier intertidal flats.

3.2.3 Relative Magnitudes of Littoral and Alluvial Sources

Determining the precise relative contributions of littoral and alluvial sediment to net sedimentation is difficult, but we can assess the order of magnitude of each source by examining the long-term rate of watershed delivery under natural conditions and assume that the remaining material was comprised of beach sands and silt eroded from nearby bluffs.

In the small, steep coastal watershed of Bolinas Lagoon, sediment production is in balance with sediment export out of the watershed when averaged over thousands of years. We have estimated the long-term watershed delivery under natural conditions based on a comparison with Holocene average erosion rate established from chemical analysis (cosmogenic isotope analysis) of stream sediments in Tennessee Valley (Heimsath and others, 1997; 1999). Similar rates were also measured from samples collected in Point Reyes (Heimsath, personal communication). Applying this rate to the Bolinas watershed, we estimate that the watershed delivery to the lagoon during the late Holocene was approximately 4,500 CY/yr when averaged over thousands of years.

Findings from the two ‘long cores’ collected during the recent UC Berkeley study reveal that for several hundreds of years prior to 1850, net sedimentation in the North Basin varied between 2 – 4 mm/yr (Byrne and others, 2005). By applying an average rate of 3 mm/yr over 1,200 acres, we estimate the late Holocene net sedimentation in Bolinas Lagoon averaged approximately 19,000 CY/yr. The implication of this finding is that, prior to significant human disturbances, watershed inputs only accounted for a fraction of the sediment accumulation in the lagoon. The availability of beach sand and silt eroded from nearby bluffs, and the capacity of coastal processes to transport this material into the lagoon, suggest that most of the sediment deposited in the lagoon originated from the littoral sources.

3.2.4 The Tidal Inlet and Estuarine Processes

The portion of the lagoon closest to the inlet is in a constant state of flux, with most of the sand transported into the lagoon on the flood tide swept out by the subsequent ebb tide currents. Sediment deposition just outside of the inlet creates a submerged ebb shoal that allows wave action to move sand across the inlet channel between Stinson Spit and Brighton Beach. Although the morphology of the tidal shoals and inlet responds to seasonal changes in wave climate, the relative balance between tidal prism and dispersion of sand by tidal currents determines their long-term size and geometry (Walton and Adams, 1976).

Open inlets provide a variety of processes required to support estuarine species, such as the transport of energy and nutrients, and the ability of passively- and actively-swimming organisms to move between the lagoon and coastal waters. The ability of the inlet to remain open largely depends upon the relative balance between tidal currents and wave-driven sand transport. Wave-driven beach sand is transported to the mouth of the inlet, where a portion of the material is deposited during flood tides. Strong ebb tidal currents, which are primarily controlled by tidal prism, scour this material and maintain a stable inlet size and location. Therefore, the potential for inlet closure is greatest when energetic coastal storms coincide with weak neap tides. While tidal currents change as the lagoon tidal prism and morphology evolves over decades, wave climate is relatively constant when averaged over long periods, although this too varies seasonally and from year to year. For this reason, changes to tidal prism largely control the average or typical closure potential over the long-term. The equilibrium form of Bolinas Lagoon has historically maintained sufficient tidal prism to keep the inlet open, partially due to the fact that Duxbury Reef shelters the inlet from the prevailing northwesterly swells.

3.2.5 Ecological Response to Changing Physical Conditions

The distribution of habitats within the lagoon is complex and constantly changing. The habitat distribution over the last century have undergone substantial change as the lagoon has evolved from a system dominated by intertidal mudflats before the 1906 earthquake; to a largely open-water lagoon immediately following the earthquake; and has been evolving towards a new equilibrium state over the past several decades. As habitats shift, we expect populations of plants and animals to respond accordingly. However, because trophic interactions are complex and are not confined within specific habitat types, the loss of acreage of one habitat type may have effects on species in other habitat types. For similar reasons, the loss or gain in acreage of a given habitat types does not always translate directly into a similar increase or decrease in the abundance of species that use that habitat type. At Bolinas Lagoon we have little empirical data on changes in the diversity and abundance of taxa with the exception of aquatic birds. Even with this population data on birds, it is difficult to ascribe direct cause and effect linkages with habitat shifts as populations of mobile animals are impacted in other locations and at varying stages of their life cycles.

Generally, the ecology of coastal lagoons is tied to two physical processes: how the accumulation of alluvial and littoral sediments change estuarine habitats; and whether and for how long the inlet is open at the lagoon mouth. When net sedimentation outpaces sea level rise, the frequency and duration of tidal inundation over mudflat change as their elevations rise relative to the tides. As mudflat elevation increase, salt marsh plants can colonize former mudflats, causing a shift to detrital (dead organic matter) food webs. In addition, sudden ‘down-drop’ of the floor of Bolinas Lagoon during large earthquakes along the San Andreas Fault results in rapid changes to ecology.

Inlet closure can also affect lagoon ecology. Depending on the season and duration of closure, the loss of tidal exchange can either result in brackish or freshwater conditions. Water levels may also fluctuate – by either flooding the marshes as water backs up, or by drying out mudflats as evaporation proceeds. The net result is a loss of species diversity as fewer plants and animals can tolerate the extreme conditions associated with these processes. Lagoons that are closed for the majority of the year may only open when river flows are high or strong waves associated with winter storms breach the beach barrier. Lagoons that are partially closed typically have significantly smaller tide ranges. Under these conditions, the lagoon may undergo similar decreases in species diversity due to the reduced tidal influences.

Ecological processes within lagoons are also influenced by other factors such as nutrient inputs from agriculture that induce eutrophication, development within the watershed that increases sediment and pollutant loading, and colonization by non-native species that reduces biodiversity. In the case of Bolinas

Lagoon, changes in elevation due to sedimentation and the potential alteration of the inlet due to a decreasing tidal prism have the greatest potential to affect habitat.

3.3 19TH CENTURY LAGOON CONDITIONS

3.3.1 Conditions Prior to Significant Disturbances

The first detailed topographic map of Bolinas Lagoon (Figure 3-4) was surveyed by the US Coast Survey (USCS) in 1854, five years after the initiation of extensive logging in the watershed. The 1854 topographic map, or 'T-sheet', provides valuable insight regarding the form of the lagoon prior to significant watershed disturbances, its habitats, and approximate tidal prism.

The 1854 T-sheet reveals that most of the lagoon at this time consisted of intertidal flats drained by a system of sinuous subtidal channels. Discovery of *Cerithidea californica* shells – a snail that lives in intertidal marshes and mudflats – just 5 cm below the logging horizon in one of the cores collected by the recent UC Berkeley study confirms that the North Basin was not a deep subtidal basin prior to the mid-1800s (Byrne and others, 2005). The 1854 map also shows a flood-tide island backed by salt marsh, which is generally similar to the present-day form of Kent Island although slightly less in overall extent. Salt marshes were also intermittingly distributed along the fringe of the lagoon and along the western shoreline from approximately the mouth of Pine Gulch Creek to the Little Mesa. Freshwater marshes are shown along the banks of Easkoot Creek. Although the main tidal channel depicted in the T-sheet is similar to its present-day location, the 1854 morphology of the lagoon included a second large channel that extended from the mouth of Pine Gulch Creek to the tidal inlet. Between these two locations, the channel ran along the western shoreline of the lagoon and what would later become Wharf Road (Figure 3-5).

Although extensive harvesting of timber in the watershed began five years before production of the 1854 T-sheet, details of the map suggest that it generally depicts the natural conditions of the lagoon prior to significant impacts associated with logging. The strongest evidence of this are: the presence of highly sinuous channels, which drain both mudflats and marsh; fully developed mudflats that lack large subtidal 'pools'; and the lack of prograding deltas at the mouths of Pine Gulch Creek and other tributaries to Bolinas Lagoon. Because of this, we assume that the distribution of habitats shown in the 1854 T-sheet are representative of natural conditions of the lagoon, prior to significant human-induced disturbances.

Because 19th century cartographers delineated the edges of high and low tide (USCGS, 1964), we can estimate the approximate 1854 tidal prism of Bolinas Lagoon by measuring the extent of subtidal channels, mudflat, and marsh (see Table 3-1) and then making assumptions regarding the tidal range inside the lagoon. Since the inlet channel was of similar depth and dimensions as today (USCS, 1854), we can assume that the diurnal tide range inside the lagoon in 1854 was as approximately equal to contemporary values. Based on this assumption and the distribution of subtidal, intertidal, and marsh habitats, we estimate 1854 tidal prism to be about 3.7 ± 0.8 MCY, assuming a ±0.5 ft error in the assumed diurnal tidal range. Details of this computation are provided in Appendix B.

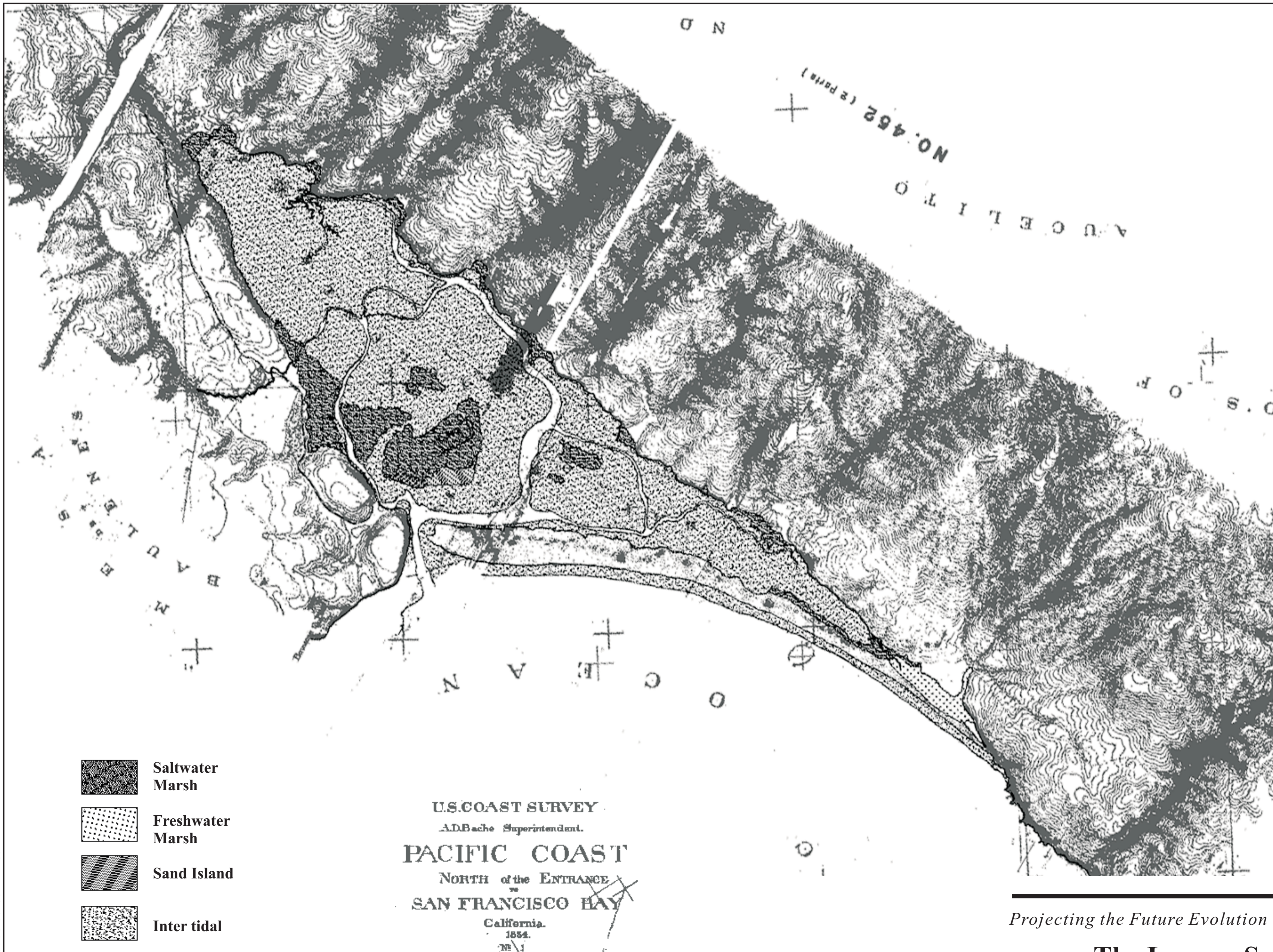


figure 3-4

Projecting the Future Evolution of Bolinas Lagoon

The Lagoon Survey of 1854

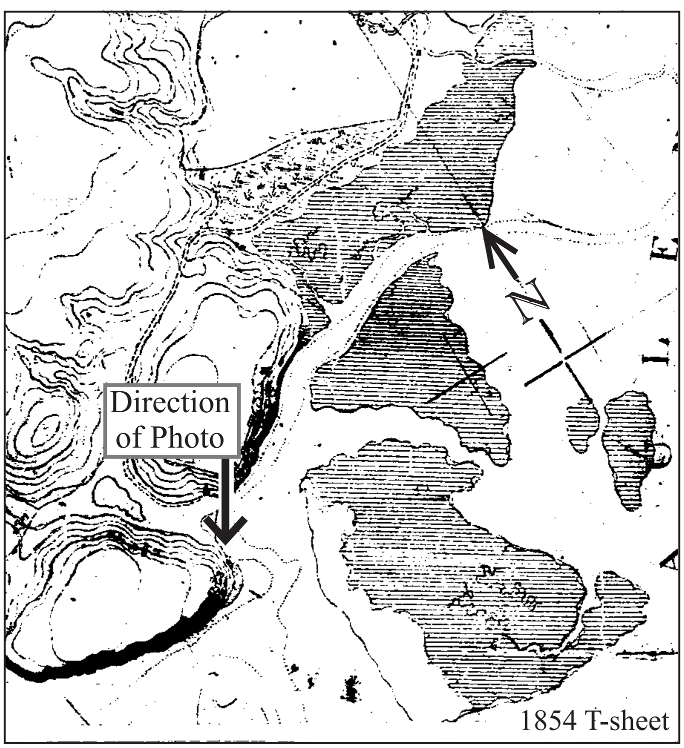
Source: U.S. Coast Survey 1854 (T-452)

PWA Ref. # 1686.02 T-8

PWA

#1686.02 /Task 8 /Corel/1854-V2. cdr

photo: 1873



Shallow draft lightering barges were used to float timber from the embarcadero to wharfs in Bolinas, where logs were then loaded to be shipped to San Francisco.

figure 3-5

Projecting the Future Evolution of Bolinas Lagoon

19th Century Lightering Wharfs and Barges

#1682.02 Tk 8 ViewWhf. cdr

PWA

Table 3-1. Habitat Distribution in 1854

Habitat	Acres
flood-tide island*	13
freshwater marsh*	21
salt marsh	170
intertidal flats	910
subtidal channels	130
Total	1,244

* does not contribute to tidal prism estimate

Prior to signs of human disturbance, lagoon habitats consisted primarily of intertidal flats, a small riparian area near the mouth of Pine Gulch Creek, narrow salt marsh fringes, shallow mudflats throughout, and open water along the large subtidal channels. The tidal prism maintained a continuously open inlet; salinity variation and tidal fluctuations within the lagoon were near that of the ocean and supported predominantly marine dependent communities.

The relative distribution of habitat types within the lagoon had a direct influence on the species that dominated the system. As a more open water and shallow mudflat-dominated lagoon, it likely supported a higher proportion of plankton, fish, large-bodied benthic invertebrates, and the migratory and resident birds that feed on these food sources than it does today. The food webs were more linear in that living organisms were feeding on other living organisms at various trophic levels. The food webs also relied less on the high primary production of the salt marsh that is processed differently than the more pelagic food web, characteristic of the open ocean, of the open water/mudflat environment associated with pre-disturbance conditions. In addition, habitat structure afforded by the salt marsh allowed less area for birds to nest and seek shelter and refuge during high tides or storms.

3.3.2 Land Use Changes in the 19th Century

Native Americans inhabited the land surrounding Bolinas Lagoon prior to the arrival of Spanish-American settlers, but humans did not significantly impact the watershed until the onset of farming, logging and cattle grazing in the latter half of the 19th century. These practices, which included channelization of Pine Gulch Creek, increased watershed delivery to the lagoon by enhancing erosion in the hillslopes, reducing sediment deposition on the Pine Gulch Creek floodplain, and increasing peak flows along the creeks tributary to Bolinas Lagoon. Although the increased watershed delivery did not directly alter the morphology across the entire lagoon, its effects did result in modifications to lagoon form near creek mouths and in the area closest to where logging practices took place.

Although the first Spanish settlers arrived in 1834, their impacts on watershed processes were relatively small due the limited number of ranchers. Significant human-induced, or ‘anthropogenic’, modifications to the watershed began in 1849 with the initiation of logging (Munro-Fraser, 1880). Logging practices altered natural conditions by increasing the effects of erosion by rain and wind in areas cleared of vegetation. Additionally, areas cleared of vegetation accelerated runnoff, which translated to greater peak flows and sediment transport capacity in creeks. Immediately following the end of logging, harvested land was exploited for cordwood production, dairy farming and cattle grazing that further degraded the land and prevented the watershed from naturally recovering. These changes in land use increased delivery of both suspended load and bedload to the lagoon; additional erosion of hillslope sediments supplied fine-grained suspended load to creeks, while greater peak flows and channelization enhanced the capability to transport coarse-grained bedload.

Recent analysis of sediment cores collected in the North Basin by researchers at UC Berkeley reveal high rates of accumulation near the mouth of Pine Gulch Creek (12 mm/yr) and in the northernmost portion of the North Basin (10 mm/yr) during the period from 1850 to 1906 (Byrne and others, 2005). Net sedimentation rates measured at these locations are about double of the average of all UC Berkeley cores collected from the North Basin (6 mm/yr) over the same period of time and are two to four times higher than rates prior to EuroAmerican settlement. These findings confirm that land use changes initiated in the mid-1800s increase watershed sediment delivery to the North Basin, especially near the former Embarcadero and the mouth of Pine Gulch Creek. Applying the average 6 mm/yr rate to the 400-acre North Basin and assuming sea level rise of 2 mm/yr over the same period, we estimate that watershed disturbances reduced the tidal prism of Bolinas Lagoon by about 0.5 MCY to approximately 3.2 ± 0.7 MCY by 1906.

3.4 THE 1906 EARTHQUAKE AND ITS EFFECTS ON SEDIMENT DELIVERY

Although watershed disturbances in the late 1800s undoubtedly altered the morphology of Bolinas Lagoon, particularly in localized areas within the North Basin, more substantial changes occurred due to the earthquake of April 18, 1906. Results from the recent sediment core study by UC Berkeley and interpretation of the 1929 T-sheet (Figure 3-6) indicate that the effects of the 1906 earthquake were greater than previously thought. The sudden down-drop of the lagoon floor induced by the earthquake instantaneously increased the volume of the lagoon and significantly altered the sediment budget, particularly the rate at which beach sands and bluff-eroded silt were swept through the inlet.

3.4.1 Subsidence During the 1906 Earthquake

When compared to the 1854 T-sheet, the 1929 survey of Bolinas Lagoon reveals the extent of the 1906 ‘down-drop’ that occurred along the San Andreas Fault (Figure 3-7). After 23 years much of the area along the eastern block of the fault remained subtidal, particularly in the North Basin, which is furthest away from the supply of beach sands. Table 3-2 summarizes the extent of the habitats mapped in the 1929 T-sheet. We can safely assume that the extent of subtidal shallows was even greater in 1906. Presumably, the lagoon bottom in other areas also dropped to subtidal elevations at the time of the earthquake, but had accumulated enough sediment by the time of the 1929 map production to reform intertidal sand and mudflats.

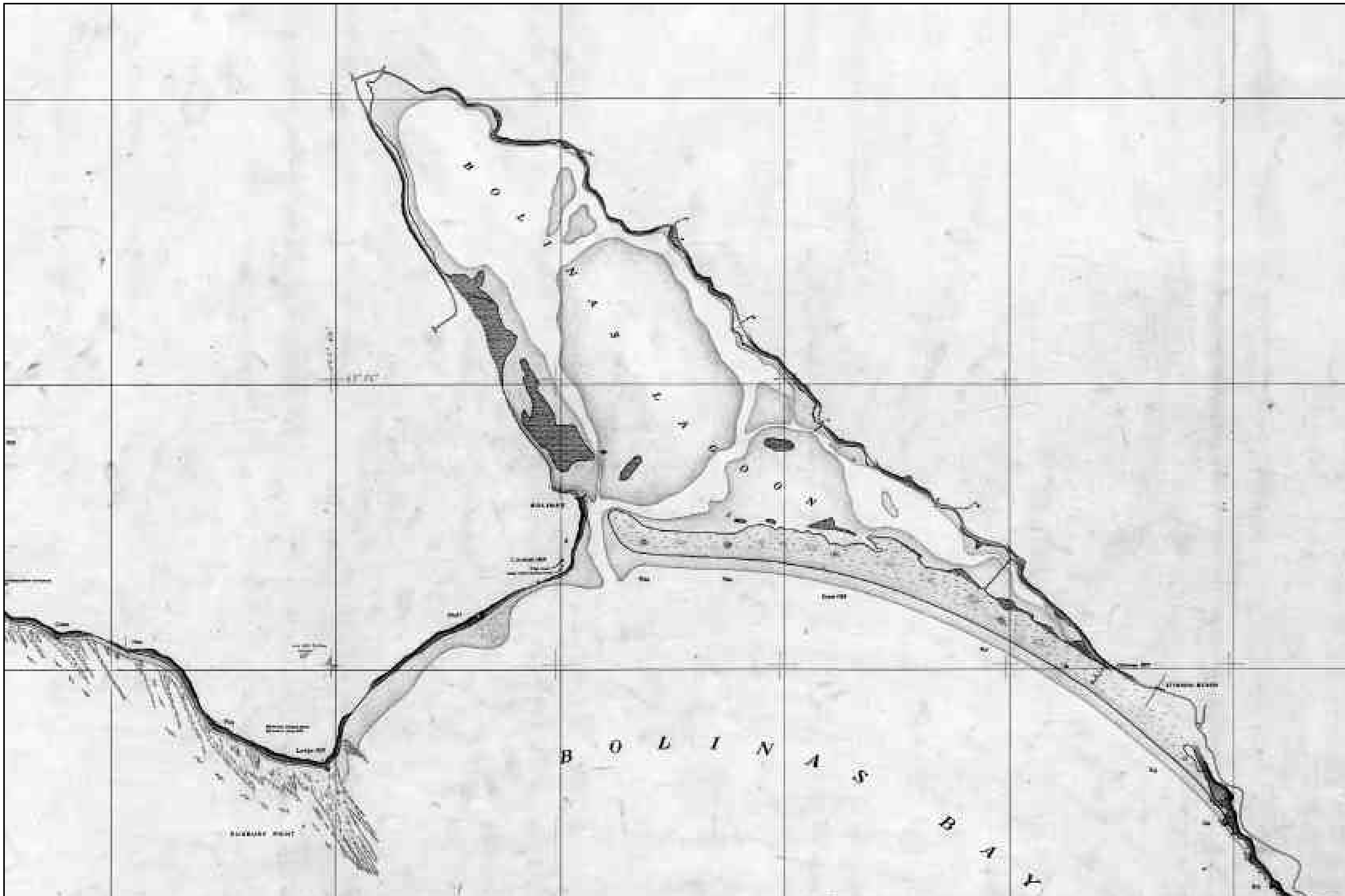


figure 3-6

Projecting the Future Evolution of Bolinas Lagoon

The Lagoon Survey of 1929

Source: U.S. Coast Survey 1929 (T-4520)

PWA Ref. # 1686.02 T-8

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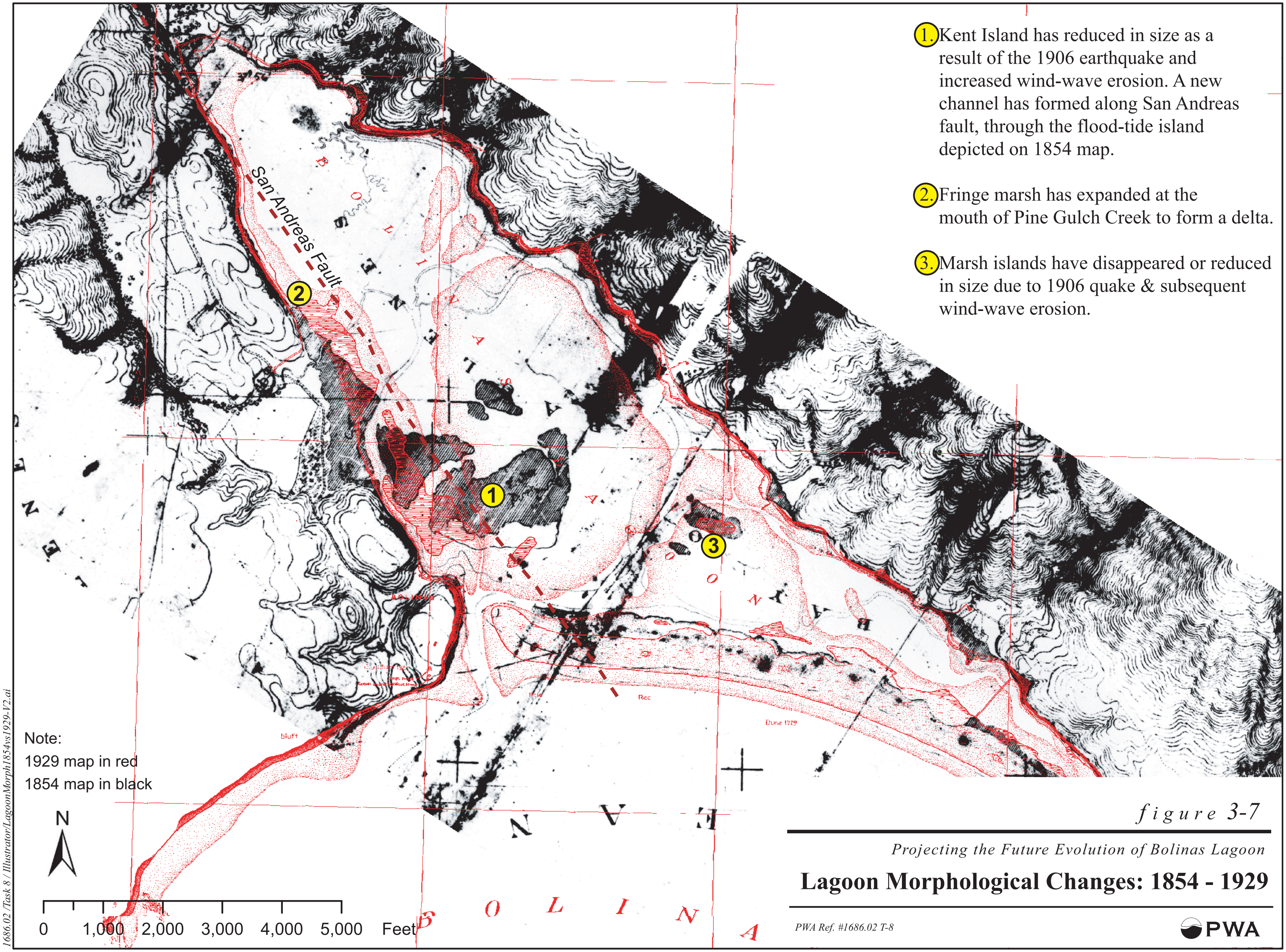
#1686.02 /Task 8 /Corel/ 1929-V2.cdr



1. Kent Island has reduced in size as a result of the 1906 earthquake and increased wind-wave erosion. A new channel has formed along San Andreas fault, through the flood-tide island depicted on 1854 map.

2. Fringe marsh has expanded at the mouth of Pine Gulch Creek to form a delta.

3. Marsh islands have disappeared or reduced in size due to 1906 quake & subsequent wind-wave erosion.

figure 3-7

Projecting the Future Evolution of Bolinas Lagoon

Lagoon Morphological Changes: 1854 - 1929

PWA Ref. #1686.02 T-8

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1686.02 /Task 8 / Illustrator/LagoonMorph1854vs1929-V2.ai

Table 3-2. Habitat Distribution in 1929

Habitat	Acres	
	1929	**1854**
flood-tide island*	-	13
freshwater marsh*	-	21
salt marsh	77	170
intertidal flats	682	910
subtidal channels & shallows	487	130
Total	1,246	1,244

Notes: * Does not contribute to tidal prism. Flood-tide island and freshwater habitats not mapped in 1929, presumably due to their absence from the lagoon. We attribute differences in the total extent of the lagoon to changes in the shoreline along Stinson Spit, which was also lowered during the 1906 earthquake.

Gilbert concluded that the earthquake had dropped the lagoon floor by approximately 1 ft, based on observations of submerged and dying marsh plants on Kent Island one year after the earthquake (*in* Lawson, 1908). However, recent analysis of sediment cores collected in the North Basin indicate that the 1906 down-drop averaged 1.5 ft on the east side of the fault, with localized down-drop up to 1.9 ft. We attribute the down-drop of the lagoon floor to a combination of processes: direct vertical displacement of the eastern block as well as compaction and local slumping of unconsolidated sands. Given that Gilbert's observations were made in an area dominated by sand, it is not surprising that down-drop was greater in the North Basin, where sediments contained a greater percentage to silts and clay and were generally more susceptible to liquefaction.

Personal accounts of the 1906 earthquake reported in the *Marin Journal* support the contention that its effects to Bolinas Lagoon and adjacent bluffs were locally dramatic. Professor Ebenezer Knowlton observed (Marin Journal, May 10, 1906 *in* USACE 2002):

> The great ocean bluffs along the south and west of the entrance to Bolinas harbor, some 165 ft high, crumbled and fell, crashing down upon the ocean beach and reducing the slope to half its former angle. Also the two bluffs along the stage road from the head of the bay to the town broke and fell from forty to sixty feet, completely blocking the stage road and driving the stage out along the upper bay beach.
>
> In the [lagoon] opposite the hillside on the Steele place, the bottom has risen into a long island, near which the bottom of the [lagoon] has sunk so that the water is now ten feet deep where muddy shoals formerly extended.

Although it is difficult to quantify the magnitude of the effects from this historical personal account, changes to the lagoon bathymetry described in the passage above support the contention of dramatic local down-drop. Anecdotal accounts and findings from the UC Berkeley sediment study also suggest that the amount of vertical displacement was different across the fault, with less down-drop west of the fault trace. Additionally, massive bluff erosion would have increased the supply of fine-grained silt available to be transported into the lagoon by tidal currents.

3.4.2 20th Century Sedimentation Rates and Sources

Net sedimentation rates since the 1906 earthquake can be estimated by multiple methods. The most reliable data come from the recent UC Berkeley study, which documents 1906-2005 net sedimentation rates in the North Basin (cores taken from the south basin were unusable due to the amount of disturbance from dredging, fill and other activities). Analysis of GIS surface models based on surveys from 1968-1998 provide a second set of data, which corroborates the UC Berkeley data. From examining the alluvial and littoral terms in the sediment budget, it is clear that the majority of sediment accumulated in Bolinas Lagoon since the 1906 earthquake originate from littoral sources. This is confirmed by recent geochemical and mineralogical analysis of sediment cores extracted from the North Basin (Byrne and others, 2005).

Analysis of 21 cores sites collected by UC Berkeley (Byrne and others, 2005) indicates that net sedimentation in the North Basin averaged approximately 6.8 mm/yr since the 1906 earthquake. As expected, higher rates were observed in the deeper central portion of the basin on the east side of the fault trace where down-drop was greater. By extrapolating the average rate derived from the North Basin over a 1,200-ac footprint, we estimate that the net sedimentation in Bolinas Lagoon has averaged approximately 43,000 CY/yr during the 20th century. It is important to note that the UC Berkeley cores were limited to unvegetated mudflats and subtidal shallows due to permit restrictions (Figure 5-4) and do not account for the delivery of coarse watershed sediments which have formed Pine Gulch Creek delta.

Surface models developed from photogrammetric/hydrographic surveys of Bolinas Lagoon generally support the estimate sediment accumulation established by extrapolating the UC Berkeley data. Based on surface models developed from the 1968 and 1998 surveys, the average rate of net sedimentation during this period has been about 48,000 CY/yr (USACE, 2002). This estimate is higher than the estimate based on extrapolating the UC Berkeley results from the North Basin, but includes approximately 4,900 CY/yr of accumulation in areas above high tide, such as the Pine Gulch Creek delta. For the purposes of the present study, we have used an intermediate value of 43,000 CY/yr to represent the average 20th century rate of net sedimentation.

This observed rate of sediment accumulation cannot be explained alone by the delivery of watershed sediments, suggesting that a substantial portion of the material accumulated in the lagoon originates from littoral sources. Based on the amount of sediment produced in the watershed (TetraTech, 2000), measurements of suspended load along Pine Gulch Creek (USGS, 1973), and the capacity for bedload transport computed at the downstream reach of Pine Gulch Creek (Appendix C), we estimate that the average 20th century rate of watershed delivery at approximately 10,000 CY/yr. This is approximately double the Holocene average and presumably due to watershed disturbances.

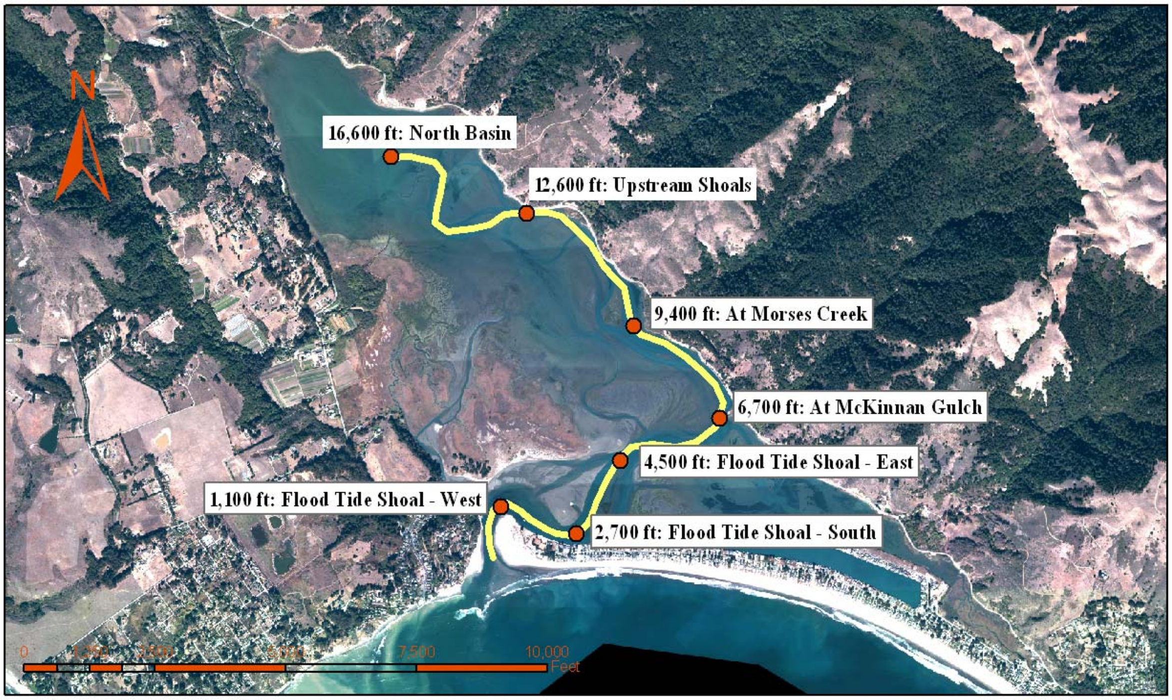
The supply and transport capacity of beach sands, supplemented by silt eroded from nearby bluffs, explain the discrepancy between net sedimentation and watershed delivery. Using standard methods that relate wave energy to sediment flux, Batelle (1984) computed the longshore sediment transport *potential* at Stinson Beach to be about 300,000 CY/yr. Although the actual amount of beach sands transported along Stinson Spit is probably less, due to the protected orientation of Bolinas Bay and the rocky shoreline at Duxbury and Rocky Points, the Batelle estimate indicates that the capacity of ocean waves to deliver sand to the inlet is an order of magnitude greater than the ability of creek flows to deliver alluvium to the lagoon.

Silt eroded from the Bolinas Bluffs supplement the beach sand as another source of littoral sediment. These bluffs are retreating at an average rate of 1 to 2 ft/yr, which delivers about 37,000 CY/yr of silt to the base of the cliffs (Ritter, 1973). Although only a fraction of this material makes its way through the inlet, fine-grained silts are able to remain in suspension long enough to be transported throughout the lagoon. The failure of coastal bluffs reported during the 1906 earthquake would have provided a large amount of silt to the littoral zone.

The basic finding that littoral sources account for the majority of sediment accumulated in Bolinas Lagoon over the past century is supported by findings from Byrne and others (2005). The geochemical and mineralogical composition of a well-dated core was compared to various potential sources: the Pine Gulch Creek delta (as a proxy for sediments from the western part of the watershed); the Bolinas Ridge; and the Bolinas Bluffs. These analyses indicate that most of the sediment in the post-1906 section of the core consisted of material derived from the bluffs.

3.4.3 Accelerated Tidal Dispersion of Littoral Sediments

We have assessed the potential for tidal currents to disperse fine beach sands into the lagoon by applying analytic equations for planar jets (Fischer and others, 1979). As shown in Figure 3-8, application of these equations indicates that flood-tide currents along the Main Channel were probably adequate to disperse sand far into the lagoon interior throughout all stages of the spring-neap tidal cycle. Tidal dispersion typically occurs over a cycle of transport: deposition as diminishing velocities cease to move sand particles, and re-mobilization during subsequent flood tides. The distribution of grain size observed by Ritter (1973), which shows coarser sands near the inlet and finer sands further away, are consistent with the expected effects of tidal dispersion. Since the amount of beach sand dispersed into the lagoon largely depends on tidal prism, the rate of delivery was undoubtedly greater immediately following the 1906 earthquake.



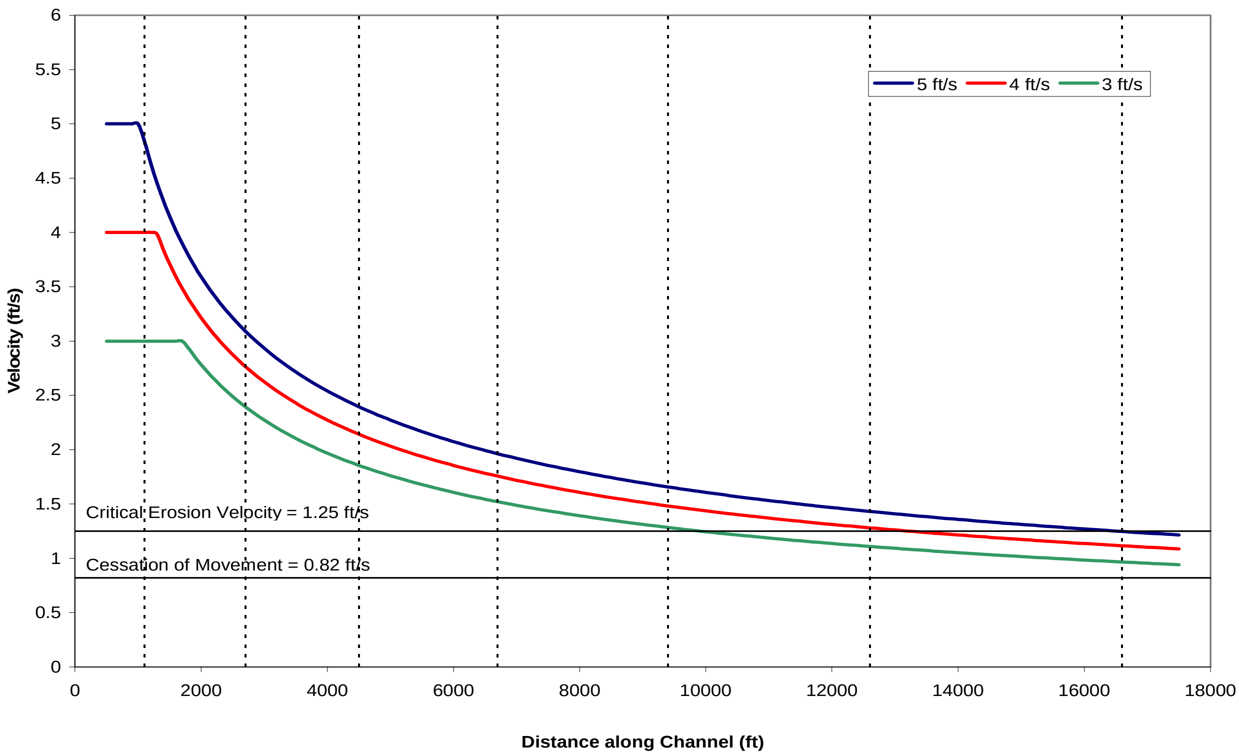


figure **3-8**

Projecting the Future Evolution of Bolinas Lagoon

Potential Strength of Tidal Dispersion After the 1906 Quake

PWA Ref# 1686.02

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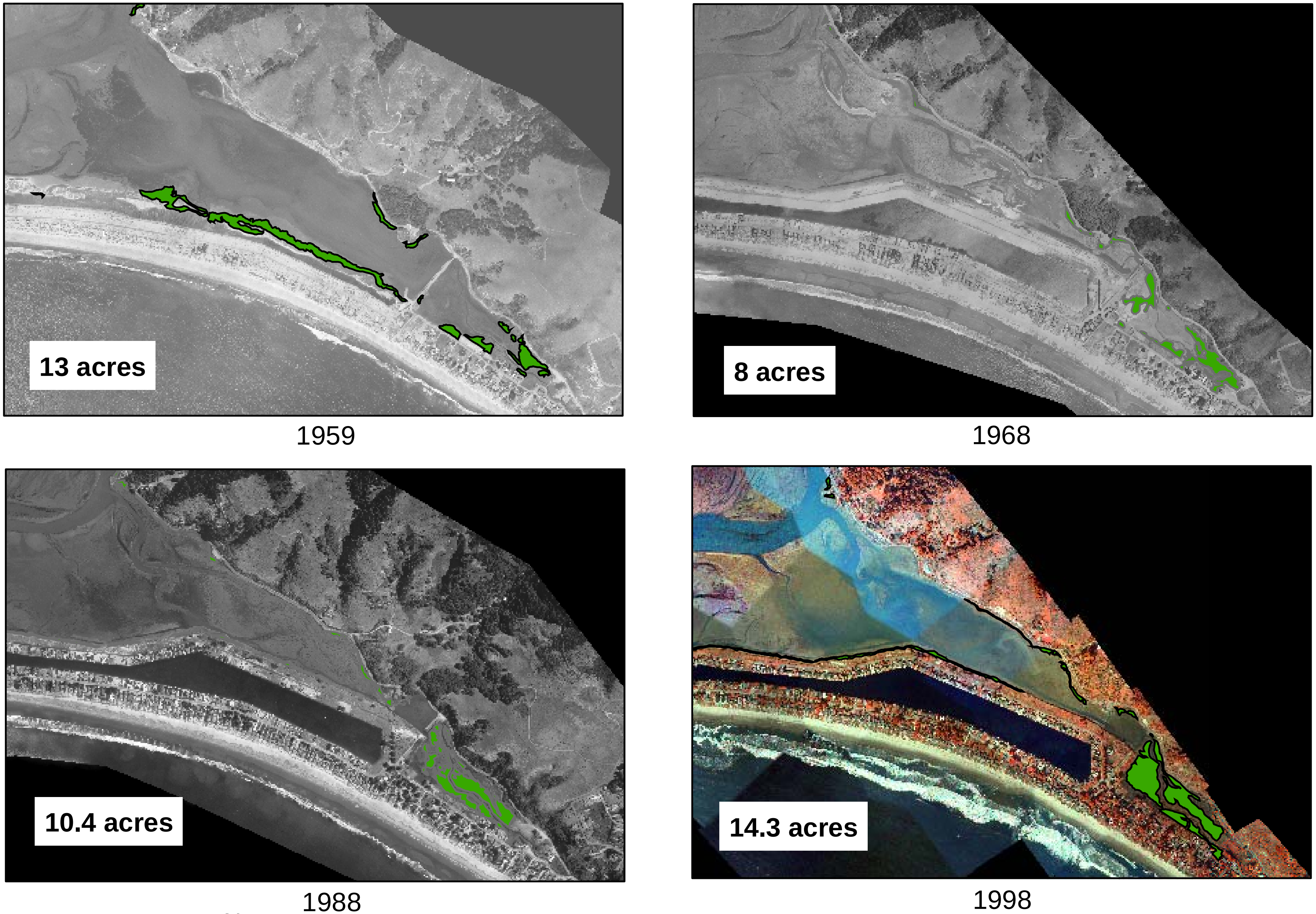
3.5 RECENT CHANGES TO LAGOON MORPHOLOGY

3.5.1 Sediment Accumulation and Marsh Expansion

As the high rate of net sedimentation raised elevations in Bolinas Lagoon, salt marsh plants established on previously unvegetated mudflats. In order to characterize late-20th century changes, PWA mapped the extent of vegetation by inspecting geo-rectified aerial photographs from 1959 to 2001. Note that the mapping of historic vegetation is approximate, due to the inability to verify conditions with ground observations and the limited resolution of black and white photographs. The following paragraphs describe results from this analysis.

- **Pine Gulch Creek.** Although most of the mudflat accretion over the 20th century is due littoral inputs, watershed delivery from Pine Gulch Creek has built a sizable delta at the creek mouth that supports salt marsh and riparian habitats. The continued progradation of Pine Gulch Creek delta and extension of Kent Island result in the increase of area sheltered from wind waves. Due to the quiescent conditions created, sediment accumulates in these sheltered areas until marsh plants colonize on previously unvegetated mudflats. Sedimentation in the vicinity of the Pine Gulch Creek delta has also filled the head of the Bolinas Channel and segregated it from its former, larger tributary area.
- **South Arm.** Figure 3-9 shows the extent of marsh vegetation in the South Arm. Human-induced changes are evident and include: construction of a solid-fill causeway and fill placement in areas shown as freshwater marsh in the 1854 T-sheet; construction of Seadrift, which reduced the footprint of tidally-affected area; progradation of a delta at the mouth of Stinson Gulch; and rapid marsh expansion following the Lone Tree Mitigation Project in the early 1990s. One important note to the vegetation change from 1988 to 1998 is that this rapid expansion of salt marsh was a product of restoring a more natural tidal range by removing the constriction caused by the Stinson Gulch delta, and not an effect of sedimentation.
- **Central Reach.** Figure3-10 shows the steady expansion of salt marsh in the area around Pine Gulch Creek delta and Kent Island. We have identified three different 'patches' of marsh: that directly on the delta plain; on accreting mudflats between Pine Gulch Creek and Bolinas Channel; and the large marsh patch directly lee of the flood-tide island (Kent Island). We attribute the growth of salt marsh between the Pine Gulch Creek delta and flood tide island to the sheltering from wind wave agitation that these two landforms provide.
- **North Basin.** Changes in salt marsh extent in the North Basin are shown in Figure 3-11. The most significant changes are: expansion of fringe marsh, particularly along the western shoreline sheltered by Pine Gulch Creek delta; progradation of marsh and more fully-developed riparian vegetation in the very head of the lagoon; and establishment of small deltas near the mouths of Pike County Gulch and Audubon Creek.



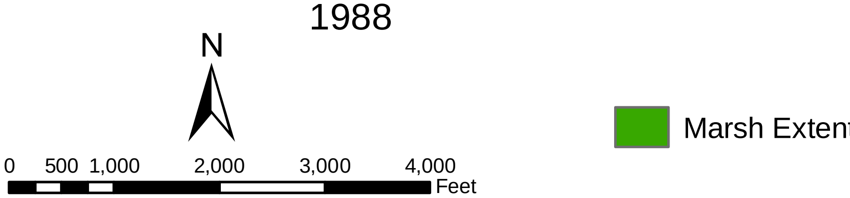


figure 3-9

Projecting the Future Evolution of Bolinas Lagoon

Late 20th Century Marsh Expansion in the South Arm

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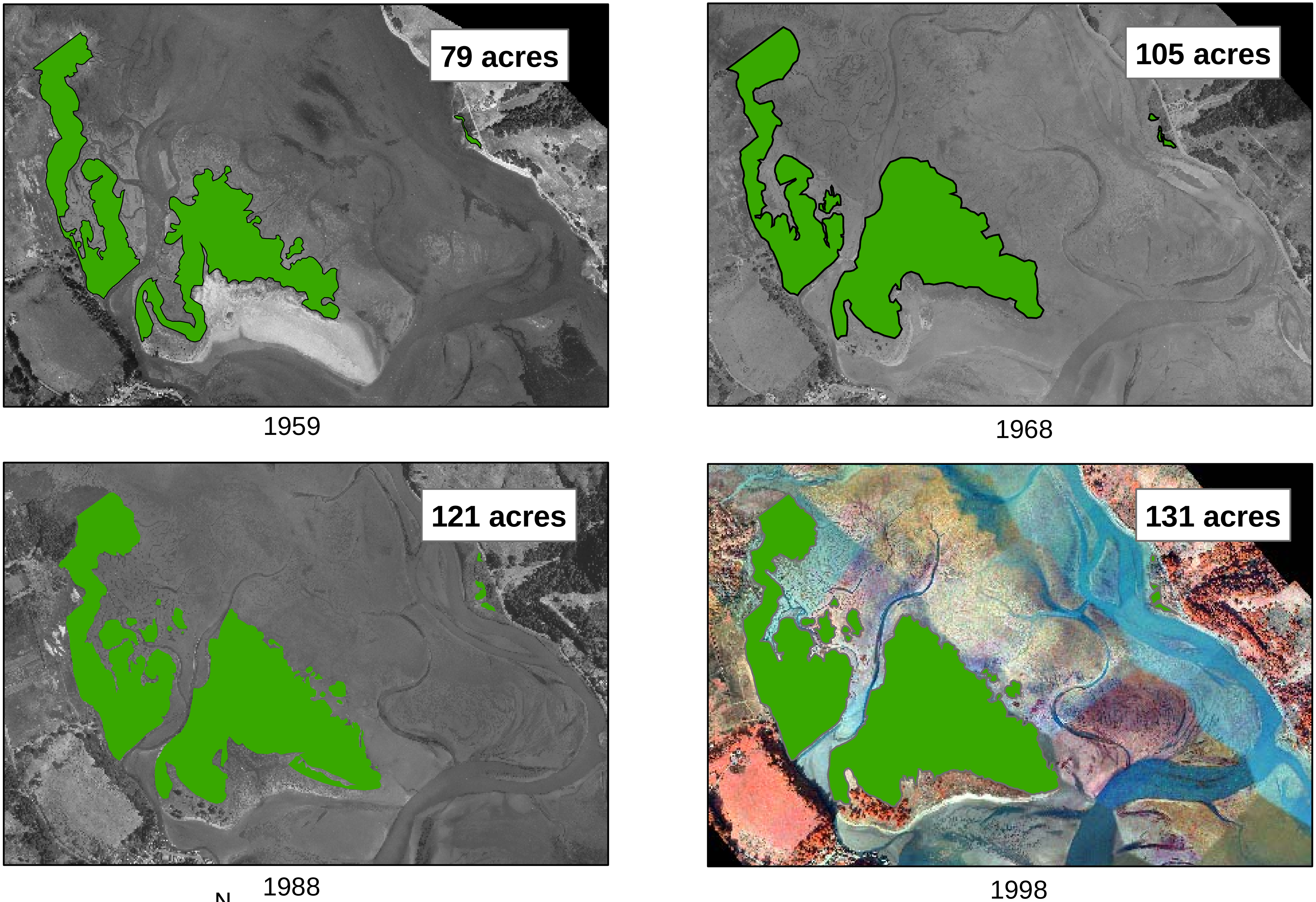

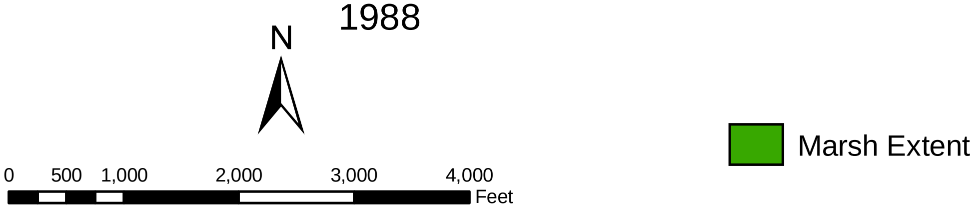

figure 3-10

Projecting the Future Evolution of Bolinas Lagoon

Late 20th Century Progradation of Pine Gulch Creek and Kent Island Marshes

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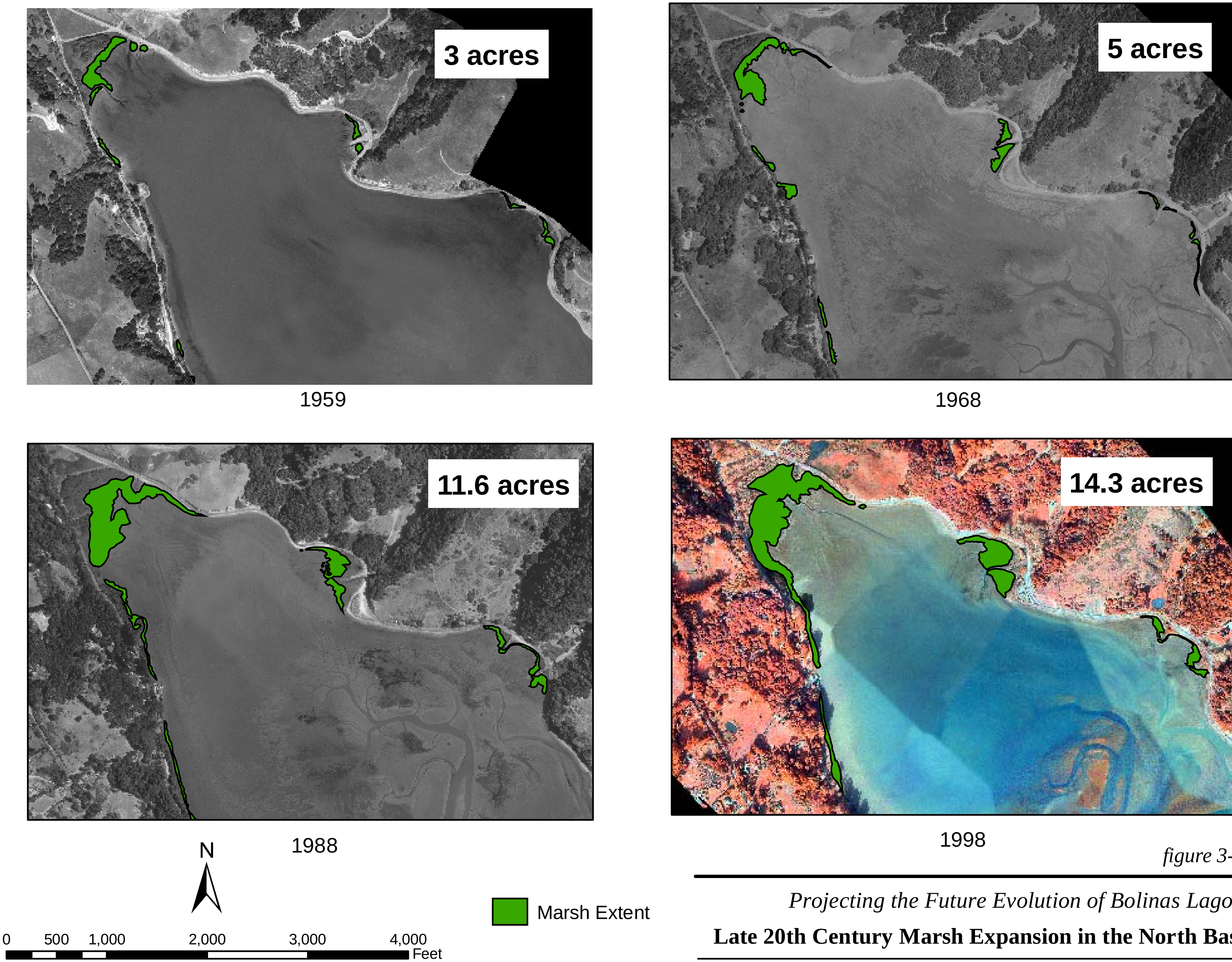

figure 3-11

Projecting the Future Evolution of Bolinas Lagoon

Late 20th Century Marsh Expansion in the North Basin

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3.5.2 Artificial Fill

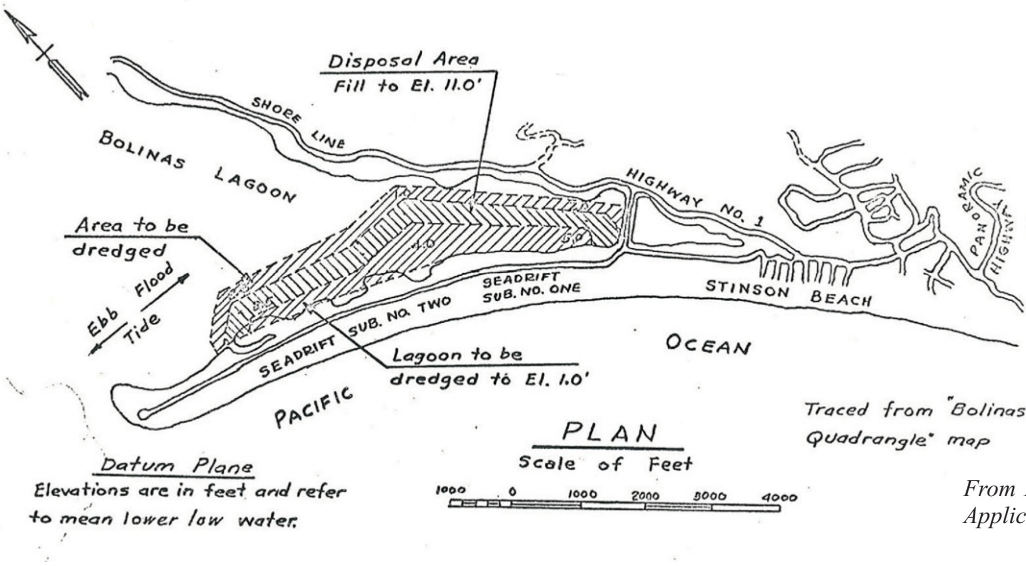
In addition to these changes in marsh expansion, construction of Seadrift in the 1960s modified the tidal portions of the lagoon by direct placement of fill and dredging (Figure 3-12). This development impounded approximately 90 acres of Bolinas Lagoon and reduced its tidal prism by about 0.3 MCY over the long-term. Dredging along the 'borrow channel' along the outside edge of the Seadrift dike temporarily offset a portion (about 50%) of this long-term loss in tidal prism.

In addition to the construction of Seadrift Lagoon, maintenance along Highway 1 (Figure 3-13) has altered the eastern shore of the lagoon. Generally, construction activity related to the roadway has resulted in the placement of fill. We have not quantified the volume of fill associated with roadway modifications, but its effect on tidal prism is considered substantially less than the impacts of Seadrift Lagoon.

3.6 HISTORIC CHANGES TO TIDAL PRISM

Since the 1854 and 1929 T-sheets delineated the interior of the lagoon in detail, we can estimate historic tidal prism values by measuring the extent of various estuarine habitats and applying our knowledge of the elevation range at which marsh plants occur. We have computed more recent values of tidal prism using surface models constructed from the 1968-1998 surveys of the lagoon bottom and elevations of Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW).

Three key findings are evident from the historic changes of tidal prism values presented in Figure 3-14. The first is that accelerated watershed delivery due to late-19th century logging decreased the tidal prism between 1854 and 1906. We have estimated this change by applying the average net sedimentation rate established by the UC Berkeley cores for this period (6.8 mm/yr), accounted for a sea level rise rate of 2 mm/yr, and assumed that late 19th century watershed disturbances were limited to the 400-acre North Basin. Based on these assumptions, we estimate that the tidal prism of Bolinas Lagoon was reduced by approximately 0.5 MCY, from about 3.7 MCY in 1854 to approximately 3.2 MCY just before the 1906 earthquake. The second major finding is that the 1906 earthquake nearly instantaneously increased the volume of the lagoon to about 6.7 MCY, or by about 3.5 MCY. This increase is equivalent to an average down-drop of 1.8 ft over the 1,200-acre lagoon. The third key finding depicted in Figure 3-14 is that net sedimentation since 1906 has resulted in an average decline of tidal prism of about 30,500 CY/yr, but has slowed to about 27,000 CY/yr over the past few decades. Based on the most recent bathymetric survey of the lagoon, the 1998 value of lagoon tidal prism is about 3.5 MCY.



From 1960 USACE Permit Application by William Kent

Photo 1963

figure **3-12**

Projecting the Future Evolution of Bolinas Lagoon

Construction of Seadrift Lagoon

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Sediment Accumulation
(Pike County Gulch)

1968

1998

Road Modifications
(Highway 1,
across the lagoon from
Pine Gulch Creek Delta)

1959

1998

Installation of Culverts
(McKinnan Gulch)

N

figure 3-13

Projecting the Future Evolution of Bolinas Lagoon

Modifications along Highway 1

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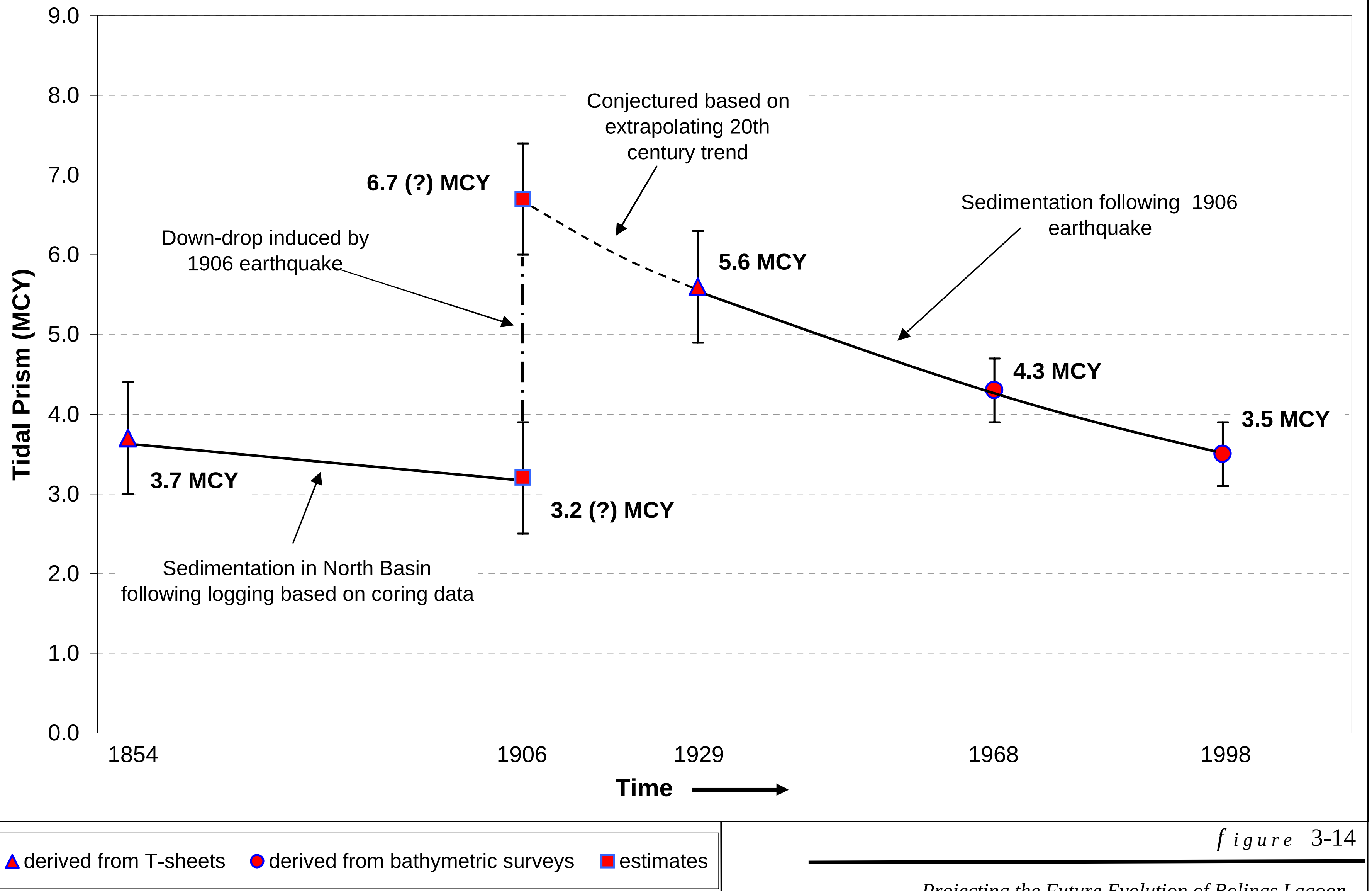

figure 3-14

Projecting the Future Evolution of Bolinas Lagoon

Tidal Prism Change: 1854 - Present

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Although it is not possible to precisely compute the errors in the tidal prism values established from historic T-sheets or the late- 20th century bathymetric surveys, we have established *probable* error bars in order to determine if the long-term trends in tidal prism outweigh uncertainties in the analysis. As mentioned earlier, we have estimated probable error bars for historic T-sheets by assuming a 1-ft range (+/- 0.5 ft) in tidal range (see Appendix B). We assume that the modern bathymetric surveys are more accurate, and have assigned a 0.5-ft range in intertidal elevations for the 1968 and 1998 tidal prism values. Even when considering the probably error bars of the historic tidal prism values, long-term trends are evident in Figure 3-14.

The 20th century trends in tidal prism are also consistent with our understanding of net sedimentation over the same period of time. As summarized in Table 3-3, the post-1906 rate of tidal prism loss established from inspection of T-sheets and GIS surface models is close to the value derived by extrapolating results from the UC Berkeley study and accounting for the effects of sea level rise. This increases our confidence that the rate of tidal prism in Bolinas Lagoon since the 1906 earthquake has averaged approximately 30,000 CY/yr.

Table 3-3. Average Rate of 20th Century Tidal Prism Loss

Based on average net sedimentation and sea level rise		
	Loss due to sediment accumulation	43,000
	Increase due to sea level rise	- 13,500
		29,500
Based on inferred 1906 value and 1998 survey		30,500

4. EXISTING LAGOON CONDITIONS

The present form of Bolinas Lagoon is an expression of littoral and alluvial sediment delivery, internal redistribution of sediments, and the legacy of the last large earthquake along the local segment of the San Andreas Fault. Overall, the rate of sediment accumulation is slowing as the lagoon approaches a new equilibrium, but the net import of beach sands and silt through the tidal inlet and the delivery of watershed sediments from creeks continue to outpace the effects of sea level rise and gradual tectonic subsidence.

Existing habitats within the lagoon are largely the result of its physical evolution, which drive the abundance and diversity of plants and animals. Environmental stresses from outside the lagoon also affect populations of species found in the lagoon. Due to the natural variability in the physical form and conditions, as well as regional fluctuations in populations, the various communities of plants and animals in Bolinas Lagoon are continually shifting.

4.1 ACTIVE PHYSICAL PROCESSES AND SEDIMENT DYNAMICS

The present rate of sediment delivery in Bolinas Lagoon appears to be outpacing the effects of sea level rise as portions of the lagoon continue to fill in. As the strength of tidal currents reduces in response to diminished tidal prism and the watershed continues to recover from historic disturbances, we expect future rates of net sedimentation to slow.

High rates of net sedimentation, relative to sea level rise, continue to result in tidal prism reductions. Since the ability to maintain an open inlet depends on the relative balance of wave and tidal power, there is a small but finite potential for inlet closure under extreme combinations of ocean storms and weak neap tides. As tidal scour has reduced in strength, there is greater potential for shoaling to reduce the depth, width, and cross-sectional area of the inlet.

4.1.1 Sediment Delivery from Littoral and Alluvial Sources

Measured current velocities at various locations (Figure 4-1) provide an indication that strong flood tide currents continue to result in a net import of beach sand and silt from the Bolinas Bluffs through the tidal inlet and into the lagoon interior. Figure 4-2 presents tidal currents velocities measured at the tidal inlet, along the Main Channel, and in Bolinas Channel. The data reveal that peak current velocities at the inlet during flood tides are about 1 ft/s greater than those during ebb tides. Dronkers (1986) has demonstrated that such asymmetry is an indicator of net transport of sand into coastal lagoons. Strong flood-dominance in tidal current velocities measured along the main channel suggests that beach sands swept through the inlet during are preferentially transported to the north. Tidal current velocities are ebb-dominated in Bolinas Channel, indicating that transport potential along this channel is directed out of the lagoon. However, the ability for the Bolinas Channel to transport substantial amounts of sediment relative to the Main Channel is very small. In addition to the beach sands swept into the lagoon, silt eroded from the Bolinas bluffs contribute to the littoral delivery (Figure 4-3).

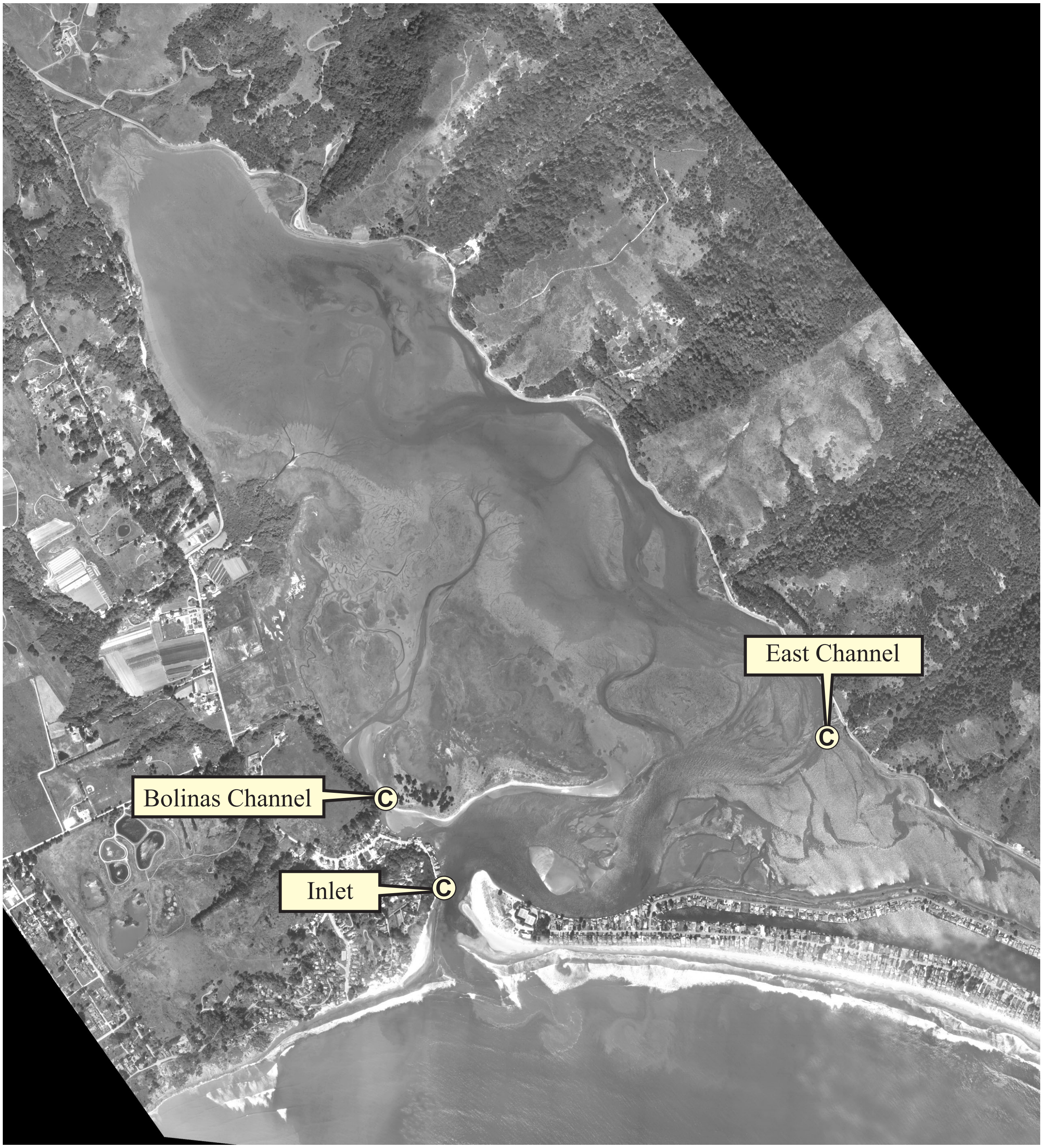

photo 1997

C = Current Meter

figure 4-1

Projecting the Future Evolution of Bolinas Lagoon

Locations of Measured Tidal Currents

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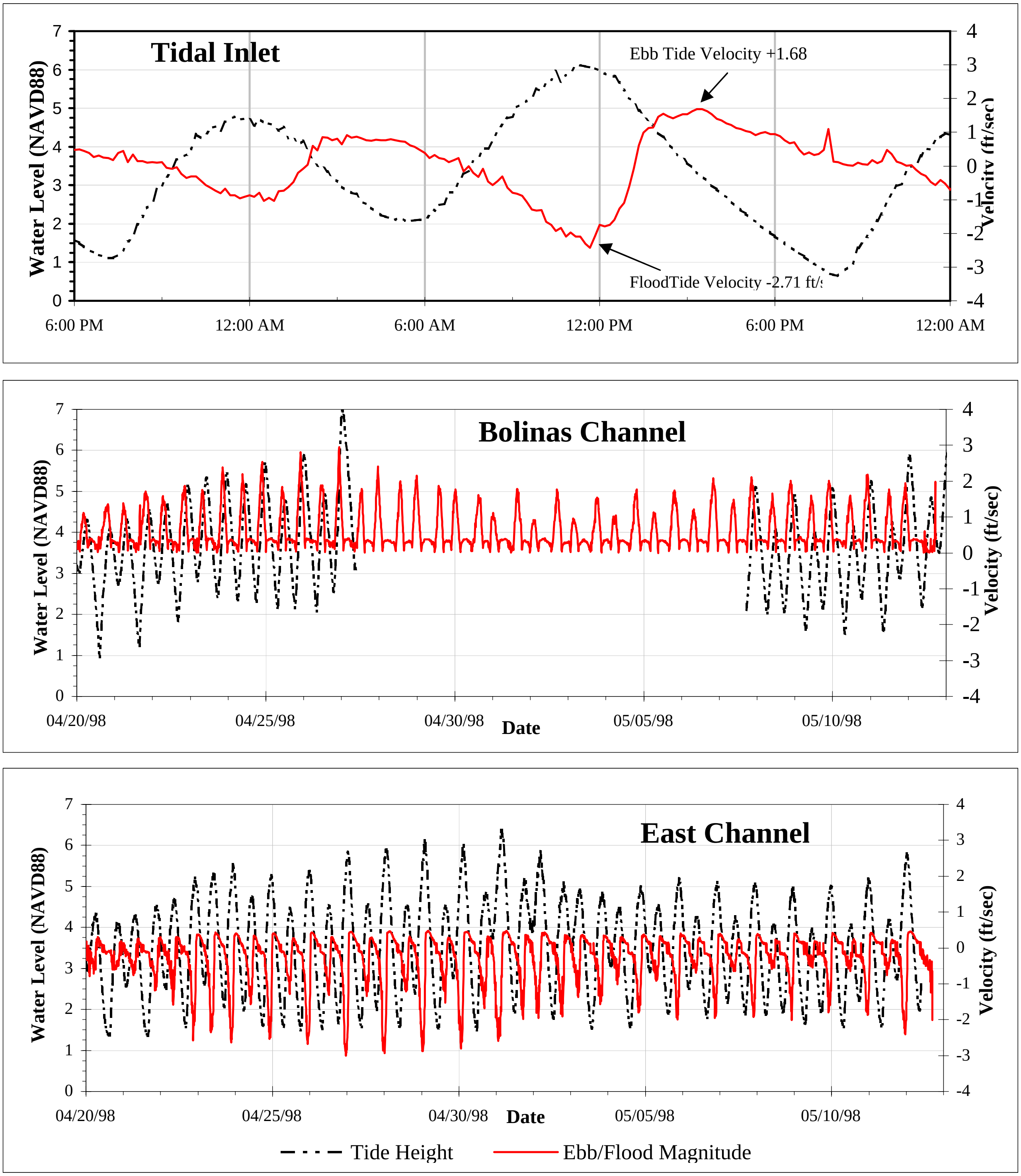

Source: PWA tide monitoring for the USACoE, 1998

figure 4-2

Projecting the Future Evolution of Bolinas Lagoon

Tidal Asymmetry at Inlet and Tidal Channels

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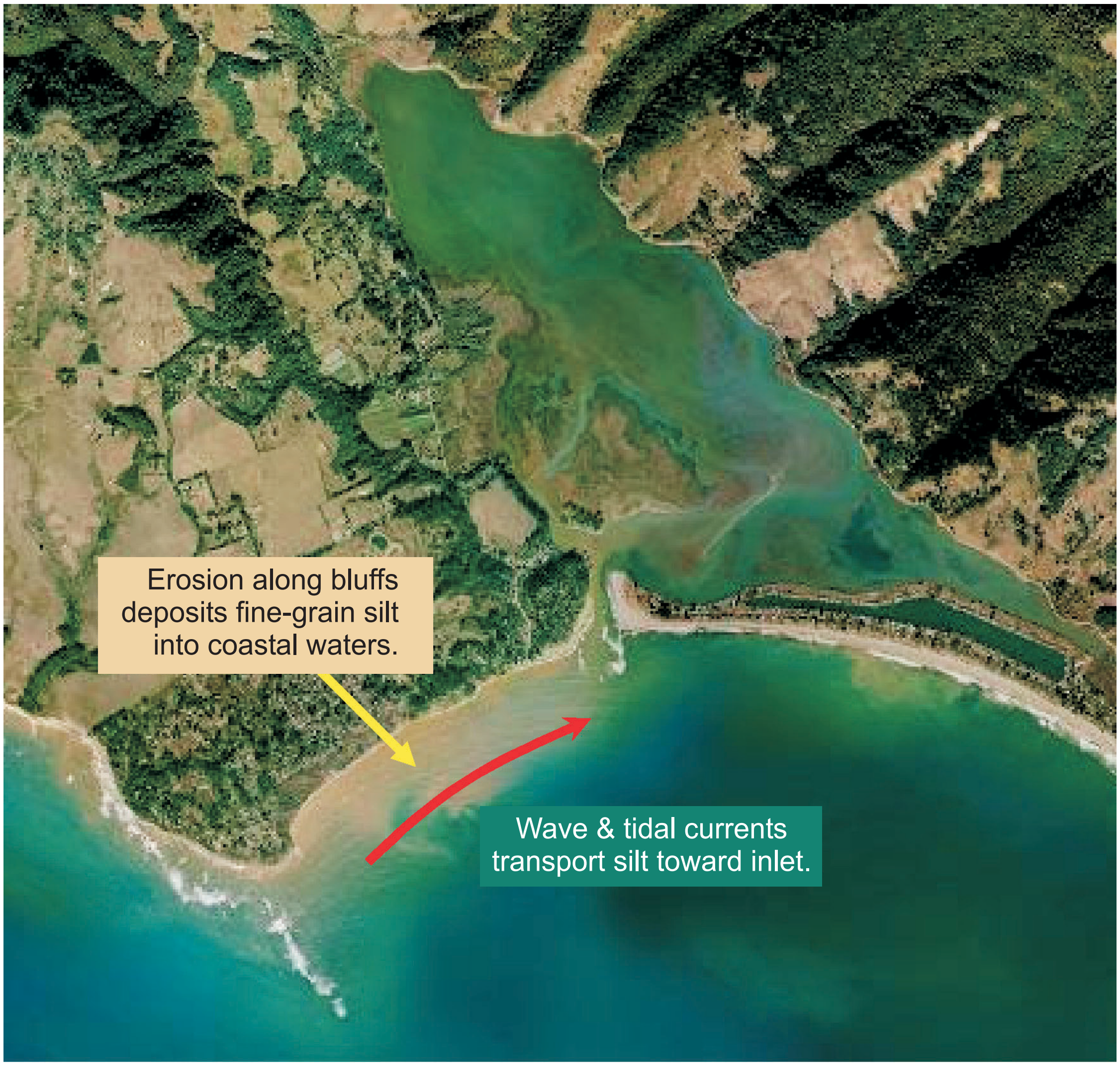

Source: AirPhoto USA; May 2003

figure 4-3

Projecting the Future Evolution of Bolinas Lagoon

Eroded Silt Transported through Inlet during Flood Tides

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Watershed delivery of coarse sediments from Pine Gulch Creek continues to advance the delta at its mouth further into the lagoon. Like other tributaries, delivery of suspended alluvium from Pine Gulch Creek varies significantly from year to year, as shown Figure 4-4; delivery during wet years (e.g., 1982) can be several times greater than the long-term average (about 5,000 CY/yr), while inputs during dry periods (e.g., 1976-1977) are almost negligible. Bedload is also highly variable, with large amounts of coarse sand and gravel delivered during high flood flows. We have estimated the long-term average bedload delivery from Pine Gulch Creek to be about 1,000 CY/yr, based on modeling of sediment transport potential along the creek channel.

4.1.2 Wind-Wave Erosion Over Exposed Mudflats

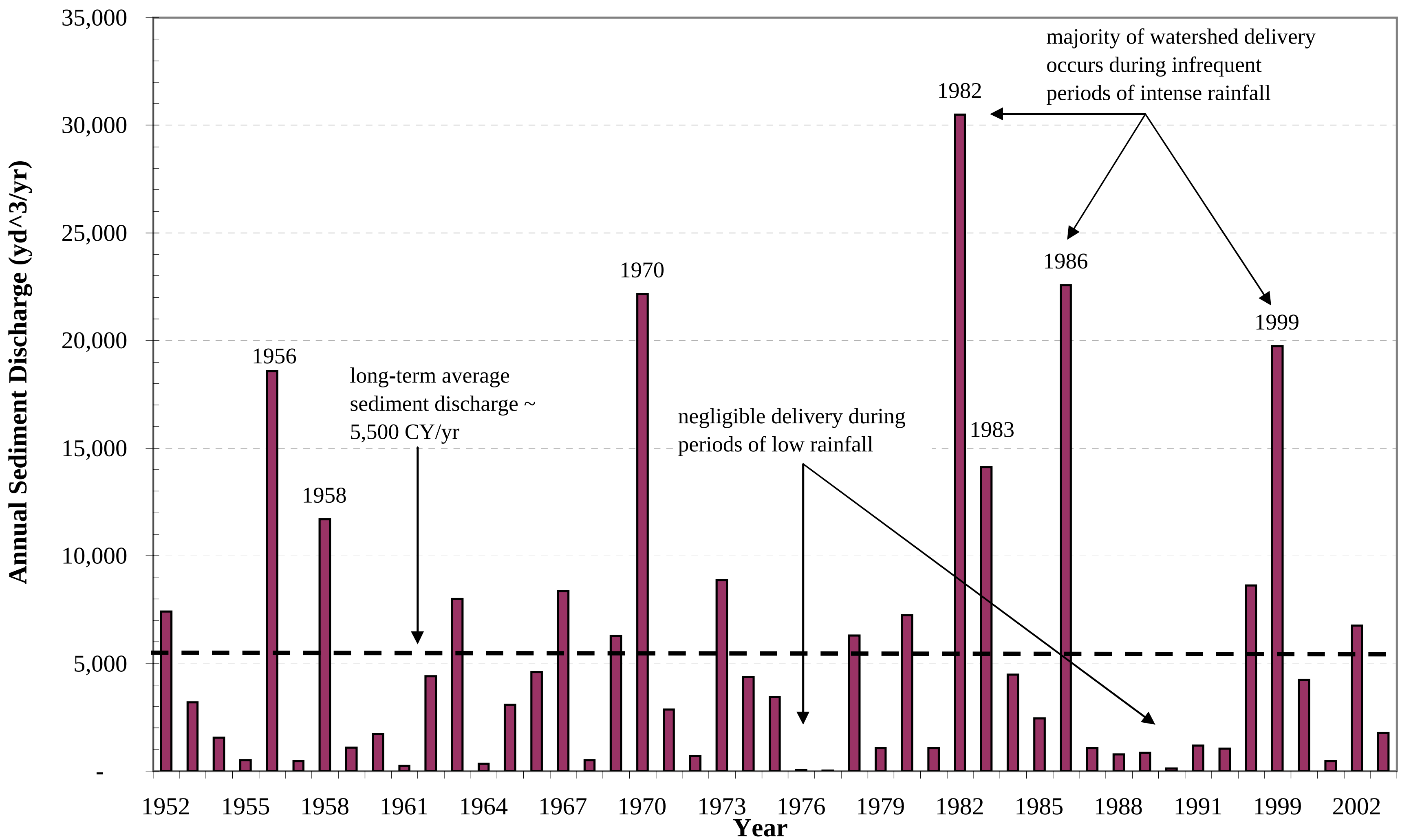
The accumulation of sediments along the prograding front of the Pine Gulch Creek delta is evident from elevation transects shown in Figure 4-5. These survey data reveal that although the delta continues to advance into the interior of the lagoon, mudflat elevations along the middle and eastern portions of the lagoon appear to have equilibrated at an elevation of about 2.5 ft NAVD88 (approximately 1 ft below local mean sea level).

As mudflats rise in elevation they become more susceptible to locally generated wind-wave erosion. Wind-wave erosion over mudflats is known to keep elevations low when wind exposure is sufficiently high (Kirby, 2000). The average long-term wind climate (fetch and speed) largely controls mudflat elevation. For a given wind speed, larger fetches generate greater wind-wave agitation and result in lower mudflat equilibrium elevations. Due to the distribution of water surface elevations over time, mudflat equilibrium elevations are slightly below the local mean sea level. At Bolinas Lagoon, the relatively stable platform shown in Figure 4-5 appears to have maintained an equilibrium form from 1978 to 2004.

4.1.3 Tidal Dispersion of Beach Sands

As tidal prism has diminished since the 1906 earthquake, the ability for flood tidal currents to disperse beach sands far into the lagoon interior has reduced. As shown in Figure 4-6, although the present tidal prism is large enough to transport sediment far into the lagoon, the distance that sediment is carried in transport will reduce with future declines in tidal prism. While tidal current velocities are sufficient to transport very fine beach sands far, coarse and medium-grained sediment deposits relatively close to the inlet.

Unlike beach sands, bluff-eroded silt has very fine grain sizes and is efficiently transported to the North Basin in suspension. However, the complex circulation patterns in Bolinas Bay will continue to limit the amount of silt eroded from the bluffs that ultimately makes its way through the tidal inlet.



Notes: Annual Suspended Sediment Discharge from Pine Gulch Creek: WY 1952 - 1993, 1999 - 2003 (based on measured flows and correlation of flows on Corte Madera Creek in period of record)

figure 4-4

Projecting the Future Evolution of Bolinas Lagoon

Suspended Sediment Delivery by Pine Gulch Creek

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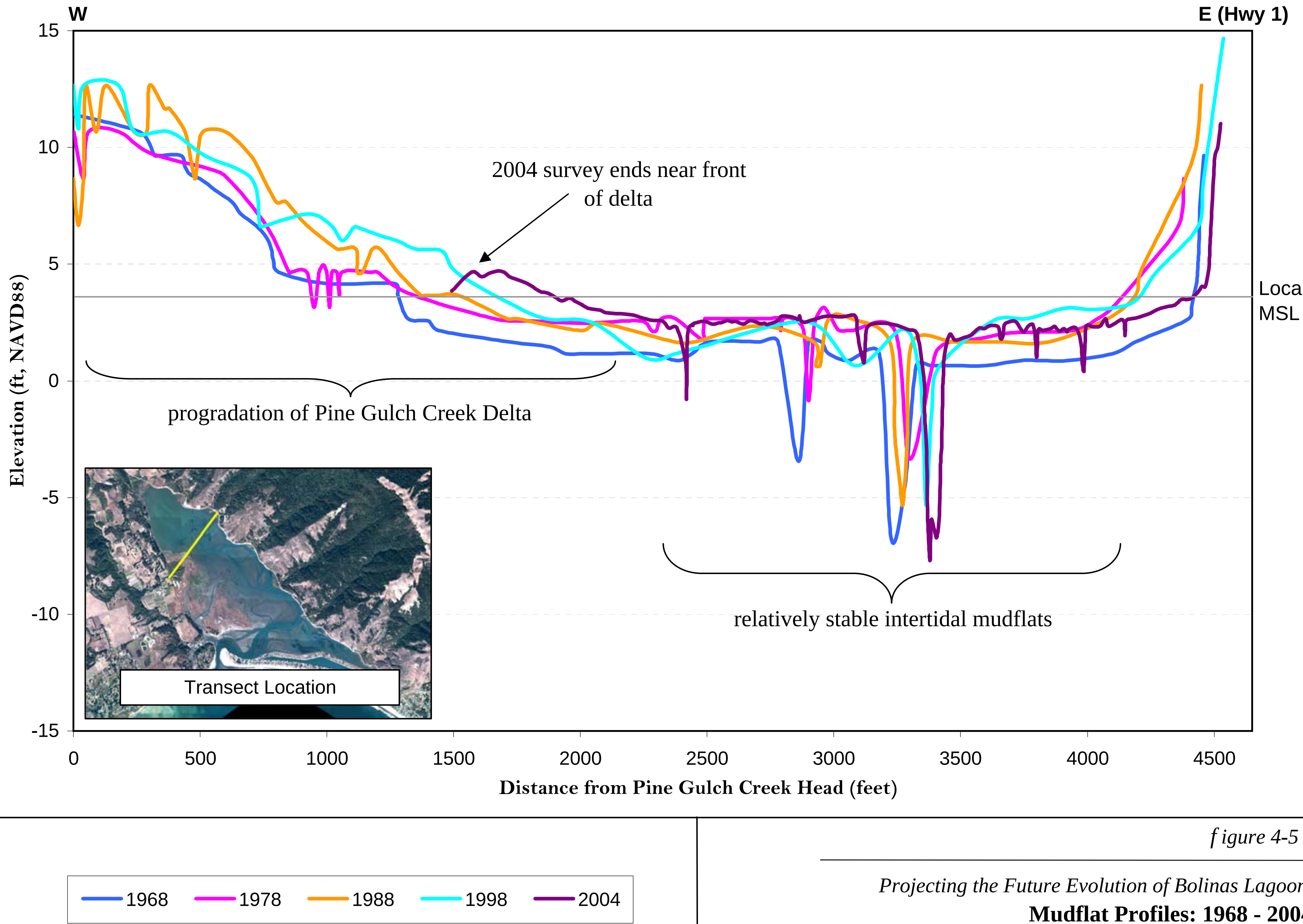

figure 4-5

Projecting the Future Evolution of Bolinas Lagoon

Mudflat Profiles: 1968 - 2004

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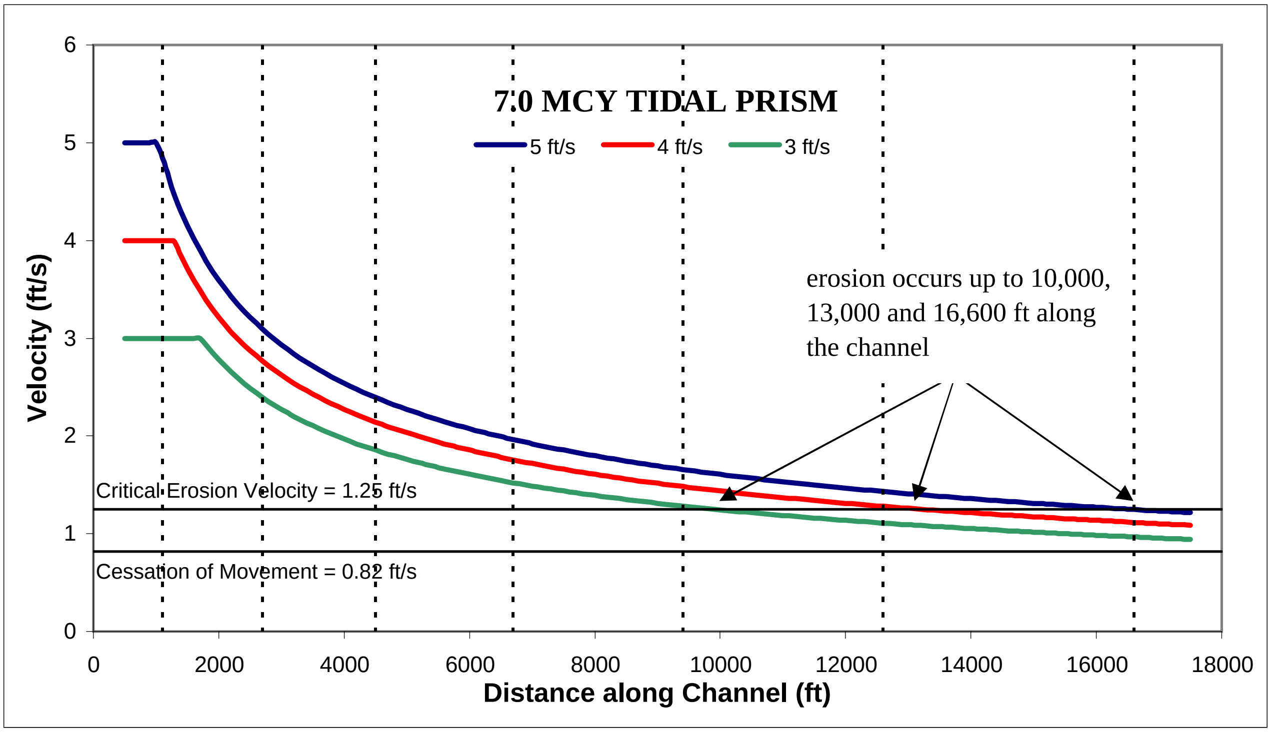

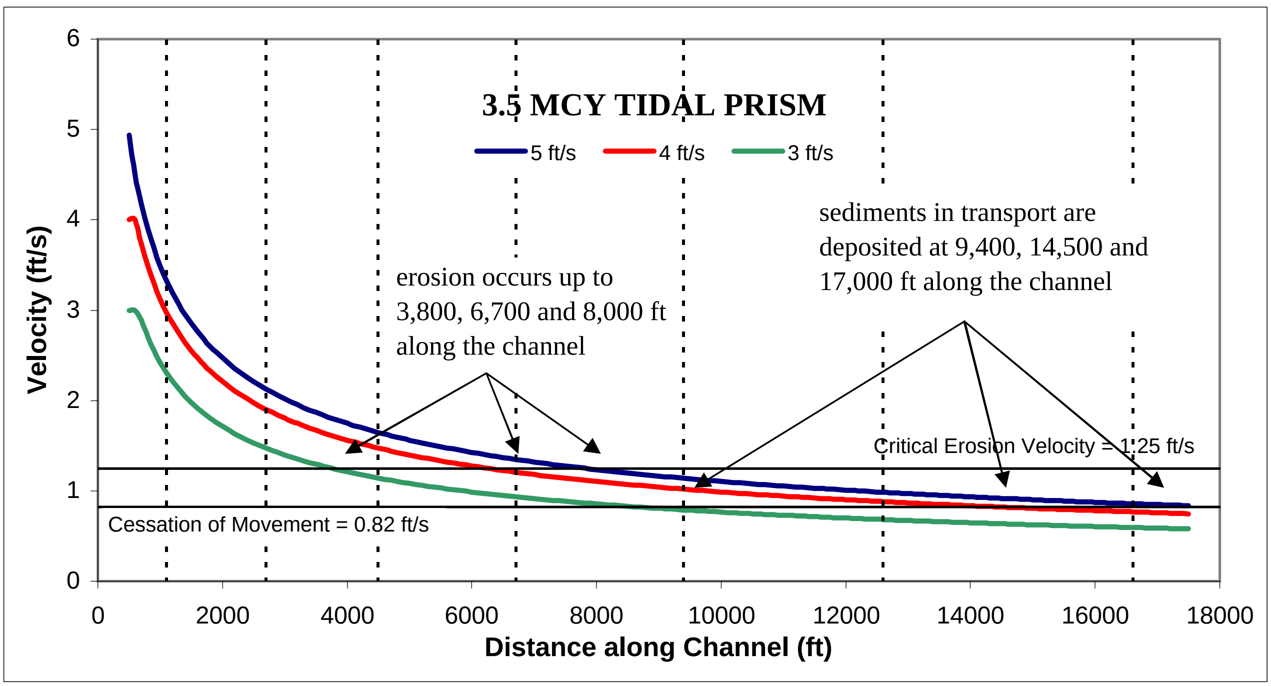

figure 4-6

Projecting the Future Evolution of Bolinas Lagoon

Declining Strength of Tidal Dispersion with Reduction of Tidal Prism

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4.2 THE PRESENT FORM OF BOLINAS LAGOON

Various landforms, or 'units', are shaped and maintained by distinct geomorphic processes. Collectively, net storage or export of sediment within the lagoon is reflected in changes to these geomorphic units. Based on our understanding of the physical processes at Bolinas Lagoon, we have identified the following geomorphic units (Figure 4-7):

- **Subtidal Shallows.** Subtidal shallows are confined to two relatively small areas at the deepest areas in the North Basin and South Arm. Since tidal flows and wind wave erosion are minimal in these regions, subtidal shallows act mostly as a sediment sink. Subtidal areas used to be accessible to recreational fishing (Jeremy Dierks, personal communication), but now are only accessibly by canoe or kayak at high tide.
- **Subtidal Channels.** Scour by tidal currents, which is largely determined by tidal prism, maintains the depth, width and cross-sectional area of these channels. These 'tidal creeks' drain both unvegetated mudflats as well as salt marshes. The primary subtidal channel in Bolinas Lagoon is the Main Channel, which runs from the inlet and along the eastern shoreline of the lagoon (adjacent to Highway 1) to the North Basin. Bolinas Channel, which extends from along Wharf Road and along the northwest side of Kent Island, is much smaller.
- **Mudflats.** Intertidal mudflats comprise the majority of aerial extent of Bolinas Lagoon. Prolonged tidal inundation precludes colonization of marsh plants on mudflats below approximately one ft above mean sea level. Locally generated wind waves control the elevation and slope of mudflats.
- **Salt Marsh.** Marsh habitats occur at relatively high elevations within the tidal frame, usually higher than one ft above the local mean sea level. Sedimentation to these elevations mostly occurs in low-energy depositional environments that are sheltered from winds, or where coarser alluvial sediments are too large to be redistributed by wind waves. At Bolinas Lagoon these environments include the following areas: in the lee of the flood tide island (Kent Island) and the Pine Gulch Creek; on portions of fluvial deltas regularly flooded by tides; the far South Arm sheltered by Seadrift; and along portions of the lagoon fringe, especially at the small coves adjacent the Highway 1. Small patches of salt marsh have recently established on high portions of the flood-tide shoals immediately to the east of Kent Island (Gary Page, personal communication) and vary from one to several meters in width.
- **Flood Tide Shoals.** As flood tide currents enter the lagoon and fan out, velocities decrease and suspended beach sands deposit to form flood tide shoals. Most of the sand is subsequently re-suspended by ebb tide currents and exported through the inlet. However, a portion is dispersed further landward by subsequent flood tide currents, or remains as flats. These intertidal flats are distinguished by their large content of beach sands, relative to mudflats that contain larger percentages of silt and clay. Flood tide shoals close to the inlet often change shape, size, location and orientation due to the dynamic nature of this high-energy environment.

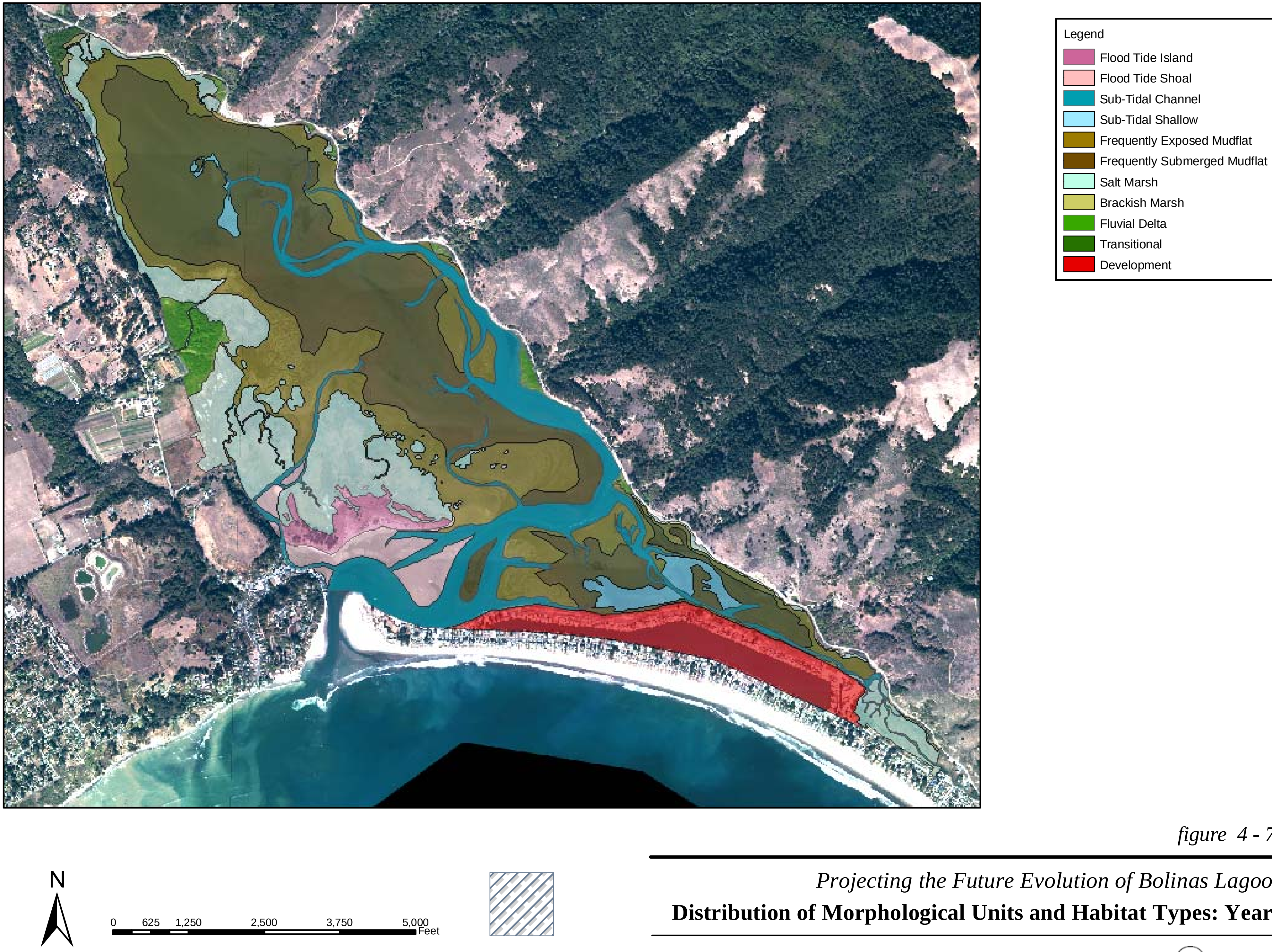

figure 4 - 7

Projecting the Future Evolution of Bolinas Lagoon

Distribution of Morphological Units and Habitat Types: Year 0

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- **Flood Tide Island.** At Bolinas Lagoon the only flood tide island occurs on the southwest face of Kent Island. This feature forms when flood tide shoals dry out during low tide, and wind-blown sand transport shapes beach and dune at supratidal elevations. Ocean waves that penetrate the tidal inlet shape the orientation of the flood tide island, while tidal prism largely determines its landward extent.
- **Fluvial Deltas.** Fluvial deltas protrude into the lagoon at creek mouths, where coarse sand and gravel accumulate. The largest fluvial delta, associated with Pine Gulch Creek, is located on the western shore of the lagoon. Deltas also occur at the mouths of drainages on the eastern shore but are much smaller due to correspondingly smaller sediment loads from their respective streams, and in some cases are limited because of their proximity to the erosive tidal scour conveyed along the Main Channel.

4.3 EXISTING ECOLOGICAL PROCESSES

Bolinas Lagoon is a diverse ecosystem supporting a complex mosaic of habitats that are home to a unique community of plants and animals. The lagoon is a nursery for several species of fish, many of which are important to commercial fishing industries, and which feed nestling herons and egrets in the nearby colony at Audubon Canyon Ranch. Harbor seals haul out onto the mudflats to rest, bask, and birth their pups. Mudflats in the lagoon are rich with invertebrate species that supply foraging habitat for wintering shore and waterbirds, including the federal endangered California brown pelican and federal threatened western snowy plovers.

As discussed below, the distribution of habitats within the lagoon is complex. Changes in habitat types, either through natural processes or through intervention measures, can have profound effects on the ecological functioning of the lagoon.

4.3.1 Lagoon Habitats

Bolinas Lagoon supports a mosaic of estuarine and palustrine habitat types. The principal estuarine habitats include subtidal channels, intertidal flats, and emergent salt marsh. Palustrine (non-tidal freshwater) habitats include riparian areas associated with freshwater marsh at the mouth of creeks. Each of the habitat types below is described from a community perspective. Strong links exist among subtidal, intertidal mudflat, and salt marsh habitats such as the twice daily tidal inflow and shared species of benthic microflora, invertebrates, and fish.

Subtidal Channels and Shallows

The subtidal or open water portion of Bolinas Lagoon occurs below Mean Lower Low Water (MLLW). This habitat is strongly influenced by its connection with the Pacific Ocean. Daily tidal action introduces a substantial volume of ocean water, carrying suspended organisms and allowing in actively swimming organisms. The benthic community is characterized by the soft nature of the substratum, the lack of vascular plant vegetation, and the predominance of invertebrates that burrow into the mud/sand surface generally within the top two feet of substrate. The most significant primary producers in this community are the phytoplankton and benthic diatoms (microflora) that become resuspended in the water column during daily tidal cycles. Generally, benthic diatoms and phytoplankton biomass is highest in the spring months and lowest in late fall and winter.

Primary consumers of phytoplankton and zooplankton in subtidal habitat include fish, filter-feeders such as clams and benthic worms, bottom feeders such as ghost shrimp, and birds. Common fish in the subtidal open water habitat at Bolinas Lagoon are arrow goby (*Clevelandia ios*), staghorn sculpin (*Certocottus armatus*), stickleback (*Gasterosteus aculeatus*), leopard sharks (*Triakis semifasciata*), dogfish (*Squalus sucklevi*), bat rays (*Myliobatis californicus*), Pacific herring (*Clupea pallasii)*, Northern anchovy (*Engraulis mordax)*, surf smelt (*Hypomesus pretiosus)*, and jack smelt (*Atherinops californiensis)* (California Department of Transportation 2000; MCOSD 1996). Bolinas Lagoon has long been considered a “nursery ground” for flatfish; however, populations of several species appear to have decreased over the past decade. The shiner surfperch (*Cymatogaster aggregate)* is another dwindling species in the lagoon; it was once typically found in large schools, which are still present in San Francisco Bay and Bodega Bay, but have been absent from Bolinas Lagoon for approximately a decade. Additional common species remaining in the subtidal areas of the lagoon include plainfin midshipmen (*Porichthys notatus*), monkey-faced eels (*Cebidichthys violaceus*), cabezone (*Scorpaenichthys marmoratus*), and juvenile rockfish (*Sebastes* sp.)(Churchman, pers. comm.). Herring, smelt and perch are important prey for birds such as grebes, brown pelicans, cormorants, ospreys, and terns that are found in the lagoon. Brown pelicans (*Pelecanus occidentalis*) feed in the lagoon for pelagic fish species such as northern anchovy, topsmelt (*Atherinops affinis)*, and Pacific sardine (*Sardinops sagax*). Terns (*Sterna* sp.) generally feed on the smaller fish found near the surface such as topsmelt and northern anchovy (MCOSD, 1996).

The deposit feeders are a major group of omnivores that obtain nutrients from the sediments of soft-bottom habitats (muds and sands). The predominant deposit feeders in subtidal habitat are polychaetes (segmented worms). Most species of polychaetes are benthic, dwelling on or in the bottom at various depths. The differences exhibited by various polychaete families reflect differences in ecological roles or ways of life, particularly differences in food and habitat utilization. Some polychaetes are carnivorous predators, some are herbivores, and still others may be omnivores, scavengers, filter feeders, or deposit feeders. In turn, polychaetes are eaten by a variety of invertebrates, fishes, and shorebirds (Morris and others, 1980). Several molluscan deposit feeders occur both subtidally and intertidally. The littleneck clam (*Protothaca staminea*), a nonselective suspension/filter feeder, is found in shallow burrows in coarse sand or sandy mud in the middle to low intertidal zones of bays and coves.

Within the subtidal habitat, fish are the primary secondary consumers. Shiner surfperch, arrow gobies, diamond turbot (*Hypsopsetta guttulata*), and staghorn sculpin were be the most common fish in subtidal habitat in the 60’s (Gustafson 1968). Arrow goby is one of the four most common fish in the lagoon and inhabits the burrows of crabs and ghost shrimp. The ghost shrimp (*Neotrypaea californiensis*) was once common in sandy substrata within the lagoon, but anecdotal evidence has indicated a sharp decline in population numbers. Juveniles and adults consume copepods, ostracods, nematodes, oligochaetes, and amphipods. Other food may include isopods, filamentous algae, and diatoms. The arrow goby is consumed by Pacific staghorn sculpin, diamond turbot, round stingray (*Urobatis halleri)*, shovelnose guitarfish (*Rhinobatos productus*), California killifish (*Fundulus parvipinnis*), and probably many species of piscivorous birds.

Harbor seals *(Phoca vitulina)* use the main channel of Bolinas Lagoon to enter and exit the lagoon and access favored haul-out and pupping sites. Haul-out sites provide seals with resting, breeding, and nursery areas (Allen and others, 1989). These sites are used daily throughout the year, and successively from year to year. The primary haul-out sites on Bolinas Lagoon are Kent Island and exposed sand bars along the main channel. At Bolinas Lagoon, harbor seals use haul-out sites primarily during daylight hours with peak numbers in early afternoon (Allen and others, 1984;1989). Harbor seals are opportunistic feeders and forage on shallow water estuarine and marine species of fish, cephalopods and crustaceans. Many of their preferred prey species (e.g., jacksmelt, topsmelt, starry flounder *(Platichthys stellatus*), and shiner perch) occur in Bolinas Lagoon; however, no feeding studies have been conducted in the lagoon.

Eelgrass (*Zostera marina*) habitat plays several important ecological roles by stabilizing sediment, contributing to primary productivity and foraging habitat, and providing nursery and spawning habitat. Eelgrass grows in beds in shallow subtidal sandy mudflats. Although eelgrass was formerly documented to occur within Bolinas Lagoon, field surveys conducted by WRA biologists on August 4, 2004 did not locate any eelgrass beds.

Intertidal Mudflats

The intertidal mudflat zone is found between MLLW and approximately one foot above Local Mean Sea Level (LMSL), and generally lacks vascular plants (eelgrass does occur in this zone and historically occurred at Bolinas Lagoon). While sand and gravel beaches can be found in high energy environments, such as near the mouth and the western side of the Seadrift Spit, mudflats form only in low energy areas in the inner lagoon, where finer sediments can settle. As in all intertidal habitats, aspects of wind-wave exposure, tidal elevation, and substrate largely determine the community composition and species distribution in mudflats (Ricketts and Calvin, 1968). These communities support numerous species of clams, polychaete worms, amphipods, and other invertebrates. They provide foraging grounds for shorebirds, ducks, fish, and marine invertebrate predators, as well as spawning and nursery habitats for forage fish and juvenile crustaceans. Harbor seals (*Phoca vitulina*) also use mudflats and protected beaches as haulout areas. Of the unconsolidated habitats, mudflats support the greatest species diversity and biomass (Lees and others, 1980; Carroll, 1994).

Several species of two green macroalgae genera, *Enteromorpha* and *Ulva*, are common in the intertidal mudflats (Gustafson, 1968). After the algae and diatoms die and fall to the bottom, they decompose and are colonized by bacteria and are carried as detritus to soft-bottom communities. Most mudflat dwellers are deposit or filter feeders, gleaning minute organic particles from the sediment or water column. Filter-feeding clams and deposit-feeding worms convert the detritus into biomass (Sanger and Jones, 1984). Common worms include phoronid worms (*Phoronopsis viridis*) and the joint worm (*Axiothella* *rubrocincta*) (Gustafson, 1968). Benthic meiofauna play a significant role in the grazing and processing of primary production by algae and benthic diatoms. Crabs, in particular the mud crab (*Hemigrapsus oregonensis*), are important grazers on the mudflat. The mud crab feeds mainly on diatoms and green algae. On the higher intertidal mudflats, the California horn snail (*Cerethidia californica*) is a dominant grazer, feeding on fine organic detritus and microorganisms occurring at the mud surface.

Fish that inhabit intertidal flats include gobies and sculpin, additionally species such as sharks and rays move from the subtidal areas into flooded tidal flats to forage on the abundant benthic invertebrates. Some small, channel-dwelling fish species (e.g., sculpin) are prey for shorebirds (egrets, herons, and kingfishers) (Stenzel and others, 1983). Topsmelt and jacksmelt enter on rising tides and are taken by osprey.

Perhaps the most distinctive feature of the intertidal mudflat is the abundance of shorebirds. At Bolinas Lagoon the most numerous are the dunlin (*Calidris alpine*), least *(Calidris minutilla)* and western sandpiper *(Calidris mauri)*, marbled godwit (*Limosa fedoa*), willet (*Catoptrophorus semipalmatus*), and American avocet *(Recurvirostra Americana)*. Willets feed on small invertebrates and insects including sand crabs, amphipods, marine worms, molluscs, and grasshoppers. The western sandpiper is a common migrant occurring in flocks of up to 30,000 at the lagoon. Western sandpipers are small shorebirds with short bills, which restrict them to foraging on the surface of mudflats and along the water's edge. Prey items include polychaete worms, small crustaceans and snails. American avocets have strongly upcurved bills that allow them to forage in shallow water channels, low marsh, and on mudflats. Their diet consists of insects and insect larvae, small crustacea, tiny snails and worms, and seeds of aquatic and marsh plants (MCOSD, 1996).

Frequently Submerged Mudflats

Frequently submerged mudflats generally occur from MLLW to approximately 0.5 foot below LMSL. Studies conducted by Gustafson (1968) concluded that a much greater abundance of invertebrate life, including polychaete worms, amphipods, and mud crabs was observed on lower elevation, frequently submerged mudflats as compared to higher elevation, frequently exposed mudflats. The distribution of invertebrates did show definite relationships with the ratios of mud to sand. However, the distributions of invertebrate species within a given area appeared to be random (Gustafson, 1968). Historically, frequently submerged mudflats supported large populations of ghost shrimp, gaper clams (*Tresus nuttallii*), Washington clams (*Saxidomus nuttallii*), and other commercially harvested clams. Population numbers and age classes of these larger crustaceans and mollusks have been greatly reduced since Gustafson’s study (1968), which may be related to a decrease in this habitat type.

Unconsolidated substrate characterizing frequently submerged mudflat habitat plays an important role as nursery and spawning habitat for several commercially and recreationally important fish and invertebrates, including Pacific herring (*Clupea pallasi*), Tanner crabs (C*hionoecetes bairdi*), and Dungeness crabs (*Cancer magister*). Pacific herring spawn in the intertidal mudflats, and in the mixed sand, gravel, and mud beaches. They are an important prey for birds, marine mammals, and predatory fish.

Fish species likely to be found in frequently submerged mudflats include topsmelt, shiner surfperch, staghorn sculpin, and longjaw mudsucker. Fish using tidal marsh and channels employ two general strategies. Relatively efficient swimming species such as topsmelt move into tidal habitats on incoming tides to feed, and move out on outgoing tides to avoid becoming stranded. Benthic species such as staghorn sculpin and longjaw mudsucker *(Gillichthys mirabilis*) remain in tidal channels in the salt marsh habitat and retreat into burrows and depressions (MCOSD, 1996).

Frequently Exposed Mudflats

Frequently exposed mudflats generally occur between 0.5 foot below LMSL and approximately one ft above LMSL. Dominant invertebrates include several oligochaetes, polychaetes including *Capitella* sp. and *Streblospio benedicti*, arthropods including *Corophium* spp. and *Leucon* sp., as well as mollusks including *Gemma gemma* (CDT, 2000).

Dowitchers (*Limnodromus spp.)*, like other "surface" feeding shorebirds, are primarily confined to tidally exposed portions of mudflat and feed on small invertebrates on and just below the surface of the mud. Their diet includes marine worms, small burrowing crustaceans, and midge and fly larvae. Marbled godwits forage in shallow water during tidal activity, on exposed mudflats, and in upland habitats.

Fish-eating wading birds such as herons and egrets are particularly abundant in intertidal mudflats along tidal channels but may also forage extensively in salt marsh and upland areas. The snowy egret (*Egretta thula*) and great egret (*Casmerodius albus*) are resident species. While egrets are opportunistic foragers and are found in a variety of habitats in Bolinas Lagoon, they are found primarily along the edge of a flooding or receding tide, seeking small fish and crustaceans. The great blue heron (*Ardea herodias*) is also a permanent resident of the area The great blue heron has similar habits to egrets and will travel several miles to and from foraging and roost sites. They also forage on similar items, however the size of potential prey items can be quite large.

Flood Tide Island (Coastal Sand Dune)

The leeward side of Kent Island is a flood tide island created by sand deposition at the inlet of Bolinas Lagoon. Shaped by wind into curving ridges, this coastal sand dune area is among the most dynamic natural formations in Bolinas Lagoon. Dune contours have shifted over time until pioneer plants have taken hold in the drifting sand to create a stable landform.

This flood tide island consists of active and stabilized sand dune communities. Active dunes occupy a zone immediately adjacent to the beach where the rate of sand accumulation exceeds the rate of colonization and establishment by plants. Stabilized dunes occur behind this zone, adjacent to the protected emergent salt marsh areas on the north side of Kent Island.

Deep-rooted succulent, matted plants grow on the stabilized dunes, along with various dune grasses, that are tolerant to wind, burial by sand, and continuous salt spray. The coastal dune area of Kent Island supports native dune species, including beach bur (*Ambrosia chamissonis*), coastal sagewort (*Artemisia pycnocephala*), sea scale (*Atriplex leucophylla*), and dune wild rye (*Leymus* x *vancouverensis*), as well as invasive species such as European beachgrass (*Ammophila arenaria*) and iceplant (*Carpobrotus chilensis*).

Emergent Salt Marsh

Emergent salt marsh is found primarily between the Pine Gulch Creek delta and Kent Island, but is also found in a band along the fringes of the lagoon in some areas where it extends over the mudflat on small creek deltas. Salt marsh vegetation grows in a relatively narrow elevational band from 0.5 ft above LMSL up to five ft above LMSL. Tidal marshes in Bolinas Lagoon are well known as critical nesting, resting, breeding, and feeding habitats for several resident birds throughout the year such as Rails (*Rallus spp.*), Savannah Sparrows (*Passerculus sandwichensis*), Northern Harriers (*Circus cyaneus*) and Mallards (*Anas platyrhynchos*). Salt marshes also serve as feeding areas in winter and nesting sites during the summer (Watson and others, 1981).

The most apparent plants of the tidal marsh are salt-tolerant or halophytic flowering plants. Due to variations in the duration of tidal inundation and differences in elevation, spatial zonation of plant communities occurs. Several environmental factors affect zonation, including salinity, elevation, drainage, and soil type (Hall, 1988). Seaward, the salinity will be closer to that of seawater. As seawater mixes with freshwater and the tidal influence is diminished, the salinity is lowered. Dominant salt marsh species in Bolinas Lagoon include Pacific cordgrass (*Spartina foliosa*), pickleweed (*Salicornia virginica*), and salt grass (*Distichlis spicata*).

Low-elevation salt marsh typically occurs from 0.5 ft above LMSL to 2.5 ft above LMSL. Cordgrass cannot tolerate the high soil salinity levels sometimes found in the higher marsh elevations but can tolerate longer periods of inundation, compared to other salt marsh species. Like many halophytes, cordgrass occurs in discrete colonies as a result of vegetative reproduction.

Benthic algae are an important element of the primary production of low-elevation tidal marshes (Zedler 1982). Algal mats in tidal marshes consist of green algae such as *Enteromorpha* and bluegreen algae such as *Microcoleus* and *Schizothrix*, as well as numerous species of diatoms. Light penetration through the vascular plant canopy, temperature, and soil moisture are important factors affecting the abundance and type of algae present. The higher the elevation of the marsh surface, the lower the diversity and abundance of the algal mats. As with the mudflat, epibenthic invertebrates within the low-elevation salt marsh are a significant group of secondary consumers and provide a forage base for a variety of fish. Molluscan communities are usually dominated by epifaunal surface feeders such as the horn snail, which are important grazers on marsh algal mats (Zedler, 1982).

Mid-elevation salt marsh typically occurs between 2.5 ft and 3.5 ft above LMSL. Pickleweed tends to be the dominant plant, occurring from approximately Mean High Water (MHW) to above tidal action where salt is still present in the soil. Pickleweed has the widest elevational range of plant species found in tidal marsh, but monotypic stands are commonly observed in the mid marsh zone.

High-elevation salt marsh occurs from 3.5 feet to five feet above LMSL. High-elevation marsh areas of the lagoon support a variety of land birds, rails and raptors, including the black rail *(Laterallus jamaicensis)* and other special status species. Small mammals such as the California vole (*Microtus californicus*) also forage on marsh vegetation, herbivores are known to feed on grasses, sedges and other green vegetation. High marsh tends to support the highest plant species diversity compared with mid and low marsh zones.

Brackish Marsh

In Bolinas Lagoon, brackish marsh is found in a transitional area between coastal salt marsh and freshwater marsh or riparian habitats. Hydrology is supplied by tidal action as well as freshwater water movement from upper reaches of the watershed. The vegetation is a mixture of salt marsh and freshwater tidal marsh species, often with no single species dominant over an extensive area. Common species include a mix of salt tolerant and glycophytic species such as alkali bulrush (*Scirpus maritimus*), salt rush (*Juncus leseurii*), common threesquare (*Scirpus pungens*), and coastal cinquefoil (*Potentilla anserina*).

Riparian

Bolinas Lagoon supports riparian habitat along the deltas of several small creeks and streams that convey water from the surrounding watershed. These areas vary from dense stands of willow shrubs to closed-canopy forests of willow and red alder. Pine Gulch Creek is the major stream that flows into the lagoon, supporting the largest proportion of riparian habitat in the lagoon. The other major stream that flows into the lagoon is Easkoot Creek. In addition, small pockets of riparian areas can also be found around the lagoon perimeter at the mouth of several small freshwater creeks.

Pine Gulch Creek supports a small, remnant population of steelhead (*Oncorhynchus mykiss*) and Coho salmon (*Oncorhynchus kisutch)*. Striped bass *(Morone saxatilis)* enter both Pine Gulch Creek and Easkoot Creek. Riparian vegetation along Pine Gulch Creek provides habitat for a variety invertebrates, reptiles, amphibians, birds, and mammals. With the cessation of grazing, dense riparian vegetation dominated by red alder (*Alnus rubra)* and willow (*Salix* spp.) has established along Pine Gulch Creek. Bird use of this area includes species rarely recorded in California such as the sulphur-bellied flycatcher *(Myiodynastes luteiventris)* and sedge wren (*Cistothorus platensis)*; rare transient species such as the long-eared owl (*Asio otus)*, mourning warbler *(Oporornis Philadelphia*), and dusky-capped flycatcher *(Myiarchus tuberculifer*); and extremely rare breeders such as the yellow warbler *(Dendroica petechia)* and yellow-breasted chat *(Icteria virens auricollis)*. The riparian habitat at the Pine Gulch Creek delta is primarily used as a migrant stop during the fall months (August-October), when deciduous trees are still in leaf, and spring breeding habitat and migrant roost cover for several rare species including green heron *(Butorides virescens)*, red-shouldered hawk (*Buteo lineatus)*, long-eared owl, yellow warbler, and yellow-breasted chat (MCOSD, 1996).

4.3.2 Lagoon Species Diversity and Abundance

The mosaic of habitats within Bolinas Lagoon supports a diverse assemblage of species, including plants, invertebrates, fish, birds and marine mammals. The following is a summary of current knowledge of the occurrence and distribution of these taxa in the lagoon.

Macroinvertebrates

Primary consumers and decomposers in Bolinas Lagoon include a wide variety of invertebrates. Distribution of these species is determined largely by particle size of the substrate, tidal current, elevation and salinity. Occurrence of these common invertebrates by elevational zone and type of substrata used are given in Table 4-1.

Chan (1967), Gustafson (1968), and Powell (1980) observed uniform-age clam beds in the lagoon and suggested that recruitment is low and abundance is declining (BLMP, 1981). However, studies by Wooden (1976), Peterson (1975), and Powell (1980) found that deposition and suspension feeders cluster in mixed species assemblages and that clam beds are often sharply demarcated from neighboring beds and that these beds are often of uniform age classes (*in* Powell, 1980). Hence, questions concerning lack of recruitment at Bolinas Lagoon may reflect normal age class distribution and variation.

Table 4-1. Selected estuarine invertebrates of Bolinas Lagoon (after Chan 1967, Payne 1968, Gustafson 1968, Powell 1980, Page *et al.* 1976, Stenzel *et al.* 1983). Terminology and nomenclature after Ricketts *et al.*. 1985.

Common Name	PHYLLUM Scientific Name	Zone[1]	Substrata[2]
CNIDER			
Burrowing anemone	*Halcampa crypta*	TF 1	sand, gravel ?
anemone	*Nematostella vectensis*	TF 1, EM	fine sediment
RIBBON WORMS	**NEMERTEA**		
white ribbon worm	*Carinoma mutabilis*	TF 3	sand , mud
red ribbon worm	*Lineus ruber* §[3]	TF 1, 2	
alaska ribbon worm	*Micrura alaskensis*	TF 2, 3	mud
purple ribbon worm	*Paranemertes peregrina* §	TF 3	mud
SEGMENTED WORMS	**ANNELIDA**		
Ophelid polychaete	*Armandia brevis*	TF 1, 2	sand
ophelid polychaete	*Armandia acuta*		
Bamboo worm	*Axiothella rubrocincta* §	TF 2	packed muddy sand
Spionid polychaete	*Boccardia proboscidea* §	TF 1	packed clay, mud
Spionid polychaete	*Boccardia hamata* §		
red tubed worm	*Capitella capitata* §	TF 1, 2, 3	mud
Eteone	*Eteone spp.* §	TF 1, 2	mud, fine sand
goniadid polychaete	*Glycinde sp.* §	EM, TF 1	wrack
capitellid polychaete	*Heteromastus filiformis*	TF 1	mud
Lumbrineris	*Lumbrineris zonata* §	TF 2, 3	mud & sand
Hartman's mediomastus	*Mediomastus californiensis*	TF	mud
freshwater polychaete	*Neanthes limnicola*	TF 1	mud, freshwater
large mussel worm	*Nereis vexillosa*	TF 1, 2	sand
nephtyid polychaete	*Nephtys sp.* §	TF 1, 2	sand
nephtyid polychaete	*Nephtys caecoides*	TF1, 2, 3	sandy mud
Red twine worm	*Notomastus tenuis*	TF 2	mud
ophelid polychaete	*Ophelia assimilis*	TF 3	sand
nereid polychaete	*Platyneries bicanaliculata* §	TF 2	rock, pilings, wrack
spionid polychaete	*Polydora brachycephala*	TF 3	clean sand, gravel
spionid polychaete	*Polydora nuchalis* §	TF 1, 2	sand
spionid polychaete	*Polydora socialis* §	TF 2, 3	sand

[1] Intertidal "zones" of occurrence are given when information is available:
TF 1 = high tidal flat;
TF 2 = mid-tidal falt;
TF 3 = low tidal flat (includes channels); and
EM = emergent habitat (marsh, riprap etc.).

[2] Substrate texture is given when available.

[3] § indicates important prey item for shorebirds (Stenzel *et al* . 1983.)

spionid polychaete	*Pseudopolydora kempi* §	TF 1	sand
orbinid polychaete	*Scoloplos acmeceps* §	TF 2,3	
paraonid polchaete	*Scolelepis squamtus*	TF 3	sand
spionid polychaete	*Streblospio benedicti*	TF 1	mud, fresh water
UNSEGMENTED WORMS	SIPUNCULA & ECHIURA		
Sipunculid worm	*Sipunculus ingens*	TF 3	sand
fat innkeeper	*Urechis caupo*	TF 3	sand and sandy mud
ARTHROPODS	ARTHROPODA		
Amphipod	*Allorchestes angusta* §	TF 1, EM	marsh, algae, wrack
Amphissa snail	*Amphissa columbiana*		algae
beach hopper	*Ampithoe lacertosa* §		algae
beach hopper	*Ampithoe valida* §	TF 1, EM	algae
tube-dwelling amphipod	*Ampelisca milleri*	TF 1, 2	mud
free-swimming amphipod	*Anisogammarus confervicolus* §	TF 1, EM	algae
free-swimming amphipod	*Anisogammarus pugettensis* §	TF1	algae
barnacles	*Balanus* spp.		
Red ghost shrimp	*Callianasa californiensis* §	TF 1, 2	sand, mud
Rock crab	*Cancer antennarius* §	TF 3	rock
mud-burrowing amphipod	*Corophium spp.* §	TF 1, 2	mud
sand dwelling amphipod	*Eohaustorius sp.*	EM	sand
tube-dwelling amphipod *[4]	*Grandidierella japonica* * §	TF 2,3	fresh water, wrack
mud crab	*Hemigrapsus oregonensis* §	TF 1, 2 EM	ubiquious
Purple shore crab	*Hemigrapsus nudus*	EM	riprap
Tube-building tanaid	*Leptochelia dubia* §	TF 3	sand
Rock crab	*Pachygrapsus crassipes*	EM	various
Hairy hermit crab	*Pagurus hirsutiusculus* §	TF 2, 3	various
sand-dwelling amphipod	*Paraphoxus epistomus*	EM	sand
Pea crab	*Pinnixia longipes* §	TF 2	packed muddy sand
Green beach hopper	*Traskorchestia* (*Orchestria*)§	EM, SS	marsh, wrack
blue mud shrimp	*Upogebia pugettensis* §	TF 3	mud
MOLLUSCS	MOLLUSCA		
Angular unicorn shell	*Acanthina spirata*	TF 1, EM	
Common limpet	*Acmea paradigitalis*	TF 1, EM	rock
Sea hare	*Aplysia sp.*	TF 3	
Hornmouth snail	*Ceratostoma foliatum*	TF 3	
California horn snail	*Cerethidia californica* §	EM, TF1	
Fingered limpet	*Collisella digitalis*	TF 1	rock
basket cockle	*Clinocardium nuttallii* §	TF 2	sand
California basket clam	*Cryptomya californica* §	TF 2,3	mud/sand
Gem clam *	*Gemma gemma* §	TF 1, 2	mud
Purple-hinged scallop	*Hinnites multirugosis*	TF 3	mud/sand/rock

[4]* indicates exotic (introduced) species.

Nudibranch	*Hermissenda crassicornis*	TF 3	
Chink shell	*Lacuna carinata*	TF 3	
Filamentous algae snail	*Lacuna marmorata* §	TF 1, 2, 3	sand, algae
Checkered littorina	*Littorina scutulata* §	EM, TF1(?)	rock, pilings, wrack
Little macoma	*Macoma bathica (nconspicua)*	TF 2,3	mud
Bent-nosed clam	*Macoma nasuta* §	TF 2, 3	sandy mud
White sand clam	*Macoma secta* §	TF 2, 3	sand
Great beach hopper	*Megaloorchestra*	EM	sand, wrack
Hawaiian clam *	*Meretrix lusonia* *		
Mossy chiton	*Mopalia mucosa*	TF 3	mud
Soft-shelled clam *	*Mya arenaria* *	TF 3	mud
Bay mussel	*Mytilus edulis* §	EM, TF 1	rock, piling
Cooper's whelk	*Nassarius mendicus cooperi*	TF 3	
Channeled purple dogwinkle	*Nucella (= Thais) canaliculata*	TF 1,2	mussel beds
Purple rock snail	*Nucella (= Thais) emarginata*	TF 2,3	rock
Wrinkled purple dogwinkle	*Nucella (= Thais) lamellosa*	TF 2,3	barnacles
Two-plated olive	*Olivella biplicata*	TF 1	clean sand near mouth
Geoduck	*Panope generosa*	TF 3	soft muck, sand, mud
Abalone jingle	*Pododesmus macrochisma*		pilings
Moon snail	*Polinices lewisii*	TF 2	muddy sand
Rock cockle	*Protothaca staminea* §	TF 1, 2, 3	clayey gravel, cobbles
Washington clam	*Saxidomus nuttalli*	TF	coarse
Japanese littleneck *	*Tapes japonica*	TF 2	sandy
Japanese cockle *	*Tapes semidecussata*		
Black turban snail	*Tegula funebralis*	TF 1	rock
European shipworm *	*Teredo navallis*		pilings
small clam	*Transennella tantillaz §*	TF 2,3	sand
gaper (horseneck) clam	*Tresus nuttallii*	TF 2,3	sand, cobbles near channels
rough piddock	*Zirifaea pilsbryi*		
PHORONID WORMS	**PHORONIDA**		
	Pheronopsis viridis		
ECHINODERMS	**ECHINODERMATA**		
White sea cucumber	*Leptosynapta albicans*	TF 3	sand, gravel
INSECTS	**INSECTA**		
Kelp flies	*Anthomyiidae*	EM	wrack
Brine flies	*Ephydridae spp.*	EM	
Mud beetle	*Heterocerus sp.* §	EM, TF 1	fresh water, wrack
	Hymenoptera	EM	
	Diptera	EM	

The distribution of gaper and Washington clams are related to tidal exchange and substrate texture (Powell, 1980). At Bolinas Lagoon, these species occurred only near the entrance channel and in the central part of the lagoon north of the Main Channel where the substrate was sandy and were not found in areas overlain with fine material. The sediment conditions that support gaper and Washington clams also are necessary to support *Macoma* spp., ghost shrimp, and other common macroinvertebrates. The only exception to the habitat preference Powell described for gaper and Washington clams was at the mouth of McKennan Gulch, an area of fine silt deposition. Powell attributes this anomaly to the fact that McKennan Gulch delta was continually disturbed by bait diggers, and this disturbance approximates conditions in sandier bottom sites. Overall, Powell identified the silting process as the main limiting factor to clam beds in the lagoon. Prime clam beds, once accessible from the east side of the original, undeveloped sandspit, were buried by dredged sediments during the fill associated with the construction of Dipsea Road during the early 1950's. Prime shellfish habitat once covered a large proportion of the southern half of the lagoon, but now is restricted to a narrow band of sandy substrate near the lagoon mouth.

Fish

Table 4-2 provides a list of fish species found in Bolinas Lagoon between 1994 and 2002 (CDFG, 2002). CDFG used a combination of otter trawls, beach seines, and crab traps to sample from various subtidal habitats. A previous year-long survey (Gustafson, 1968) found the most abundant species in the lagoon to be surf smelt, jack smelt, shiner surfperch, staghorn sculpin, topsmelt, speckled sanddab *(Citharichthys stigmaeus),* English sole (*Pleuronectes vetulus),* pacific herring, dwarf perch (*Micrometrus minimus),* cabezon, and leopard shark. Similarly, the CDFG survey found that the most abundant species were topsmelt, shiner surfperch, English sole, speckled sanddab, staghorn sculpin, dwarf surfperch, cabezon, surf smelt, Pacific herring, and jack smelt.

In general, fish abundance and species diversity are greater in the lagoon from May to September than from November to February (Gustafson, 1969 *in* Allen, 1984). This pattern mirrors that known at other temperate mudflat-dominated estuaries where the immigration of marine fishes is synchronized with the seasonal increase in the biomass of potential prey organisms (see previous section; McLusky, 1981).

Resident fish species at Bolinas Lagoon include arrow goby, staghorn sculpin, possibly shiner perch and other small, channel dwelling species. Some of the schooling, surface-feeding fish like jacksmelt and topsmelt may enter on tidal cycles during most months, yet other species (anchovies, herring) are episodic and seasonal. Vast numbers of juvenile anchovies migrating northward (Richardson, 1980) sometimes enter the lagoon. These fish are often followed by flocks of brown pelicans and elegant terns. These episodic events are determined by oceanographic conditions, occurring in warm water periods in early fall. Pacific herring are seasonal visitors, but Bolinas Lagoon is not considered a spawning ground for this species (Spratt, 1981; Suer, 1987). Bird numbers give some indication of the biomass of fish that enter the lagoon. There were an estimated 3,800 brown pelicans and 3,700 terns on August 24-25, 1985; 6,000 terns on August 28, 1985; 6,000 pelicans and 2,500 terns on September 7-8, 1984; and 2,000 to 3,000 terns on September 26-28, 1984 (Shuford and others, 1989).

Table 4-2. Fish species documented to occur in Bolinas Lagoon (CDFG 2002).

Common Name	**Species**	**Comments**
ATHERINIDAE		
Jacksmelt	*Atherinopsis californiensis*	Common
Topsmelt	*Atherinopsis affinis*	Common
BOTHIDAE		
California halibut	*Paralichthys californicus*	Benthic species
speckled sanddab	*Cytharichthys stigmaeus*	Benthic species
ClLINIDAE		
striped kelpfish	*Gibbonsia metzi*	Rare
crevice kelpfish	*Gibbonsia montereyensis*	Rare
CLUPEIDAE		
Pacific herring	*Clupea pallasii*	
COTTIDAE		
Cabezon	*Scorpaenichthys marmoratus*	Benthic species
Pacific staghorn sculpin	*Leptocottus armatus*	Benthic species
prickly sculpin	*Cottus asper*	Benthic species
CYPRINIDAE		
California roach	*Lavinia symmetricus*	Occurs in Pine Gulch Creek
EMBIOTOCIDAE		
barred surfperch	*Amphistichus argenteus*	Rarely encountered
black surfperch	*Embiotoca jacksoni*	
dwarf surfperch	*Micrometrus aurora*	Common in some years
rainbow surfperch	*Hypsurus caryi*	Rarely encountered
shiner surfperch	*Cymatogaster aggregate*	Most common surfperch in Lagoon
silver surfperch	*Hyperprosopon ellipticum*	Rarely encountered
walleye surfperch	*Hyperprosopon argentium*	Common in some years
white surfperch	*Phanerodon furcatus*	Uncommon
ENGRAULIDAE		
northern anchovy	*Engraulis mordax*	Seasonally common
GADIDAE		
Pacific tomcod	*Microgadus proximus*	Rarely encountered
GASTEROSTEIDAE		
threespine stickleback	*Gasterosteus aculeatus*	Can occur in fresh and saline waters
GOBIIDAE		
arrow goby	*Clevelandia ios*	Benthic species
yellowfin goby	*Acanthogobius flavimanus*	Non-native species
HEXIGRAMMIDAE		
Lingcod	*Ophiodon elongates*	Benthic species
MYLIOBATIDIDAE		
bat ray	*Myliobatus californica*	Forages over submerged mudflats
OSMERIDAE		
surf smelt	*Hypomesus pretiosus*	Seasonally common
PERICHTHYIDAE		
striped bass	*Marone saxatilis*	Introduced game fish

PETROMYZONIDAE		
Lamprey	*Lampetra sp.*	Spawns in tributary streams
PHOLIDIDAE		
red gunnel	*Pholis schultzi*	Rarely encountered
PLEURONECTIDAE		
diamond turbot	*Hypsopsetta guttalata*	Benthic species
English sole	*Parophrys vetulus*	Benthic species
starry flounder	*Platichthys stellatus*	Benthic species
SALMONIDAE		
Steelhead	*Oncorhynchus mykiss*	Spawns in tributary streams
SCORPAENIDAE		
Rockfish	*Sebastes sp.*	Probably brown rockfish
STICHAEDAE		
Monkeyface prickleback	*Cebidichthys violaceus*	Common in rocky areas
SYNGNATHIDAE		
bay pipefish	*Syngnathus leptorhynchus*	Rarely encountered
TRAKIDIDAE		
leopard shark	*Triakis semifasciata*	Forages over submerged mudflats

Juvenile leopard sharks and bat rays occur on the tidal flats and adults of both species enter the lagoon regularly to forage on large clams and probably to breed. Concentrations of leopard sharks in summer occur on channel edges and sandier tidal flats where they are likely depositing eggs.

Central California Coast Steelhead, a federal threatened species, were documented in Pine Gulch Creek during the CDFG surveys. Steelhead are also believed to spawn in other suitable lagoon tributaries. Anecdotal information indicates that the state and federal threatened Coho salmon were common in Pine Gulch Creek, but have since become rare locally (Bolinas Lagoon Foundation, 2003). Pine Gulch Creek and similar streams support other freshwater species, including threespine stickleback (*Gasterosteus aculeatus*), prickly sculpin *(Cottus asper)*, and California roach (*Hesperoleucus symmetricus*).

Birds

Since 1965, staff and volunteers of the Point Reyes Bird Observatory (PRBO) have conducted field research on the birds of Bolinas Lagoon and other estuaries in the Point Reyes area. The results of these surveys (Page and others, 1979; Shuford and others, 1989) provide information on seasonal use and waterbird abundance.

Bolinas Lagoon is used primarily as a wintering destination by waterbirds, secondarily as a migrant stop, and relatively little by year-round or summer residents and local breeders (Shuford and others, 1989). Shuford and others (1989) classified the 70 most numerous species using the lagoon into five primary use patterns and found that two-thirds of those species occurred as winter residents. An exception to this general overall pattern is the importance of Bolinas Lagoon (and other local sites) as a staging area for the abundant western sandpiper in spring (Shuford and others, 1989), a breeding site for great egrets and great blue herons (Pratt, 1983), and a roosting site for dispersing brown pelicans and elegant terns. Although there is broad overlap in the types of habitat used, the subtidal and intertidal flats are of primary importance to most of the waterbirds that use the lagoon.

Bolinas Lagoon is an important biological resource that supports: 1) a high species diversity of aquatic birds; 2) a nearby egret and heron rookery; 3) a wintering site for waterfowl, shorebirds, and a raptor; 4) a black-crowned night heron *(Nycticorax nycticorax)* roost; 5) traditional roost for fish-eating flocks of pelicans, cormorants, and terns; 6) a riparian migrant stop-over (Pine Gulch Creek); 7) habitat for 25 species of special concern; 8) breeding habitat for several threatened species (western snowy plover (*Charadrius alexandrinus nivosus)* California black rail); and 9) foraging habitat for several raptors of special concern osprey *(Pandion haliaetus)*, peregrine falcon *(Falco peregrinus)*, and merlin (*Falco columbarius*).

Harbor Seals

The population of harbor seals (*Phoca vitulina richardsi*) in the Gulf of the Farallones are estimated to comprise 20 percent of the California population (MCOSD, 1996). Harbor seals have been closely monitored in the San Francisco Bay area and at Bolinas Lagoon since 1970. Both the total population and the number of pups at Bolinas Lagoon have increased in recent years. Bolinas Lagoon and adjacent waters are important to the Gulf's harbor seal population. Surveys by PRBO between 1971 and 1976 found a maximum of 66 seals hauled-out in the lagoon; surveys in 2003 found a maximum of 421 seals in the lagoon (Tezak and others, 2004). The number of pups has increased from 12 pups in 1978-79; 40 in 1992; and 28 in 1993, to 45 in 2003 (Tezak and others, 2004). Seals are present throughout the year in Bolinas Lagoon; however, they are most numerous between April and July.

Haul-out sites secure from disturbance are critical for harbor seal populations (MCOSD, 2002). Haul-out sites provide seals with resting, breeding, and nursery areas. These sites are used daily throughout the year, and successively from year to year. The primary haul-out sites in Bolinas Lagoon are Kent Island, Pickleweed Island, and exposed sand bars along the main channel (Tezak and others, 2004).

Harbor seals are opportunistic feeders and forage on shallow water estuarine and marine species of fish, cephalopods, and crustaceans. Many of their preferred prey species (e.g., jacksmelt, topsmelt, starry flounder, and shiner perch) occur in Bolinas Lagoon (Table 4-2), but no feeding studies have been conducted in the lagoon.

Plants

Bolinas Lagoon supports an assemblage of plant species associated with riparian, brackish, and salt marsh habitats. Willow (*Salix* spp.) and red alder (*Alnus rubra*)-dominated riparian areas occur in areas that receive perennial freshwater input, such as Pine Gulch Creek. Typical glycophytic or freshwater-adapted understory species include marsh parsley (*Oenanthe sarmentosa*), cow parsnip (*Heracleum lanatum*), blackberry (*Rubus ursinus*), and marsh hedge nettle (*Stachys chamissonis*). Other common species include spreading rush (*Juncus effusus* var. *brunneus*) and scouring rush (*Equisetum arvense*). A dense riparian area also occurs at the northern end of the lagoon, at the Highway 1 and Bolinas Road intersection. This area is sustained by an un-named stream conveyed from the slopes of Bolinas Ridge. Along the eastern portion of the lagoon, adjacent to Highway 1, small riparian patches occupy the mouths of small creeks (e.g., Pike County Gulch and Morses Gulch) discharged from the base of Bolinas Ridge. These areas have a willow-dominated canopy, subcanopy of blackberry, and glycophytic understory comprised of rushes and forbs.

Where freshwater flows into the lagoon, a transitional, brackish marsh is present along the upper edge of tidally influenced marsh. Species composition slowly changes along an environmental gradient between fresh and salt water zones. Four species common throughout brackish marshes in the lagoon include alkali bulrush (*Scirpus maritimus*), common threesquare (*Scirpus pungen*s), coastal cinquefoil (*Potentilla anserina* ssp. *pacifica*), and salt rush (*Juncus leseurii*).

The upper edge of tidally influenced emergent marsh, or high marsh areas, supports a higher cover of salt grass (*Distichlis spicata)*, growing in association with pickleweed, interspersed with rush (*Juncus* spp.), marsh gumplant (*Grindelia stricta* var. *angustifolia*), alkali heath (*Frankenia salina*), and sea lavender (*Limonium californicum*). Mid marsh areas are dominated by pickleweed interspersed with fleshy jaumea (*Jaumea carnosa*), arrow grass (*Triglochin concinnum)*. Salt marsh dodder (*Cuscuta salina)* is a parasitic plant found in association with pickleweed and other salt marsh species at various elevations. Alkali heath *(Frankenia salina)* can be found in the midrange elevation. Cordgrass (*Spartina foliosa*) is the dominant species in low elevation marsh habitats, usually growing in association with pickleweed, down to the emergent marsh/mudflat interface.

4.4 FIELD STUDIES: CHARACTERIZING BASELINE ECOLOGICAL CONDITIONS

Understanding how both natural and anthropogenic changes have effected plant and animal populations and ecological functions in the lagoon is difficult, especially because of the lack of quantitative data on baseline ecological conditions at any time in past. Anecdotal reports of changes in some fish and invertebrates are helpful, but more studies will be of particular use in evaluating the response of plants and wildlife as the lagoon continues to evolve. Previous analyses of habitat types within the lagoon were too broad and did not reflect the detail necessary for understanding the ecological shift in lagoon function. A clearer understanding of this shift in function can be achieved by examining the change in habitat quantity and diversity, related to lagoon sedimentation, over time.

With the goal of determining whether a significant change in the type, amount, and distribution of habitat has occurred, a characterization of the current mix of habitats was undertaken to address the significance of these ecological elements and to provide baseline conditions for monitoring and possible future adaptive management actions. Field studies undertaken by WRA in spring 2004 focused on key ecological elements from the EIR that were most frequently commented on by the public as not receiving adequate discussion or consideration in the environmental impact analysis process. These elements include estuarine habitat characterization and quantification (including riparian area of Pine Gulch Creek delta), assessment of special status species occurrences and habitat availability, and extent and distribution of eel grass beds within Bolinas Lagoon. The following field surveys were conducted to characterize baseline conditions:

- Habitat transect sampling: elevation, vegetation composition, and sediment texture
- Wetland habitat mapping
- Invertebrate sampling
- Special status species surveys and habitat quality assessment
- Other botanical surveys: eelgrass bed mapping and invasive species monitoring

A detailed discussion of study methods and results of analyses is provided in Appendix A.

5. FUTURE EVOLUTION OF BOLINAS LAGOON

The relative importance of the processes shaping Bolinas Lagoon will change over the next 50 years as mudflats continue to rise, tidal prism diminishes, and sea level rise accelerates. Erosive forces of wind waves and the diminishing rate of tidal dispersion of beach sands into the lagoon will slow the rate of net sedimentation. Continued recovery from 19th century logging will likely result in less erosion in the watershed, although the effects of channelization – particularly along Pine Gulch Creek – will maintain high rates of bedload delivery.

Changes in lagoon morphology will affect habitat distribution and result in shifts in plant and animal species. The subsections below summarize our projected evolution of each geomorphic unit within the lagoon and how these cumulatively affect lagoon shape, tidal prism, habitats, and ecological processes.

5.1 METHODOLOGY FOR PROJECTING FUTURE LAGOON CONDITIONS

Our projection of how the morphology and associated habitats of Bolinas Lagoon are likely to evolve is based on the following methodology:

1. We first reviewed each of the major constituents of the sediment budget to assess whether or how the different sediment inputs, outputs, and storage terms were likely to change in the future.
2. We analyzed how key physical processes affecting sediment dynamics within the lagoon are likely to change in the future due to anticipated adjustments in the lagoon morphology.
3. Based on this understanding of changing sediment budget and sediment dynamics, we projected sedimentation rates and future elevations relative to the tidal frame for each of the geomorphic units described in Section 5.2. (Note: We did *not* extrapolate one uniform rate of net sedimentation across the entire lagoon.)
4. We aggregated the cumulative affect of changes in each geomorphic unit into a single planform map and hypsometric curve for future morphologic conditions.
5. The projected future hypsometric curve was used to estimate the future tidal prism. This estimate of future tidal prism was used to evaluate the associated potential for inlet closure.
6. Based on the planform map and projected tidal exchange, we projected the future extent of different habitat types within the lagoon.
7. We described changes to plants, wildlife, and ecological processes based on the projected habitat distribution and expected tidal exchange.

Due to the 50-year planning horizon of this study, we developed a ‘snapshot’ of the anticipated lagoon conditions at approximately 2050 (Year 0 conditions correspond to approximately 2000, due to the composite nature of the available information). Since Bolinas Lagoon will continue to evolve beyond Year 50 towards an equilibrium morphology, we also described trends in the physical processes that will shape the lagoon over the longer term. These trends, and the same assumptions applied to our Year 50 analysis, were used to develop a map to conceptually illustrate the ultimate equilibrium state of the lagoon. As mentioned earlier, the projections of future lagoon morphology do not include the effects of a large earthquake along the San Andreas Fault, which would produce a sudden increase in tidal prism and subtidal habitats. Since the projected changes are based on average rates of sediment delivery, which include large but infrequent events such as rainstorms, lagoon morphology will differ year-to-year depending on climatic variability.

These maps represent best estimates based on our present understanding of physical processes affecting lagoon evolution. We recognize, and describe, the most significant uncertainties in our predictions and assumptions. Reducing these uncertainties is a key focus of the adaptive management program described in Section 7.

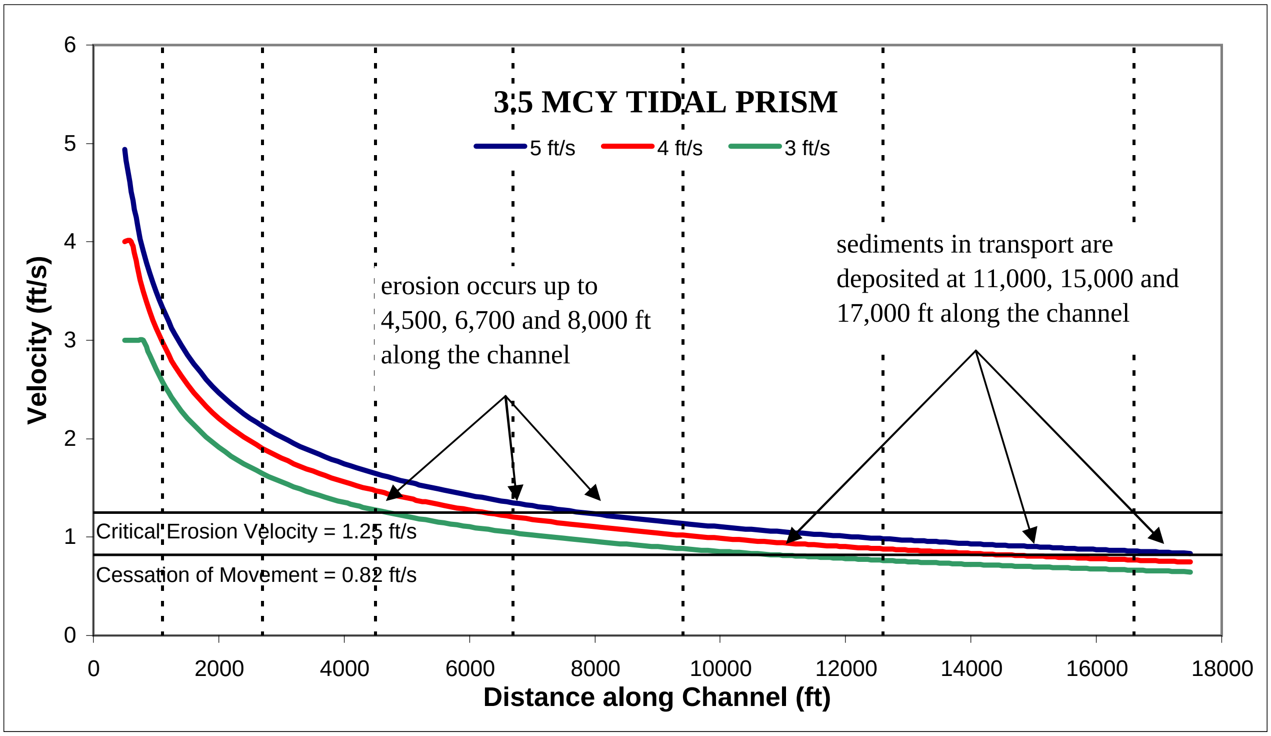
Finally, to inform future management decisions, we have estimated the degree to which human induced physical changes will have caused reductions in tidal prism and shifts in habitat distribution as compared to pre-colonization conditions.

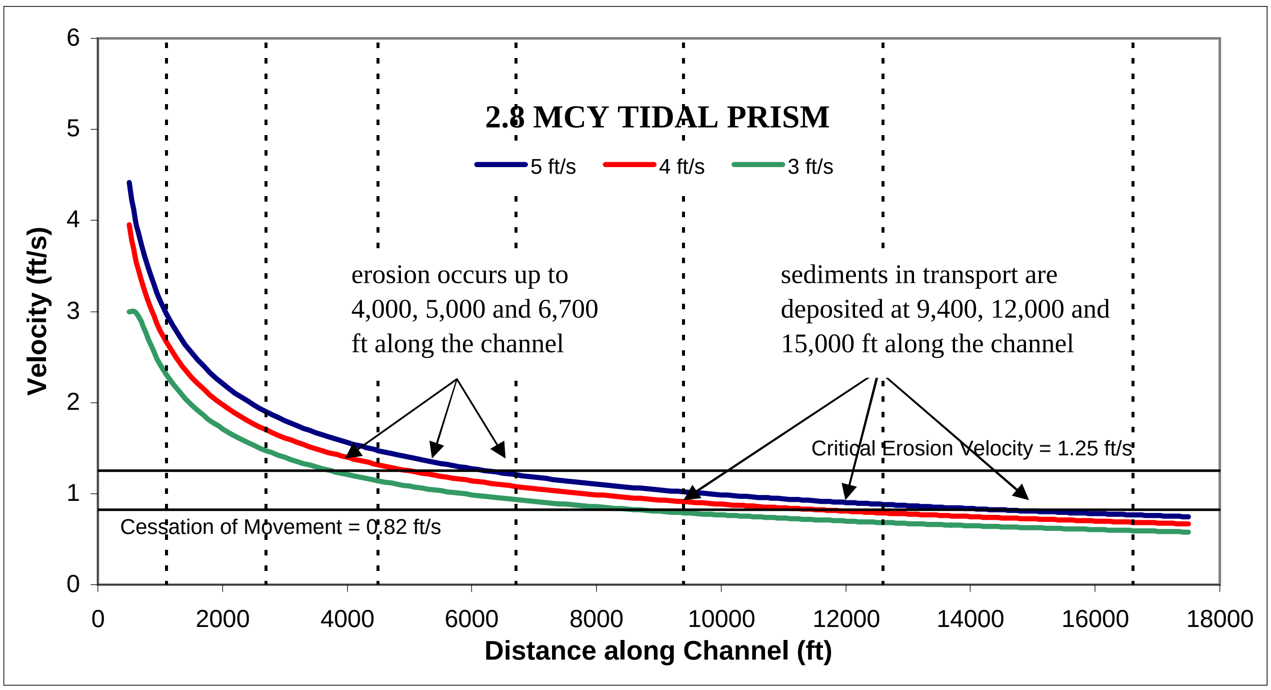
5.2 CHANGES IN THE SEDIMENT BUDGET

5.2.1 Changes to Inputs and Outputs

Under natural conditions, sediment that accumulates in Bolinas Lagoon originates from either watershed or littoral sources. As indicated in Figure 3-1 and discussed previously, watershed delivery and littoral sediment transport are the two most significant input/output terms in the sediment budget. Over the next 50 years, we expect the following changes to these two inputs.

- **Watershed Sediment Delivery.** Over the next 50 years, alluvial inputs are expected to continue at their present rates (10,000 CY/yr) when averaged over several decades. Although sediment yield is expected to diminish as the watershed recovers from the effects of past disturbances, such as the 19th century logging, man-made channelization along Pine Gulch Creek will continue to limit floodplain-channel interactions and result in above-natural rates of sediment delivery to Bolinas Lagoon.
- **Littoral Sediment Delivery.** We expect the ability of flood tide currents to transport and disperse beach sands far into the lagoon will diminish over the next 50 years, as tidal prism continues to reduce. Although tidal flows will be sufficiently strong to move beach sands in the vicinity of the inlet, resulting in a dynamic system of flood tide shoals and channel migration, smaller current velocities mean that the rate of dispersion of medium-size beach sands far into the lagoon interior will diminish in the future (Figure 5-1). Overall, we expect the diminished tidal dispersion will result in the future rates of littoral sediment delivery to decline below the 20th century average.





Note: Peak flood current velocity computed by analytic equations for a 2-dimensional planar jet (Fischer et al., 1979)

figure 5-1

Projecting the Future Evolution of Bolinas Lagoon

Potential Future Reduction in Tidal Dispersion Strength

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5.2.2 Changes in Storage Terms

As described earlier, increases in the sediment storage capacity of Bolinas Lagoon is accommodated by gradual sea level rise and large earthquakes that occur along the San Andreas Fault approximately every 150 to 600 years (Byrne and others, 2005). For the purposes of our analysis, we have assumed the following changes in these storage terms.

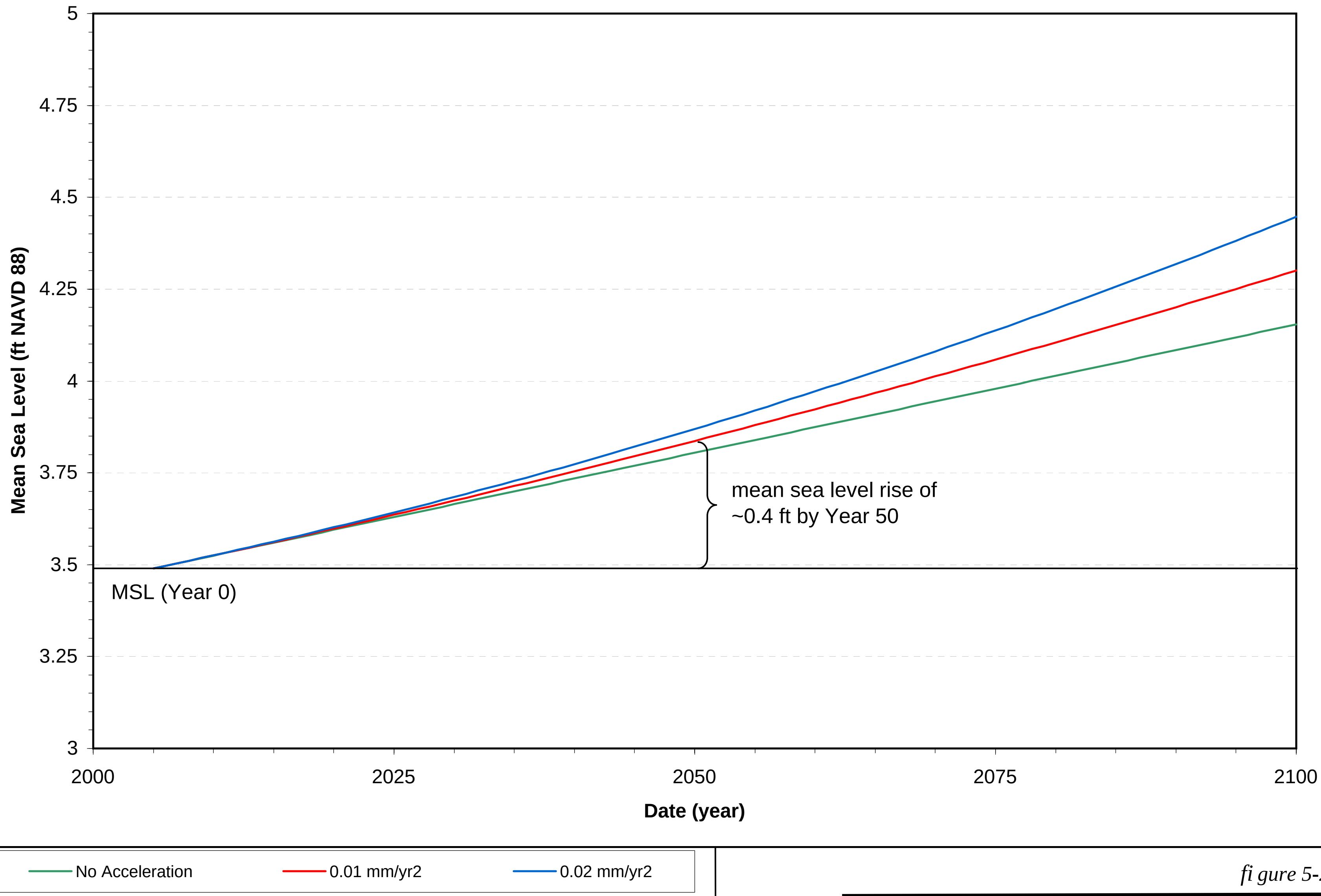
- **Sea Level Rise.** As ocean waters continue to feel the effects of global warming, the rate of sea level rise will accelerate and offset net sedimentation in the lagoon to a greater degree than in the past. For the purposes of establishing the effects of sea level rise over the next 50 years, we have increased the 20th century rate measured at the Presidio in San Francisco (2.13 mm/yr) by the median estimate of future acceleration (0.01 mm/yr^2) predicted by global warming models (IPPC, 2001). This results in approximately 0.4 ft of sea level rise over the next 50 years. The median estimate of future acceleration was then doubled (0.02 mm/yr^2) and set to zero (0.00 mm/yr^2) to test the sensitivity of sea level rise on tidal prism (Figure 5-2). These scenarios would respectively result in Year 50 mean sea levels 0.43 ft and 0.35 ft higher than today.

  Since habitat type generally depends elevation relative to tides, the expected change in sea level (0.4 ft) as incorporated into the projected future lagoon morphology. As described below, the amount of vertical sediment accretion within the lagoon was modified by the expected rise in sea level in order to assess changes relative to mean sea level.

- **Tectonic Subsidence.** Because the frequency of large tectonic events (earthquakes) is on the order of hundreds of years and unpredictable, we did not account for the effects of a large earthquake along the San Andreas Fault over the next 50 years.

5.3 CHANGES IN SEDIMENT DYNAMICS

The relative balance between erosive and depositional processes affects how sediment is redistributed within the lagoon and shape particular geomorphic units. These sediment dynamics may also affect the sediment, as pathways of sediment movement are strengthened or weakened by geomorphic evolution. Over the next 50 years, we expect the following changes to the sediment dynamics of Bolinas Lagoon.



Notes
1. MSL in 2005 = 3.49 ft NAVD 88
2. Assume rate of sea level rise in 2005 is equivalent to that at Presidio tide gauge (2.13 mm/yr)
3. Acceleration (0.01 and 0.02 mm/yr2) based on IPCC (2001) average modeled SLR acceleration from thermal expansion from 1900-1990; 0.04 mm/yr2 potential in next century for compariso

fi gure 5-2

Projecting the Future Evolution of Bolinas Lagoon

Potential Sea Level Rise

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- **Reduction in Wind-Wave Fetch.** Fetch, the distance of open water over which wind blows, is reduced as the delta at Pine Gulch Creek and the supratidal flood tide island protrude into the interior of the lagoon. Smaller wind fetches diminish the erosive effects of wind-waves and result in sheltered areas where sediment accumulation converts mudflats to vegetated salt marsh. For the purposes of the present study, we have assessed the change in wind fetch by extending the Pine Gulch Creek delta and the flood tide island further into the lagoon based on the existing rates of growth (see Section 6.4 below).

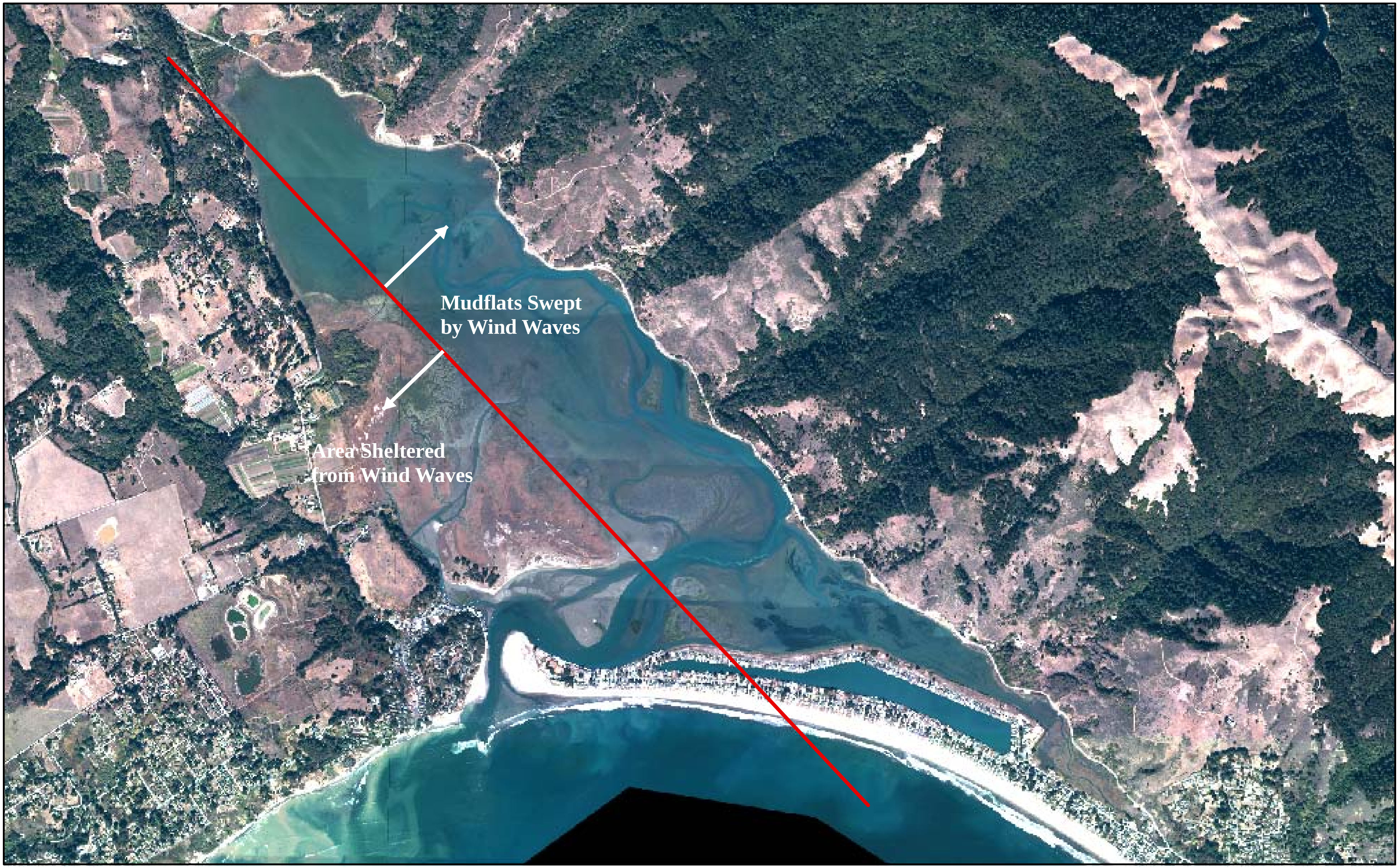
- **Mudflat Equilibrium.** We expect the erosive influence of wind waves to strengthen over the next 50 years as exposed mudflats slowly approach elevations slightly below the local mean sea level. Eventually, erosive and depositional forces will balance, resulting in an equilibrium mudflat elevation. Since wind waves only affect mudflats in areas exposed to the prevailing winds, the protrusion of Pine Gulch Creek delta and Kent Island into the lagoon interior limits wind-wave erosion to the areas shown in Figure 5-3. Results from mudflat elevations collected over a period of 40 years (Figure 4-5) indicates that the equilibrium elevation of wind-swept mudflats is about 1 ft below local mean sea level in areas of large fetch. We expect that this value may be conservative, and have assumed an equilibrium depth of 6 inches below local mean sea level.

  As erosive and depositional processes over mudflats reach a relative balance, more sediment is re-suspended by locally generated wind-waves and transported out of the lagoon by ebb tide currents. The overall result of mudflat equilibrium is an increase in the amount of previously deposited fine-grained sediment – both alluvial suspended load and silt from nearby bluffs – that is re-mobilized and exported from the lagoon during ebb tides (wind-waves will be unable to re-mobilize coarse alluvial bedload and beach sands that deposit on fluvial deltas and flood tide shoals, respectively).

5.4 EVOLUTION OF GEOMORPHIC UNITS

Given the expected future changes to the sediment budget and sediment dynamics, we projected the evolution of the individual geomorphic units introduced previously using various methods.

- **Subtidal Shallows.** Due to the lack of wind-wave agitation and tidal scour, subtidal shallows act largely as sediment sinks and accumulation of alluvial and/or littoral material is largely unchecked by any significant erosional process. Thus, these units typically accumulate sediments at higher rates than other intertidal units. Therefore, we preferentially applied future sedimentation to the existing subtidal shallows in projecting future lagoon morphology; projected accretion in subtidal shallows was based on results from sediment core analysis and not subject to the erosive effects of wind waves (unlike our projection of mudflat evolution – see below).



Source: National Park Service (October 2001)

N

0 625 1,250 2,500 3,750 5,000
Feet

25 Acres

figure 5-3

Projecting the Future Evolution of Bolinas Lagoon

Sheltering of Wind Waves in Bolinas Lagoon

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- **Subtidal Channels.** We do not expect significant changes in the shape or size of the Main Channel, expect for lateral migration in the vicinity of the tidal inlet. However, the size of Bolinas Channel is expected to diminish as salt marsh expansion and protrusion of the Pine Gulch Creek delta continue to reduce the volume of water conveyed through the channel during the daily ebb and flood of tides. Over the past few decades, sedimentation at the head of the Bolinas Channel has segregated this channel from ebb tidal flows from the North Basin.

- **Mudflats.** To project future morphologic evolution of mudflats, we applied rates of vertical sediment accumulation derived from sediment cores and adjusted for accelerated sea level rise. Measured mudflat slopes from the North Basin and South Arm collected by ground-based surveys in 2004 were then used to estimate the change in horizontal extent of frequently exposed and frequently submerged mudflat.

  In the North Basin, results from the recent UC Berkeley core study (Byrne and others, 2005) indicate that the average net sedimentation in the North Basin since the 1906 earthquake has been approximately 6.8 mm/yr. Figure 5-4 shows the locations of the UC Berkeley sediment cores in the North Basin relative to the geomorphic units. Projecting this rate 50 years into the future translates into an average accumulation of 1.1 ft. Accounting for accelerated sea level rise over the same period (0.4 ft), the sediment accretion relative to local mean sea level is expected to be 0.7 ft. This relative vertical accretion was then multiplied by existing mudflat slopes to estimate future horizontal change of mudflat habitats (Figure 5-5). Since the western shore of Bolinas Lagoon is partially sheltered by the Pine Gulch Creek delta, mudflats in this area generally have flatter slopes that result in greater horizontal protrusion of exposed mudflats relative to the eastern shore.

  Unlike the North Basin, sediment accumulation in the South Arm has been studied less extensively. Cores taken in the South Arm were generally not useable because of the disturbance to the sediments from dredging and fill activity. Therefore, rates of sediment accumulation here are not as well understood. For the purposes of this analysis, we projected mudflat change in the South Arm by the method described above but extrapolated results from single core extracted between the Seadrift dike and Highway 1 and analyzed by Macdonald and Byrne (*in* Byrne 2002). Pollen dating from this core suggests a sediment accumulation rate of 6 mm/yr in the South Arm. It is unclear if this sample was affected by dredging activity during the construction of Seadrift or other man-induced changes in this area. Although the sediment accumulation based on the Macdonald and Byrne core is sufficient to fill all of the subtidal shallow and raise all mudflat elevations above the local mean sea level, our projection retains a portion of the area in the South Arm exposed to the prevailing winds as submerged mudflats.

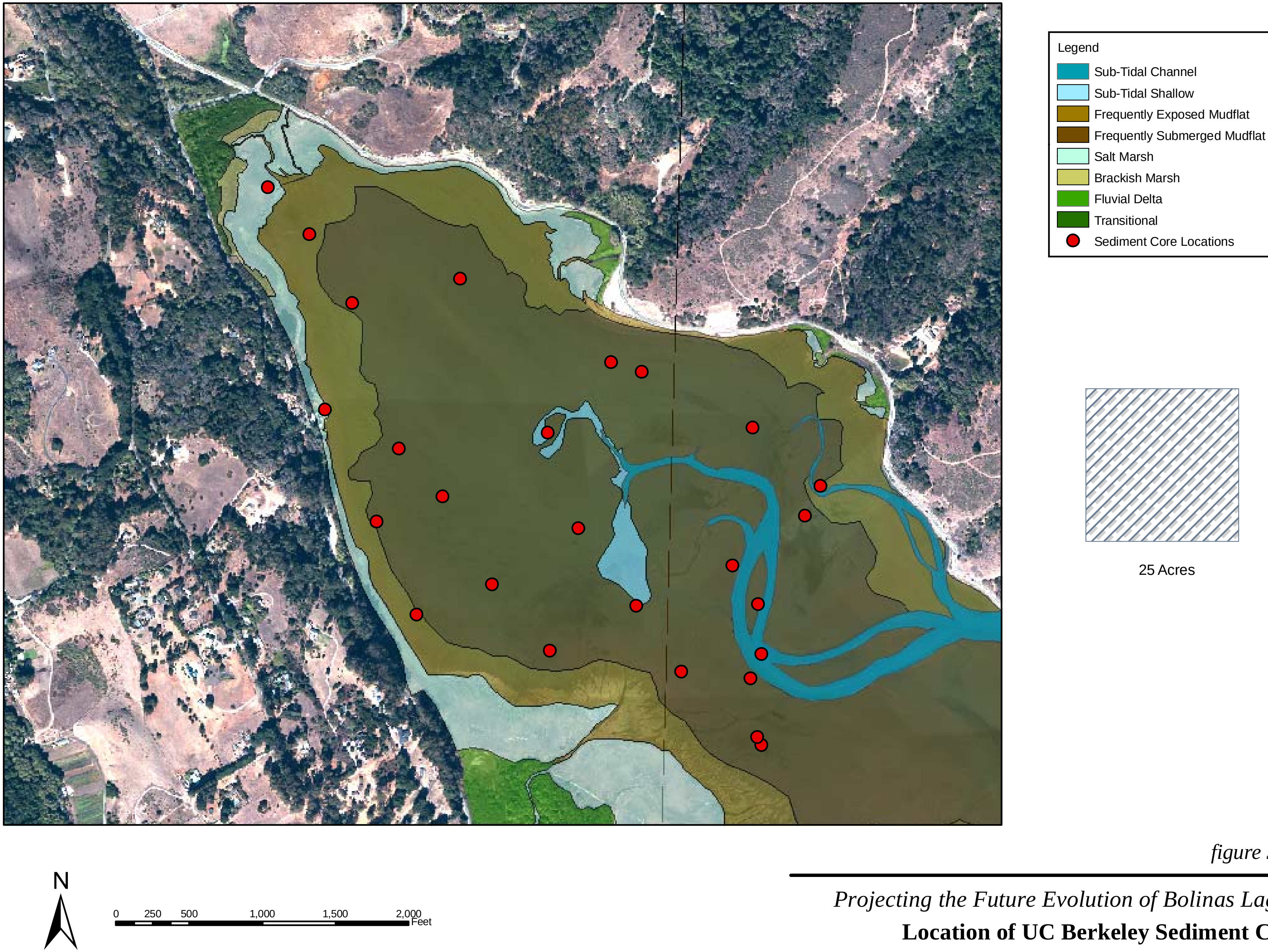

figure 5-4

Projecting the Future Evolution of Bolinas Lagoon

Location of UC Berkeley Sediment Cores

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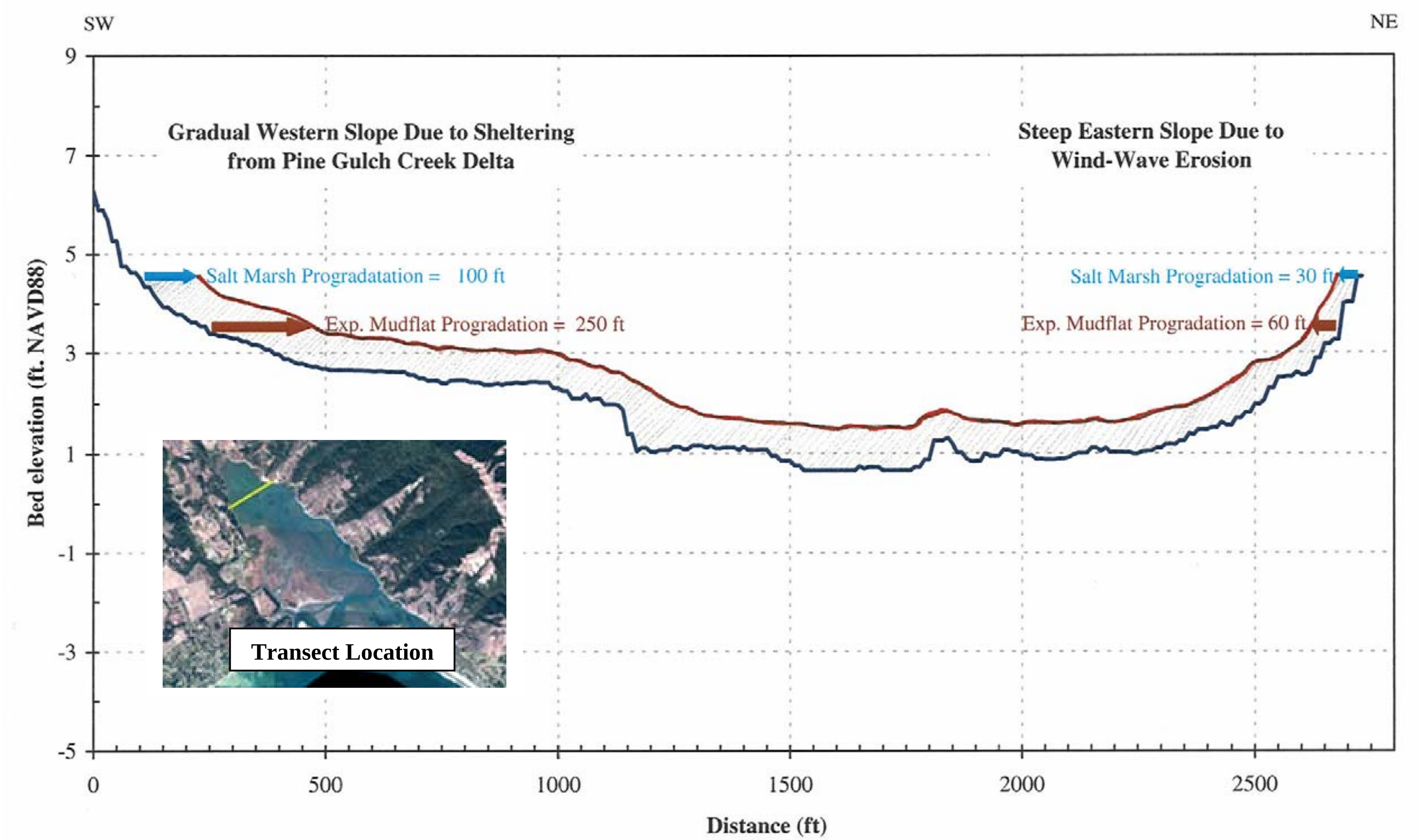

1998 — Year 50

Source: Transect profile extracted from 1998 TIN

f igure **5-5**

Projecting the Future Evolution of Bolinas Lagoon

Vertical and Horizontal Accretion in the North Basin

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- **Fluvial Deltas.** As a result of continued above-natural rates of watershed delivery, the delta at Pine Gulch Creek is expected to protrude further into the lagoon interior over the next 50 years. However, the rate of horizontal extension will slow as watershed sediments are distributed over an ever-growing delta and accumulation is partially offset by accelerated sea level rise.

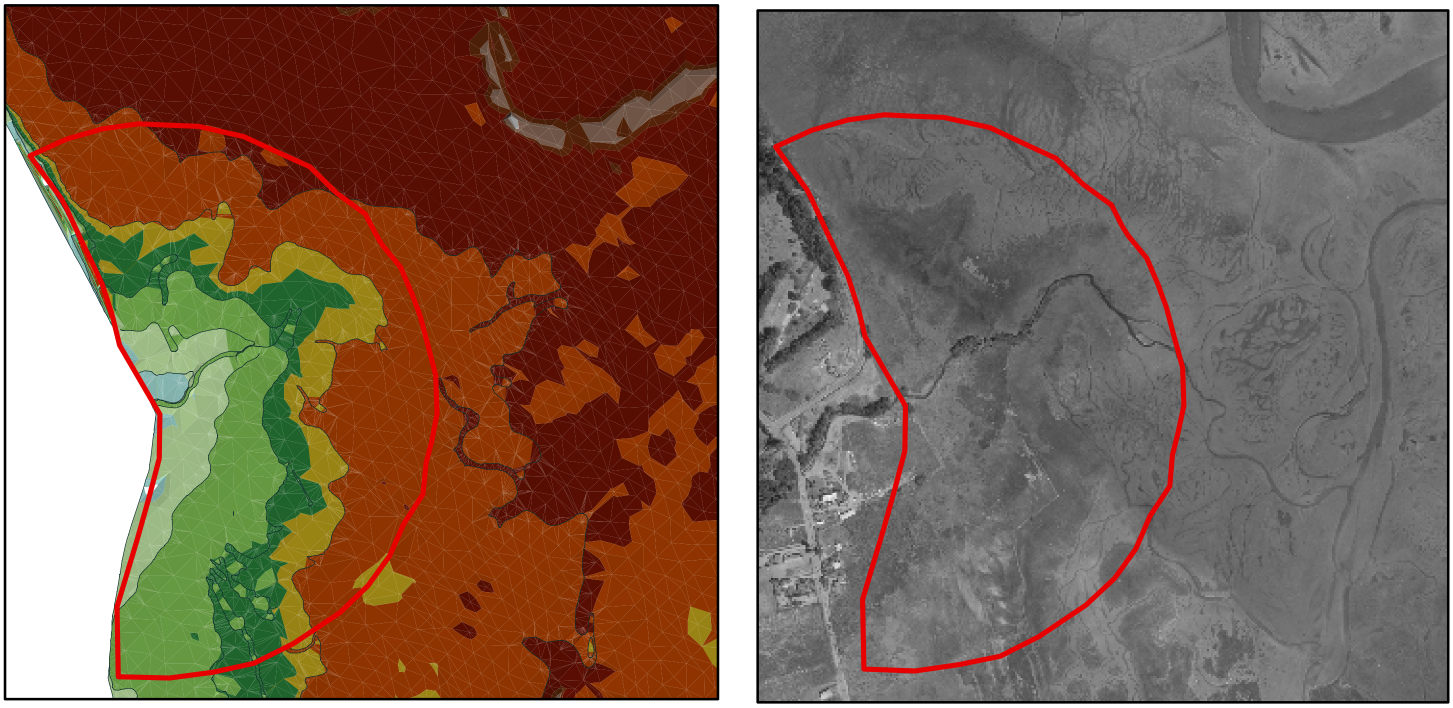
  The aerial expansion of the delta was projected from estimates of sea level rise and watershed delivery. The average annual rate of sediment accumulation (3,900 CY/yr) was estimated by computing the volumetric change on the delta and down to the wind-swept mudflat elevation (approximately 1 ft below local mean sea level) using the 1968 and 1998 GIS surface models (Figure 5-6). (Note: accumulation on the Pine Gulch Creek delta is less than the delivery of stream-borne sediments since a portion of the suspended load is dispersed into the lagoon interior.) The volume, height and radius of the delta measured from the 1998 surface model were used as the starting dimensions of half a cone. Annual volumetric accumulation was then distributed evenly atop the delta cone assuming the ratio of height-to-radius is kept constant and that mudflat bed elevation keeps pace with sea level rise. Based on these assumptions, we project that Pine Gulch Creek delta will grow radially by about 425 ft over the next 50 years (Figure 5-7). Over the long-term, vertical accretion will be outpaced by sea level rise. We expect this to occur in about 177 years, at which point the delta will have grown 530 ft.

  Existing deltas at the mouths of the steep tributaries along Bolinas Ridge were also projected to protrude into lagoon. However, we limited the evolution of these features to 'coves' protected from the prevailing winds and unlikely to be subject to tidal scour along the Main Channel. Overall, aerial and volumetric change of the deltas along Highway 1 were significantly less the projected change at the Pine Gulch Creek delta.

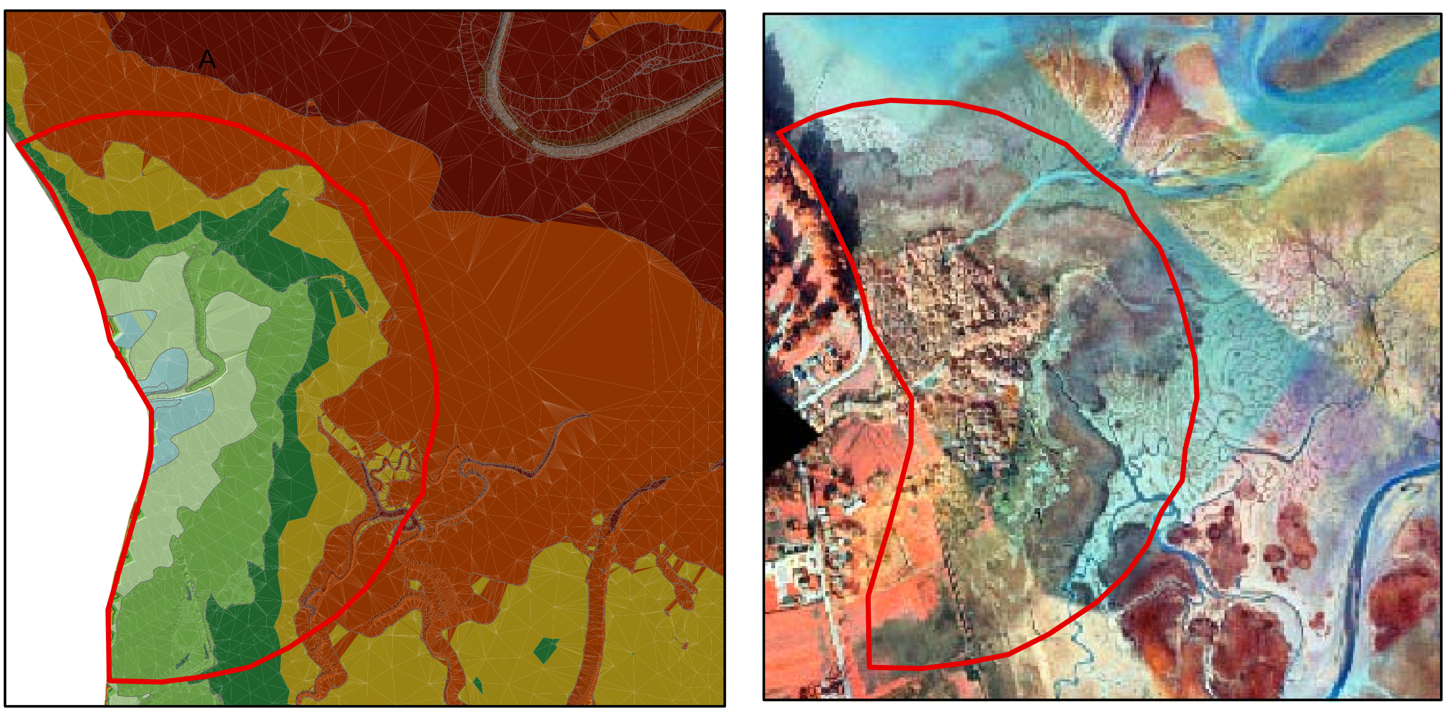
- **Flood Tide Island.** Accumulation of beach sands on the supratidal flood tide island (Kent Island) is expected to be minimal, although the shoreline orientation may adjust due to ocean swells that penetrate the tidal inlet and aeloian (wind-blown) transport as sediment dries during low tide. One biological feedback that may stabilize the flood tide island is future expansion of European beach grass. This species acts to stabilize beach and dune habitats by trapping wind-blown sand. We applied the rate of linear extension of Kent Island established from the recent (1968-2001) aerial photographs to project future elongation over the next 50 years (Figure 5-8).

- **Salt Marsh.** Future protrusion of Pine Gulch Creek delta into the lagoon interior facilitates the continued expansion of salt marsh between the delta and the flood-tide island (Kent Island), as these supratidal landforms shelter mudflats from the erosive effects of wind-waves. As discussed earlier, this sheltering effect allows sedimentation to raise mudflats to elevations suitable for marsh vegetation to establish.

1968



1998



Note: Volumetric change calculations derived from the delta cone (red mask) portion of the 1968 and 1998 TINS

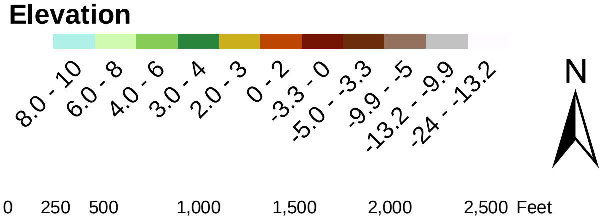


figure 5-6

Projecting the Future Evolution of Bolinas Lagoon

Calculating the Volumetric Change of Pine Gulch Creek Delta: 1968-1998

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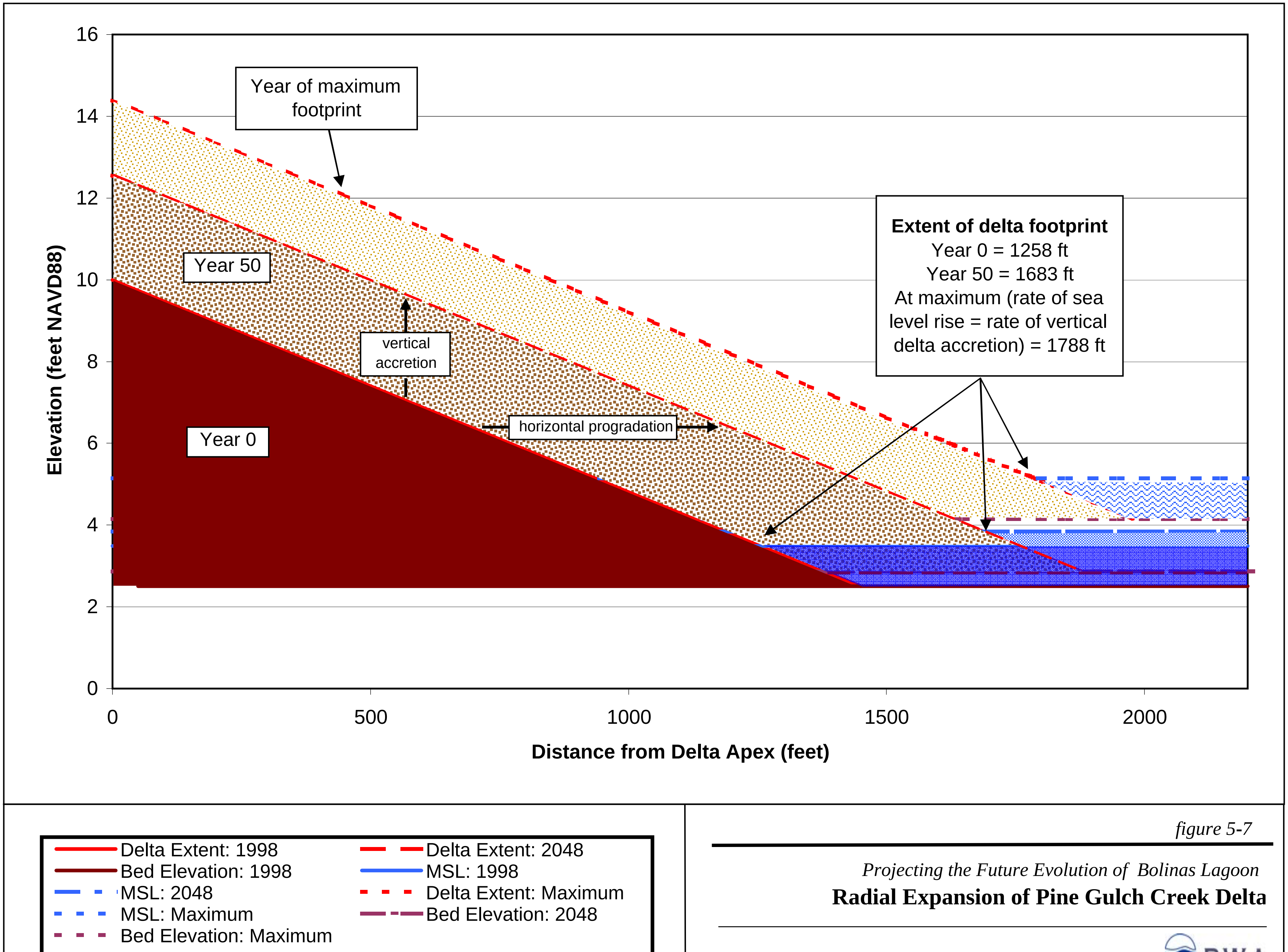

figure 5-7

Projecting the Future Evolution of Bolinas Lagoon

Radial Expansion of Pine Gulch Creek Delta

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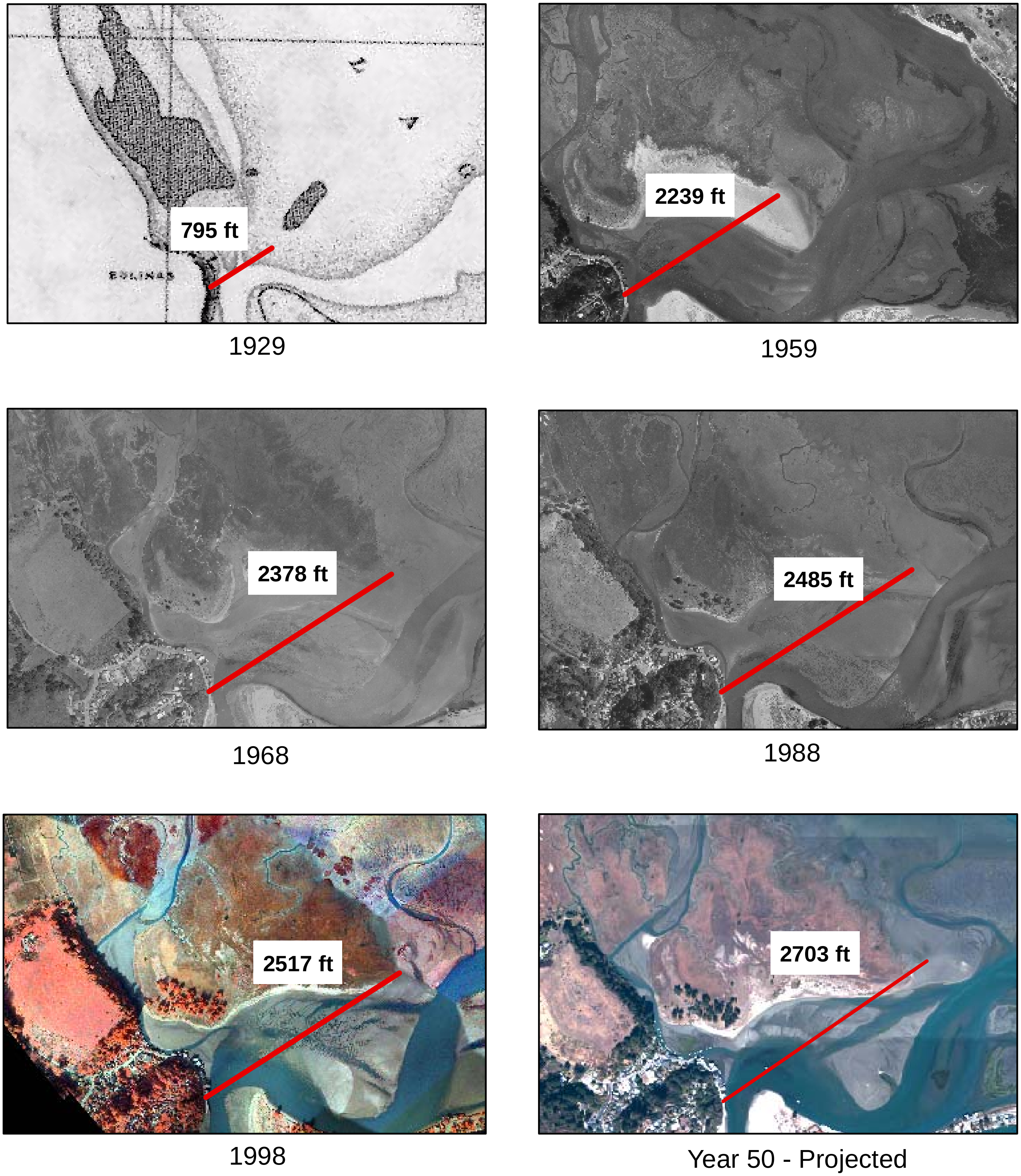

N

0 500 1,000 2,000 3,000 4,000 Feet

figure 5-8

Projecting the Future Evolution of Bolinas Lagoon

Linear Extension and Fetch Blocking Effects of Kent Island

We estimated future marsh expansion in this sheltered area by extrapolating the late 20th century rate of marsh expansion in this region derived from aerial photographs (Figure 3-10). Not surprisingly, the rate of marsh expansion in this calm area (1.65 acres/yr) is significantly higher than in areas exposed to wind waves (0.25 acres/yr). We projected future expansion of salt marsh in this sheltered area by first estimating future extension of Kent Island and Pine Gulch Creek to assess the extent of wind-wave sheltering (Figure 5-3). We then applied the salt marsh expansion rate of 1.65 acres/yr observed during the late 20th century to estimate the amount of marsh expansion over the next 50 years.

In addition to marsh growth in sheltered areas within the central ‘reach’ of Bolinas Lagoon, small pods of vegetation recently established on the flood tide shoal immediately east of Kent Island were included in this analysis. Since these areas are exposed to the dominant winds, the slower rate of 0.25 acres/yr was applied to estimate the future size of salt marsh on these shoals.

- **Flood Tide Shoals.** We expect deposition of beach sands on flood tide shoals and subsequent re-distribution by energetic tidal currents, locally generated wind-waves, and swell penetration through the inlet to continue over the next 50 years. These processes will result in a dynamic tide delta system, but we do not expect significant changes in the volume of sediment stored in the sandy shoals; net sedimentation of beach sands are expected to keep pace with sea level rise.

5.5 CUMULATIVE CHANGES IN LAGOON MORPHOLOGY

Figure 5-9 depicts the expected changes in various geomorphic units and habitat types over the next 50 years, as established by the methods discussed in Section 6.1. The aerial extent and net change for each unit is also summarized in Table 5-1. Generally, we expect sedimentation rates to completely fill subtidal shallows and raise the average mudflat elevations, and for future progradation of Pine Gulch Creek to continue relatively rapid expansion of salt marsh in sheltered areas.

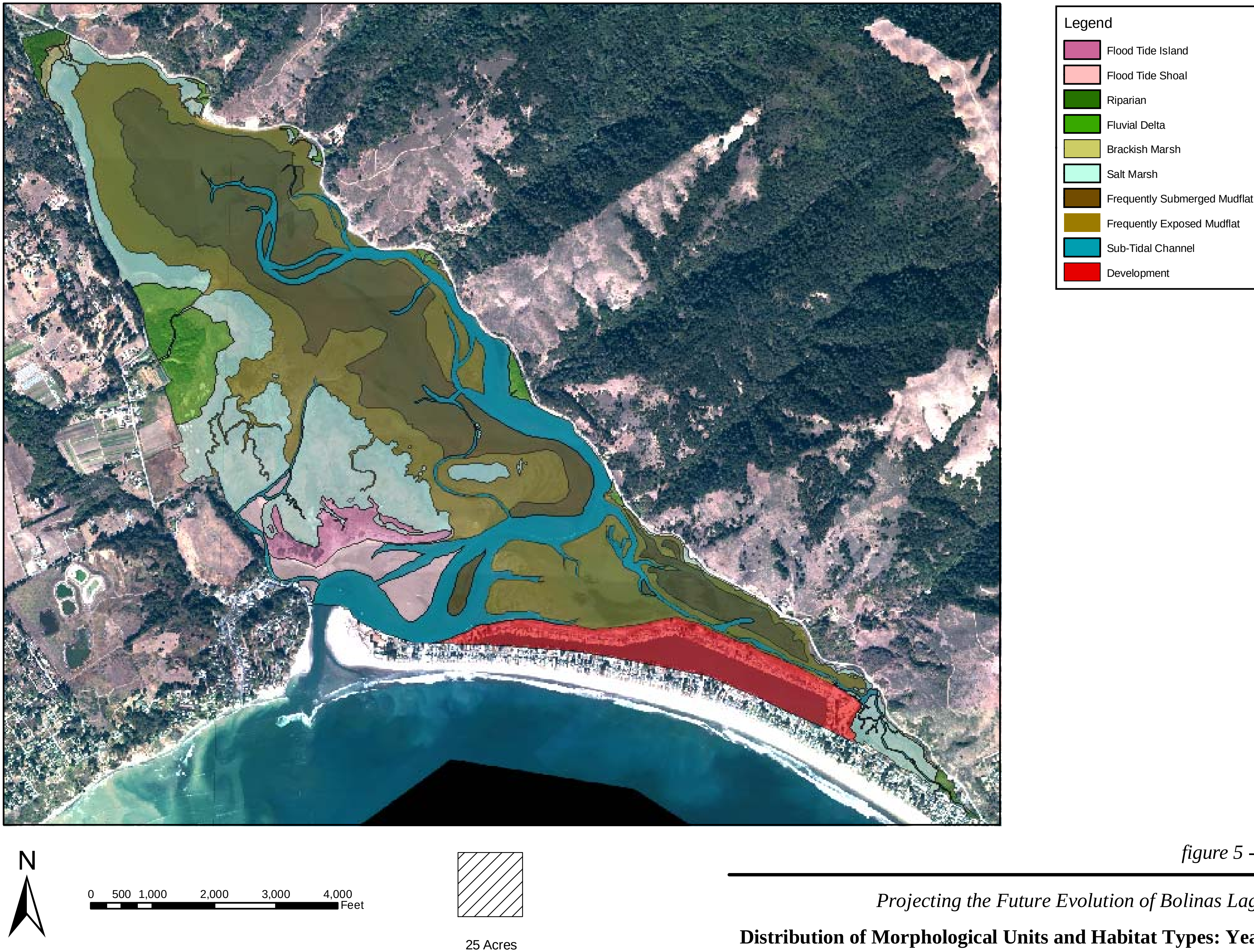

figure 5 - 9

Projecting the Future Evolution of Bolinas Lagoon

Distribution of Morphological Units and Habitat Types: Year 50

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Table 5-1. Projected Change in Lagoon Morphology

Morphologic Unit	Year 0 Area (acres)	Year 50 Area (acres)	Change in Area (acres)	Percent Change (%)
Flood Tide Island	28	28	0	0
Flood Tide Shoal	40	40	0	0
Subtidal Channel	171	169	- 2	- 1
Subtidal Shallow	27	0	- 27	- 100
Frequently Submerged Mudflat	399	293	- 106	- 26
Frequently Exposed Mudflat	264	327	+ 63	+ 24
Salt Marsh	200	244	+ 44	+ 22
Brackish Marsh	3	5	+ 1	+ 46
Fluvial Delta	30	54	+ 24	+ 82
Transitional	5	6	+ 1	+ 17
Total*	1,165	1,165		

* Values have been rounded to the nearest acre, resulting in slight differences between the total report and the sum of individual rows. Total value is smaller than ca. 1,200-acre value since developed areas of Seadrift Lagoon are excluded.

The greatest changes result from the conversion of frequently submerged mudflats to frequently exposed mudflats. This is largely because mudflats cover the greatest extent of all habitats within the lagoon and provide accommodation space for sediments. Mudflat conversion is primarily concentrated in areas such as the North Basin and South Arm, where extensive mudflats surround small subtidal basins. In areas exposed to the predominant winds, we expect a substantial portion of the mudflats to remain below the local mean sea level (e.g., as frequently submerged mudflats).

Substantial changes are also evident in the aerial coverage of fluvial delta. Watershed delivery is expected to continue at present rates, resulting in the protrusion of deltas and fringing salt marsh into the lagoon. As salt marsh establishes along the toe of Pine Gulch Creek delta, reduced exposure to wind-wave erosion and increased sediment trapping accelerates further marsh expansion. Over the past several decades, the majority of salt marsh conversion is occurring within the sheltered area between Kent Island and Pine Gulch Creek delta. Salt marshes are also expanding to a lesser extent on the fringes of fluvial deltas throughout the lagoon.

5.6 CHANGES IN TIDAL PRISM AND INLET STABILITY

Cumulative geomorphic adjustments result in changes to the intertidal volume of Bolinas Lagoon. In order to assess this change, we used the projected changes in geomorphic units to re-draw the elevation-area characteristics (hypsometry) of the lagoon. The associated change in tidal prism was then established by graphically integrating the area between the Year 0 and Year 50 hypsometric curves that extend from MHHW to MLLW. Sediment deposition above MHHW or below MLLW does not directly affect tidal prism even though it may impact the habitat distributions in these elevation ranges.

Over the next 50 years, future net sedimentation in Bolinas Lagoon will result in a loss in tidal prism and less ability for ebb tidal currents to maintain a stable inlet. Based on the difference between the elevation-area curves for Year 0 and Year 50 (Figure 5-10), we expect the tidal prism to diminish by about 1 MCY. This estimate represents an average loss of approximately 20,000 CY/yr over the next 50 years, which is less than the 20^{th} century rate (about 30,000 CY/yr) due to the projected changes in sediment budget and sediment dynamics discussed above. PWA assessed the corresponding changes to closure potential by computing the how this reduction in tidal prism will affect the balance between wave and tidal power.

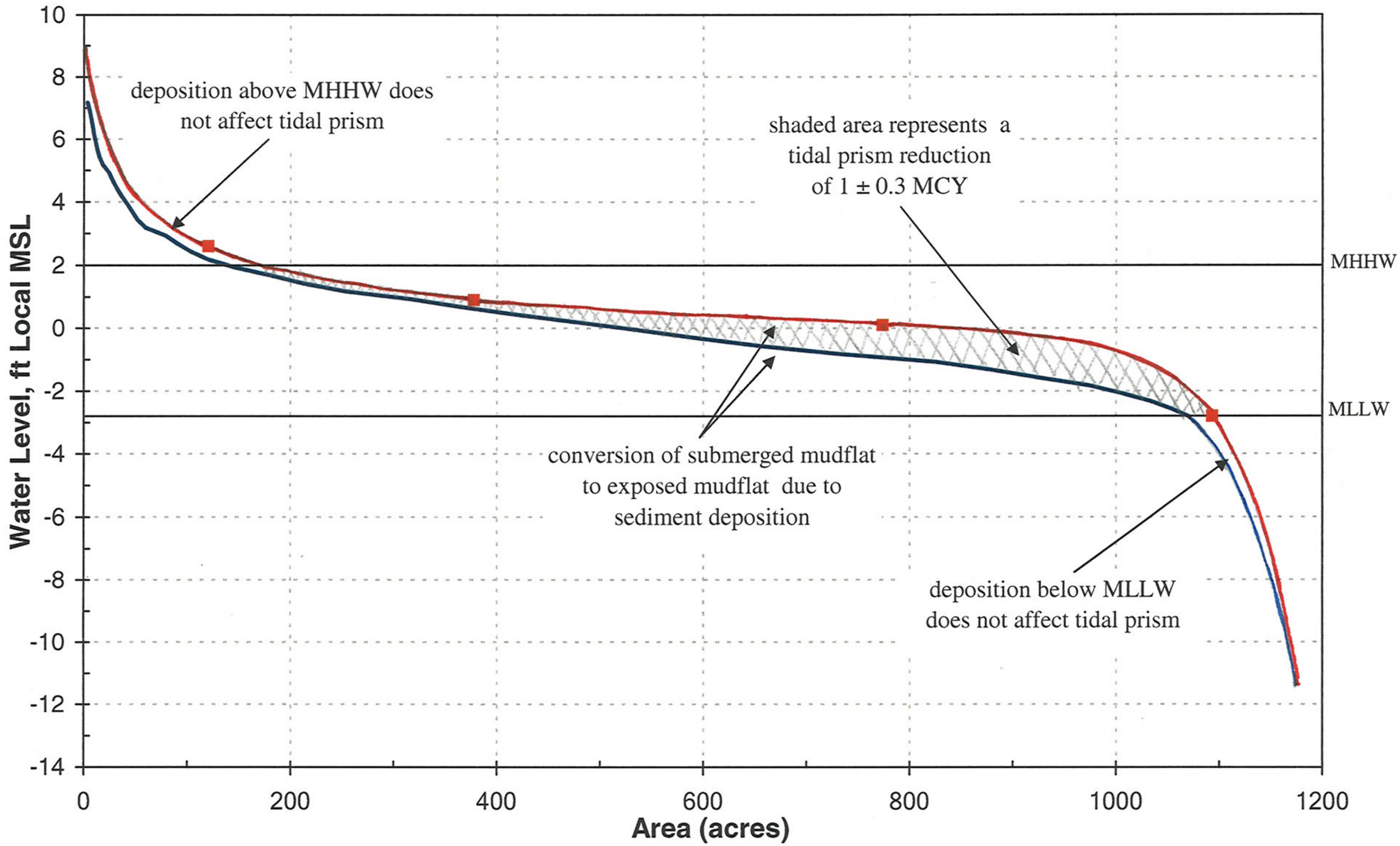
Since closure potential is largely determined by the relative balance of wave-driven transport of beach sands and scour by ebb tidal currents, we assessed closure potential by computing the ratio of wave power (P_{WAVE}) to tidal power (P_{WAVE} / P_{TIDAL}) over a six-hour moving average. This provides the following time-varying stability index that was first proposed by O'Brien (1971):

$$S = P_{WAVE} / P_{TIDAL}$$

Wave power increases with wave height and period; while tidal power is directly proportional to the tidal prism and lagoon tide range but inversely proportional to inlet width (i.e., smaller inlet widths produce larger values of tidal power). Thus, the potential for inlet closure is greatest when large ocean swells coincide with weak neap tides. Figure 5-11 presents a portion of the simulated stability index, and reveals how closure potential varies in response to the prevailing wave climate and fortnightly fluctuations in the spring-neap tidal cycle. Based on documented closures of coastal lagoons, we considered values over 12 as indicators of inlet closure.

PWA simulated a 17-year time series of the stability index by transforming offshore wave buoy data to nearshore values representative of conditions at the Bolinas Inlet, and adjusting high and low tides measured at the Presidio in San Francisco based on published conversion factors for Bolinas Lagoon. Results of this analysis are summarized in Table 5-2 and suggest that the inlet is not expected to close over the 50 year planning period. The first instance of predicted inlet closure over this simulation period occurred for a lagoon tidal prism value of 2 MCY – slightly below the value predicted in 50 years – and an inlet width of 300 ft, although no closure was simulated when the inlet width was reduced to its expected value of 200 ft.

Based on these results, we expect that closures with an approximate frequency of once a decade may occur if the tidal prism of Bolinas Lagoon reduces to 2 MCY (the approximate tidal prism of the 'ultimate' tidal prism before the next large earthquake), although the inlet could close under higher values of tidal prism if extreme wave conditions coincided with unusually weak neap tides.



1998 — Year 50

Notes:
1. Elevation- Year 0 curve generated from 1998 TIN; Year 50 curve generated from projected changes in lagoon habitat extents
2. Year 0 local MSL = 3.49 ft NAVD88; Year 50 local MSL includes 0.39 ft of sea level rise
3. Assume no change in tidal range

figure 5-10

Projecting the Future Evolution of Bolinas Lagoon

Changes to Lagoon Elevation-Area Characteristics

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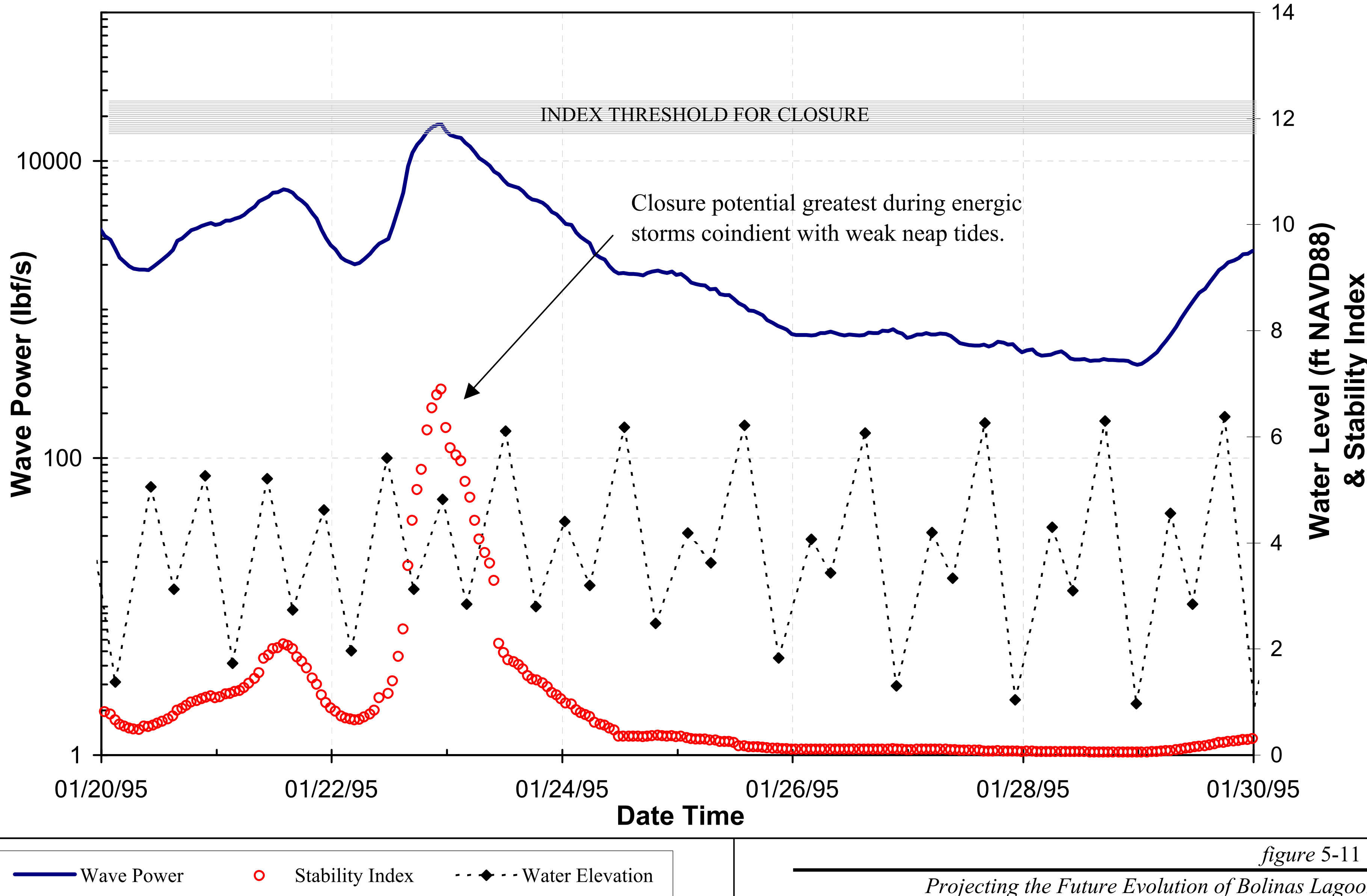

Notes:
Waves from Monterey Buoy (transformed to Bolinas Bay) and Tides from Bolinas Inlet (transformed from Presidio Tides). The current tidal prism (100 mcf) was used in this analysis.

figure 5-11

Projecting the Future Evolution of Bolinas Lagoon

Fluctuations in Inlet Stability due to Changing Tides and Ocean Waves

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Table 5-2. Results of Inlet Stability Analysis

Scenario	Tidal Prism (MCY)	Inlet Width (ft at MSL)	Number of Closures (S > 12)	Maximum Value of Stability Index
1	3.5	300	0	6.9
2	2.5	300	0	9.2
3	2.0	200	0	9.4
4	2.0	300	2	13.8

Although the O'Brien parameter captures the joint probability of energetic coastal storms and coincident weak neap tides, this simplified approach does not capture details of the hydraulic flow through the inlet. Rapid accumulation of beach sands in the entrance channel could increase the friction, thus reducing the ability of ebb tides to scour previously deposited material. Once in the 'friction-dominated' mode, complete inlet closure could occur rapidly. Also, differences in grain size of beach material between the Bolinas Inlet and the two references sites (Crissy Field and the Russian River mouth) may lead to closure occurring at different values of wave-to-tidal power (i.e., S=12 is only an approximate value).

5.7 TRENDS IN LAGOON EVOLUTION BEYOND 50 YEARS

Changes in form and tidal prism will continue beyond the 50-year planning horizon as the lagoon approaches an equilibrium form in response to future depositional and erosional processes. The anthropogenic modifications discussed above will result in an equilibrium form different from the natural conditions that existed prior to significant changes in the watershed in two important ways: the long-term losses of tidal prism and intertidal mudflat habitat due to the presence of Seadrift Lagoon; and an increase in riparian and salt marsh vegetation due to increased watershed delivery along Pine Gulch Creek and the sheltering effect of its delta which decreases the extent of wind-swept mudflats.

Although we expect accelerated sea level rise will limit the extent of the fluvial delta at the mouth of Pine Gulch Creek, salt marsh vegetation will continue along the western shoreline of the lagoon. High elevations of the Pine Gulch Creek delta, and the riparian vegetation it supports, protect areas to the north and south of the delta from erosive wind-waves that would otherwise keep mudflat elevations low and unvegetated. Figure 5-12 shows the potential equilibrium extent of salt marsh, which consists of 80 additional acres of salt marsh distributed in areas sheltered from winds that blow along the longitudinal northwest-southeast axis of the lagoon. Based on the rate of salt marsh growth measured in the late 20th century, vegetation would fill the remaining 80 acres of sheltered mudflats in approximately 75 years and could result in an additional loss of about 0.2 MCY in tidal prism.

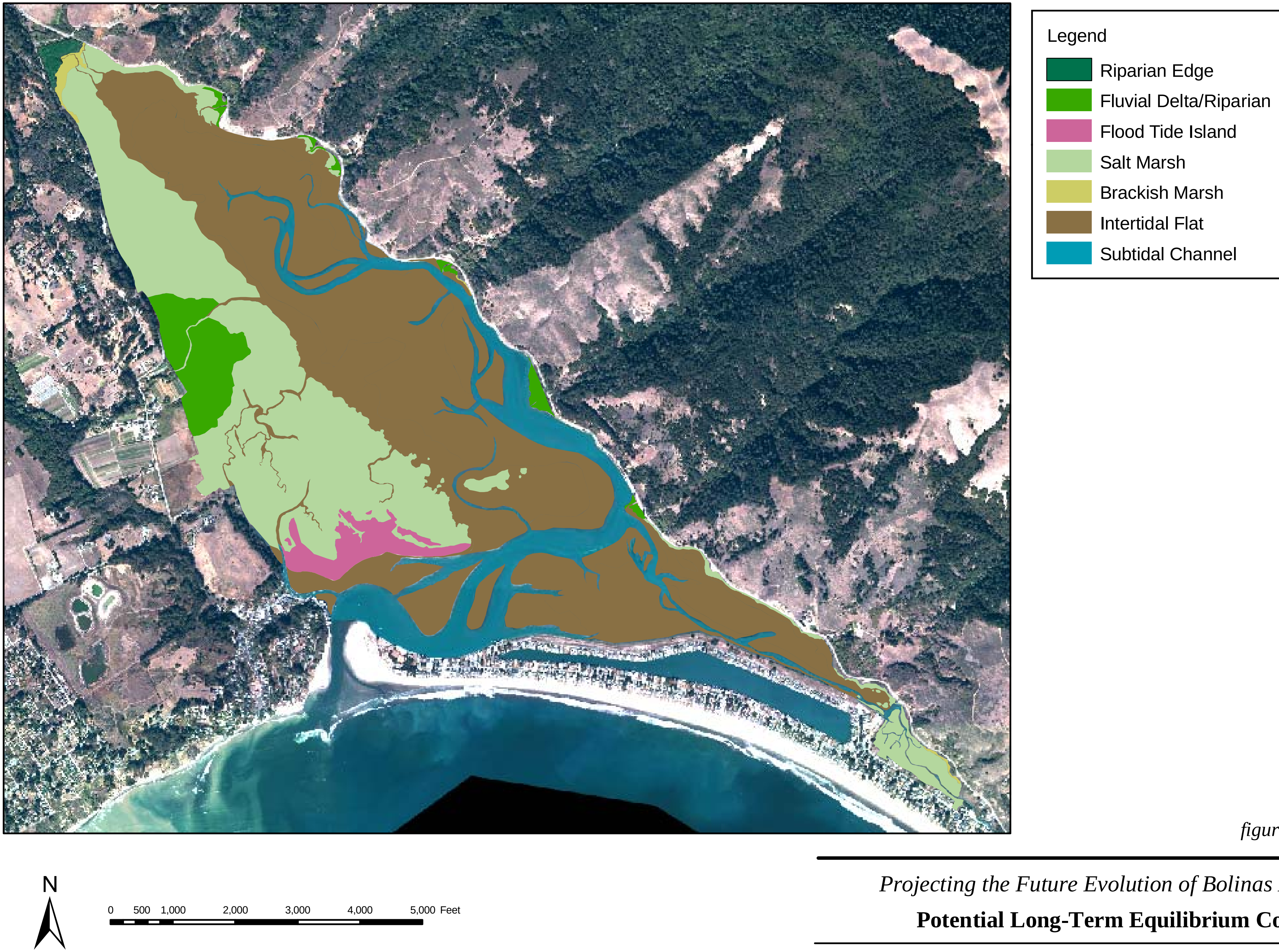

figure 5 - 12

Projecting the Future Evolution of Bolinas Lagoon

Potential Long-Term Equilibrium Condition

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These projections of future conditions were developed assuming no large earthquake occurs along this region of the San Andreas Fault over the planning horizon. However, findings from Byrne and others (2005) indicate that Bolinas Lagoon does respond to large tectonic events every few hundred years. The occurrence of a large earthquake in the future would presumably result in a sudden down-drop of the lagoon floor and an increase in tidal prism similar to that following the 1906 earthquake. Given the structure of the fault, subsidence is expected to occur preferentially, with the greatest down-drop on the east side of the lagoon. The magnitude of future tectonic down-drop and its associated tidal prism increase will largely depend on the specific details of the earthquake.

5.8 POTENTIAL ECOLOGICAL CHANGES

Based on projected changes in habitat distribution of Bolinas Lagoon over the next 50 years, some changes in species diversity and abundance are expected with the shift in habitat types. Most changes will occur with those species associated with Frequently Submerged Mudflat, Frequently Exposed Mudflat, and Salt Marsh, which currently account for 863 acres (74 percent) of the lagoon. It is projected that the area of Frequently Submerged Mudflat will decrease 26 percent, while Frequently Exposed Mudflat will increase by 24 percent.

Mudflat habitat is important for foraging shorebirds in winter and during migration. The gradual increase in Frequently Exposed Mudflat over the next 50 years should provide an increase in potential foraging habitat for shorebirds. The decrease in Frequently Submerged Mudflat will reduce the availability of high-tide foraging habitat for some fish; however, Subtidal Channel habitat will remain relatively unchanged.

The projected increase of 44 acres of Salt Marsh would provide additional habitat for rails, saltmarsh common yellowthroats, other birds, and Point Reyes bird’s beak. In addition, the increase in Salt Marsh and 24 acres of Fluvial Marsh will likely result in an increase in the export of detritus and nutrients into the lagoon.

5.8.1 Expected Shifts in Habitat Distribution and Abundance

Predicted changes in the distribution of habitat types at Bolinas Lagoon, particularly mudflats, will affect the abundance of associated plants and animals and may ecological functions within the lagoon. Projected changes for each morphological unit are discussed below.

Flood Tide Island

Projected change of the Flood Tide Island, which currently represents 2.4 percent of the lagoon, over 50 years, is negligible. No significant change to the general wildlife diversity and abundance in Bolinas Lagoon is expected, and this geomorphic unit will continue to provide haul-out habitat for harbor seals and high-tide roosting areas for shorebirds. However, as noted above, Kent Island is subject to colonization by non-native, invasive plant species. If these species continue to spread, they will have an adverse impact on the native plants of the Island and could also contribute to a more substantial increase in sand accretion.

Flood Tide Shoal

Changes to the aerial extent of Flood Tide Shoal, which presently represents 3.4 percent of the lagoon, are expected to be negligible. Therefore, wildlife diversity and abundance in the lagoon will not be significantly affected.

Subtidal Channel

Several key species of fish and birds are associated with Subtidal Channel, which represents approximately 15 percent of the total area of Bolinas Lagoon. It is projected that this morphologic unit will decrease by about 2 acres over 50 years.

One of the important habitats that has been previously reported in the subtidal channels is eelgrass. According to the Bolinas Lagoon Ecosystem Restoration Project DEIR (MCOSD, 2002), an eelgrass bed approximately 1200 square feet in size existed in the Kent Island Channel in 2000. In 2005, WRA conducted a visual survey of the channel and did not observe eelgrass beds. It is not known what caused the apparent loss of eelgrass habitat nor how much may have existed prior to 2000 though it had been reported by Gustafson in 1968 and by CDFG in 1992. According to PRBO Conservation Science data, brant (*Branta bernicla*) have not been regularly observed at Bolinas Lagoon between 1970 and the present. Since migrating and wintering brant heavily favor eelgrass as a food source where it is available (Zeiner and others, 1990), the absence of brant suggests that eelgrass was not very widespread in Bolinas Lagoon in the last 30 years. However, eelgrass is used by herring for egg laying and other fish species utilize this habitat for shelter. According to the CDFG Marine Region Laboratory, the eelgrass beds associated with the Bolinas Channel represented a unique and valuable habitat in the lagoon and supported the highest diversity of fish in a number of life stages compared to other sampling sites.

The loss of eelgrass beds have been documented in other estuaries and coastal lagoons subject to heavy sedimentation, eutrophication, and closure. While the documented amount of eelgrass within Bolinas Lagoon was relatively small, its loss may be indicative of changes in the subtidal habitat that are adverse to other subtidal species. Some species such as pipefish are most frequently found in eelgrass beds and may be affected by this loss. Further investigation on the past distribution of this species in the lagoon is warranted and a more detailed field investigation should be conducted to determine its presence or absence.

The decrease in Subtidal Channel will potentially reduce available foraging habitat for two feeding guilds of birds. Diving fish-eating birds, such as common loon, double-crested cormorant, brown pelican, western grebe, osprey, red-breasted merganser, and Forster’s tern have had stable or decreasing population trends in the lagoon since 1970 (PRBO Conservation Science data). These species occur in very low densities, and it is not known if local, gradual habitat loss will contribute to further declines in these species. Diving benthos feeders that forage in Subtidal Channel include horned grebe, greater scaup, ruddy duck, common goldeneye, bufflehead, and surf scoter. PRBO data suggests that although wintering populations of some of these species have been decreasing since 1970, other diving benthos feeders have shown increasing trends in wintering populations. Diving benthos feeders occur in greater densities than diving fish-eating birds, possibly because benthos feeders may also forage in Frequently Submerged Mudflat.

Subtidal Shallow

It is assumed that accumulated sediment will eliminate Subtidal Shallow areas over the next 50 years. This unit represents 2.3 percent of the total area of Bolinas Lagoon. This habitat type is used as a nursery area for many marine fish (as are the subtidal channels). While these fish may also move into other areas (such as frequently submerged mudflats), there will be some loss of habitat to benthic flatfish species and longer lived benthic invertebrates such as mollusks and ghost shrimp. This gradual habitat loss will affect multiple species, at different life stages, and part of an important prey base.

Frequently Submerged Mudflat

Frequently Submerged Mudflat is an important morphologic unit to benthic invertebrates, fish, shorebirds, and waterfowl. Studies conducted by Gustafson (1968) concluded that greater abundance of invertebrate life was observed on frequently submerged mudflats as compared to frequently exposed mudflats. Frequently submerged mudflats also play an important role as nursery and spawning habitat for several commercially and recreationally important fish. Fish and invertebrates in turn provide important prey for waterbirds and shorebirds.

It is projected that this unit, which now occupies 399 acres (34 percent) of the lagoon, will decrease by 106 acres over 50 years. The decrease in Frequently Submerged Mudflat will reduce habitat for invertebrates and the availability of high-tide foraging habitat for some fish and diving waterfowl and other waterbirds.

Approximately one-third of the invertebrates listed in Table 4-1 are identified as occurring in mid and low tide habitats or just low tide habitats. The loss of 31 percent of Frequently Submerged Mudflat over 50 years will result in a loss of habitat for these invertebrates, including fat innkeeper worm, rock crab, blue mud shrimp, and soft-shelled, geoduck, Washington, and gaper clams. According to Gary Page (personal communication), the Washington clam may no longer occur in Bolinas Lagoon, and the beds of gaper clams are greatly reduced in extent.

Shifts in species and abundance for many fish may occur as adult and juvenile fish will eventually be concentrated in smaller subtidal and frequently submerged mudflat areas where an increase in predation and competition for resources can be expected. It is reasonable to expect that most fish species listed in Table 4.2 will be affected by the loss of 106 acres of Frequently Submerged Mudflat and 27 acres of Subtidal Shallow morphologic units.

In the last 30 years, PRBO Conservation Science data suggest that the numbers of fish-eating birds have remained fairly stable. One species, the Forster's tern, has increased as a wintering species. The presumed loss of fish habitat over the past 30 years (assuming a linear trend with the projected future changes) and the relative stability of fish-eating birds may not be related or may simply be a matter of reaching a particular threshold before an effect is noted. Many factors, in addition to habitat type, affect the occurrence of fish species (Meng and Powell, 1999). In addition to monitoring invertebrate and fish communities, it is worthwhile to consider focusing on the abundance and diversity of resident and migratory fish-eating birds as indicators of adverse changes in fish abundance associated with the decline of this habitat type.

Another group of birds for which a shift in diversity and abundance could occur is the shorebirds. It would be expected that a decrease in shallow, submerged mudflat would possibly reduce invertebrate prey of long-billed shorebirds. However, the PRBO data since 1970 indicate that wintering long-billed shorebirds, including whimbrel (*Numenius phaeopus*) and long-billed curlew (*Numenius americanus*), have increased in numbers. Because migratory birds are subject to many influences throughout their migratory range, it may be difficult to relate habitat change in Bolinas Lagoon to any change in migratory bird abundance or diversity.

The decrease in Frequently Submerged Mudflat will potentially reduce available foraging habitat for three feeding guilds of birds. Diving benthos feeders, dabbling benthos feeders, and long-legged shorebirds may all forage in Frequently Submerged Mudflat. Diving benthos feeders also may utilize Subtidal Channel (discussed above). According to PRBO data, dabbling benthos feeders, including American wigeon, northern shoveler, and gadwall, have shown increasing wintering population trends since 1970. The northern pintail, however, has experienced a decreasing trend. Although dabbling benthos feeders occur in low densities (0.3 to 6 birds per acre of potential foraging habitat), the proposed 26 percent decrease over 50 years will result in less available winter foraging habitat. Winter populations of long-legged shorebirds, such as marbled godwit, whimbrel, long-billed curlew, and American avocet, have increased since 1970. It is uncertain how the projected gradual decrease in Frequently Submerged Mudflat will affect these species.

Frequently Exposed Mudflat

Frequently Exposed Mudflat is also very important to foraging shorebirds. This unit is currently second only to Frequently Submerged Mudflat in total area (264 acres); however, it is projected that this unit will increase by 63 acres in 50 years and become the dominant unit in the lagoon, covering about 28 percent of the total area. The gradual increase in Frequently Exposed Mudflat over the next 50 years should provide an increase in potential foraging habitat for shorebirds, including black-bellied plover, least sandpiper, western sandpiper, dunlin, sanderling, black turnstone, and willet. These species forage on smaller, shorter-lived benthic invertebrates such as polycheates that are associated with the more frequently exposed mudflat. According to the PRBO data, small shorebirds currently constitute the largest number of migratory shorebirds utilizing the lagoon

Salt Marsh

The expected 22 percent increase in the aerial extent of salt marsh (from 200 to 244 acres) will provide an increase in abundance of associated plant species and wildlife species dependent upon salt marsh. Once marsh plants begin to colonize the mudflats, the primary production of the lagoon can be expected to shift more towards vascular plants–species that are known for their high productivity, but also high carbon content and relative indigestibility to marine organisms. Insects and birds feed on the seeds and plant parts; but for the most part the primary production from salt marsh plants is processed through the detrital food web. Generally, smaller invertebrates such as amphipods and polychaetes utilize this material–eventually being consumed by small shorebirds that forage over the mudflats.

The increase in Salt Marsh will also provide additional habitat for the state-threatened California black rail, saltmarsh common yellowthroat, and savannah sparrow. Increases in this morphologic unit will result in greater availability of high-tide roosting habitat for shorebirds, such as long-billed curlew and whimbrel. In addition, expansion of high elevation salt marsh areas will provide additional suitable habitat for the existing Point Reyes bird's-beak population on Kent Island.

It is important to note that for purposes of the 50-year projection, salt marsh habitat was combined into one category. However, the detailed habitat classification performed for this work shows that many types of habitat are found within the salt marsh. This internal diversity within the salt marsh category is important as it provides a diverse production base and supports differing animal composition. Future monitoring efforts should use the classification system and the baseline information to determine changes within this habitat complex as a potential monitoring tool. For example, increases in riparian, freshwater, and brackish marsh habitat types could be indicative of increased sedimentation from the watershed; whereas increases in salt marsh, especially low marsh areas may be indicative of greater sedimentation over mudflats. In addition, the occurrence and slope of the low marsh may also be indicative of habitat change. The more gentle slope along the western portion of the lagoon has become established in an area of recent sedimentation whereas the steeper marsh slope along the eastern edge of the lagoon is presumably maintained by wind-generated wave erosion of the mudflat and low marsh. If the slope along the eastern edge becomes more shallow, it is an indicator of more rapid sedimentation in this area either due to a decrease in open water fetch (which generates the waves) or sediments that are accumulating from either upland or ocean sources.

Brackish Marsh

Brackish Marsh is projected to increase by 1 acre over the next 50 years and will represent less than 1 percent of the total area of Bolinas Lagoon. The small increase will contribute to a slightly greater detritus export into aquatic habitats of the lagoon. The increase in Brackish Marsh will also benefit the state-threatened California black rail and saltmarsh common yellowthroat.

Fluvial Delta / Riparian Habitat

The largest percentage increase in any one morphologic unit is projected to occur in Fluvial Delta. This unit will increase by 24 acres over the next 50 years. Productivity in aquatic portions of the lagoon should increase as detritus is exported from increases in the extent of Fluvial Delta, Salt Marsh, and Brackish Marsh. The increase in riparian and aquatic habitat associated with Fluvial Delta will provide additional habitat for the federal-threatened California red-legged frog, saltmarsh common yellowthroat, and several common passerine birds.

The increase in fluvial delta will displace some existing salt marsh; however, based on the projections, this loss will be compensated by expansion of the salt marsh over mudflats. Therefore, this particular locational shift will not affect overall vegetative diversity within the lagoon. The increase in Brackish Marsh will benefit the state-threatened California black rail, saltmarsh common yellowthroat, and marsh wren.

Transitional Habitat

Transitional habitat currently occurs on 5 acres of the lagoon, and represents less than 1 percent of the total area. This morphologic unit is projected to increase by about 1 acre over 50 years; wildlife diversity and abundance in the lagoon will not be significantly affected.

5.8.2 Effect of Habitat Types on Ecological Function

The distribution and relative size of habitat types within Bolinas Lagoon directly affect ecological functioning in the following ways:

- Open water systems tend to be dominated by phytoplankton-dominated food webs. The phytoplankton consist of species that remain suspended in the water column as well as those that are resuspended from mudflats by currents and waves. All are fed upon by zooplankton that in turn support small forage fish. Filter feeding benthic invertebrates also feed on the plankton in the water column or on the mud surface. Mudflats are dominated by microalgae that grow on the surface and large macrophytic algal like sea lettuce (*Ulva* sp). In some cases, the large drift algae may increase in abundance such that it has an adverse impact on the benthic community by smothering filter feeders and contributing to anoxic conditions. Declines in open water habitat will lead to decreases in demersal fish which are often dependent upon filter feeding bivalves but will lead to increases in shorebirds that feed on the smaller, short-lived invertebrates on the mudflats. However, these shifts are likely to be masked by many other factors that affect species diversity and abundance in coastal lagoons and, to date, have only been detected through anecdotal information. To date, long term studies of birds and fish in the lagoon by PRBO and DFG have not detected any long-term trends associated with habitat change.
- *Sediment accretion:* Colonization of mudflats by salt marsh plants can also lead to increased sediment accretion due to the stilling of water. Seedling establishment by cordgrass in Bolinas Lagoon occurs at 0.3 to 1 ft above NGVD (Greer, 1998). Once established it can effectively

increase the rate of accretion, both through accumulation of organic matter and settling of fine mud particles. Accretion data for Bolinas Lagoon marshes has not been collected; however, in San Francisco Bay marshes it can lead to substantial increases in sedimentation rates (Larrson, 1996). However, as the elevation of the marsh plain increases, the rate of sedimentation decreases as the period of inundation is reduced. This results in an equilibrium being reached in which the high marsh plain tracks sea level rise (Josselyn, 1983). An exception occurs where sediment is being delivered from a river source such as the Pine Gulch Creek or where sand brought into the lagoon from littoral currents is being deposited by wind action as on portions of Kent Island.

- *Breeding*: Habitat types are directly related to ability of organisms to breed within the lagoon. Lagoons are often referred to as nursery grounds for fish and wildlife. At certain times of the year, the open water and subtidal areas provide important breeding areas for coastal fish and many benthic invertebrates. Often these species spend critical life stages within the lagoon before moving offshore. Eelgrass habitats can provide additional advantages for breeding where eggs are laid on the blades and are oxygenated by the flow of water through the eelgrass bed. While sand and mudflats are not usually considered breeding habitats, they are important for benthic invertebrates that deposit eggs on the surface. Salt marsh and riparian habitats offer numerous breeding opportunities, especially for birds, and in the case of riparian habitats, for amphibians, fish, and mammals. However, the structure of the vegetative canopy and the size of the suitable breeding territory often dictate the success of breeding by a particular species.
- *Foraging/Refugial Habitat*: Fish and wildlife are specialists and are limited by their adaptations to specific foraging techniques and the availability of suitable habitat for all stages of their life histories. Of particular interest to Bolinas Lagoon is the distribution of habitat types that provide a range of foraging opportunities on all stages of the tide and in different seasons. For example, many resident fish forage over mudflats during most of the time, but during the highest tides penetrate the marsh. Fish that access the marsh surface often grow faster than those without access (Madon and others, 2001). In addition, different habitat types offer differing foraging opportunities–subtidal areas are more used by fish and diving birds whereas mudflats are used by shorebirds and wading birds. Refugial habitats, such as those used by harbor seals as haul out areas and salt marshes and low sand bars that support shorebirds during high tide, are important components habitat mix within Bolinas Lagoon.

Though not considered an ecological function, the presence of sensitive species of wildlife in the lagoon is also dictated by the presence of specific habitat types.

6. HUMAN-INDUCED CHANGES TO LAGOON CONDITIONS

A number of human-induced or ‘anthropogenic’ activities have resulted in direct changes to the habitat distribution and tidal prism of Bolinas Lagoon. These modifications have also affected the physical processes that drive the evolution of the lagoon. The dynamic behavior of Bolinas Lagoon makes it difficult to precisely quantify the amount of anthropogenic change. This is especially true following the 1906 earthquakes since anthropogenic changes and large adjustments to lagoon morphology and sediment delivery have overlapped. However, we can describe the influence of anthropogenic effects on lagoon form by considering the processes driving its evolution and the history of human activity.

Overall, the combined effects of direct and indirect anthropogenic modifications to Bolinas Lagoon have reduced its tidal prism. We estimate this reduction to be approximately 1.2 MCY, based on comparison of the predicted Year 50 condition and tidal prism derived from the 1854 T-sheet. In addition to the reduction in intertidal lagoon volume, human-induced changes have altered the subtidal channel system that runs along Wharf Road, as well as the distribution of mudflat, salt marsh and riparian habitats.

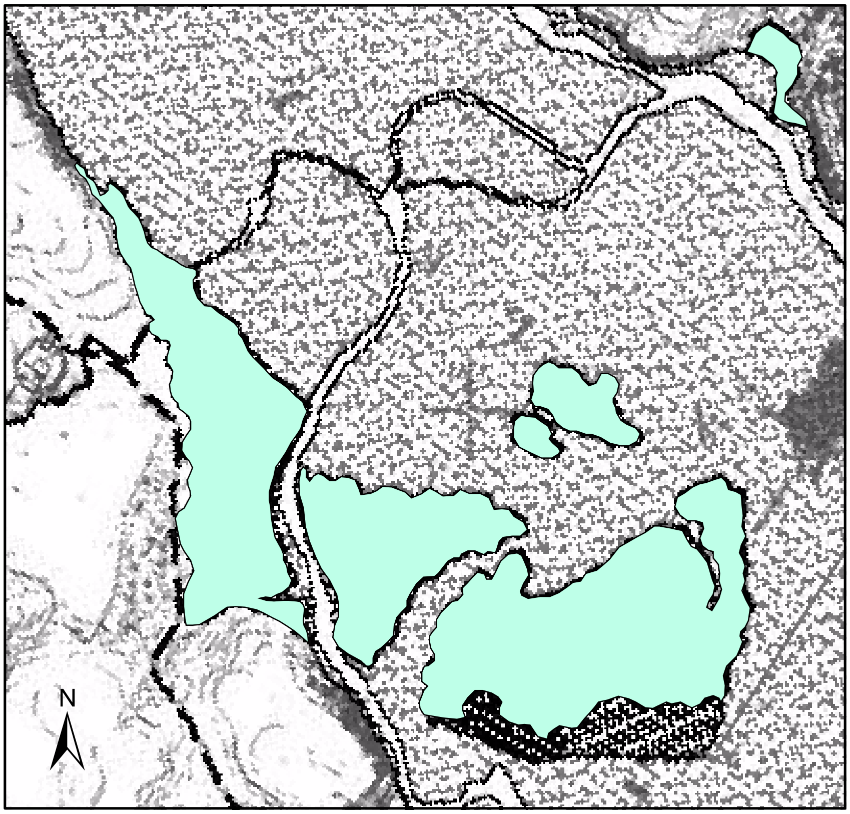
Based on our understanding of the history of Bolinas Lagoon and the processes driving its evolution, we have summarized the largest anthropogenic effects summarized in Table 6-1. The most obvious anthropogenic change to Bolinas Lagoon was the placement of earth during the 1960s to construct Seadrift Lagoon, which impounded about 90 acres of tidal mudflat. However, borrow-ditches constructed on the outboard side of the Seadrift dikes have temporarily offset the long-term effects. Fill placement along other portions of the lagoon, mostly due to construction and maintenance of Highway 1, have had a smaller effect on tidal prism. Although the direct impact of creek channelization was the formation of a large delta at the mouth of Pine Gulch Creek, more subtle changes include its influence on wind-wave agitation (Figure 6-1). In general, the reduction in wind-wave agitation has allowed salt marsh to expand between the delta and Kent Island (about 75 acres beyond its 1854 value). Construction of the Seadrift dikes in the interior of the lagoon has also altered the balance between depositional and erosional processes.

Other anthropogenic factors that have affected Bolinas Lagoon include:

- Conversion of native dune plant community to non-native shrub and tree communities at Seadrift;
- Elimination of overwash along Stinson Spit;
- Hardening of Stinson Spit (both on the ocean- and lagoon-side);
- Creation of Seadrift Lagoon;
- Fill for road and housing along Wharf Road;
- Fill placement and construction of the causeway in the South Arm;
- Construction of the Bolinas Groin and bulkheads at the base of the Bolinas bluffs;
- Hardening at the Bolinas side of the inlet (at the end of Wharf Road);
- Rapid marsh expansion following the Lone Tree Mitigation Project;
- Channelization of Easkoot Creek and diversion of storm discharge to “Poison Lake”; and
- Conversion of native bunch grass to annual grassland in the watershed.

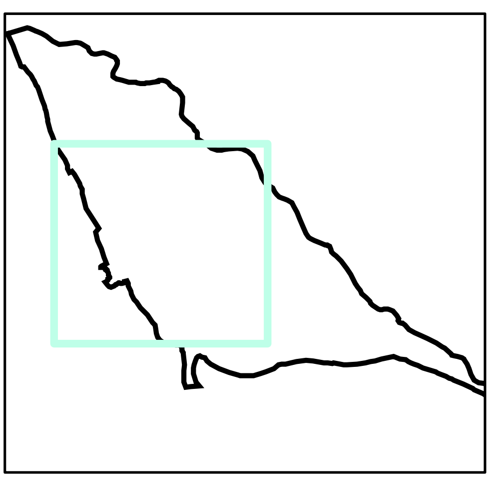
Natural Conditions (1854)

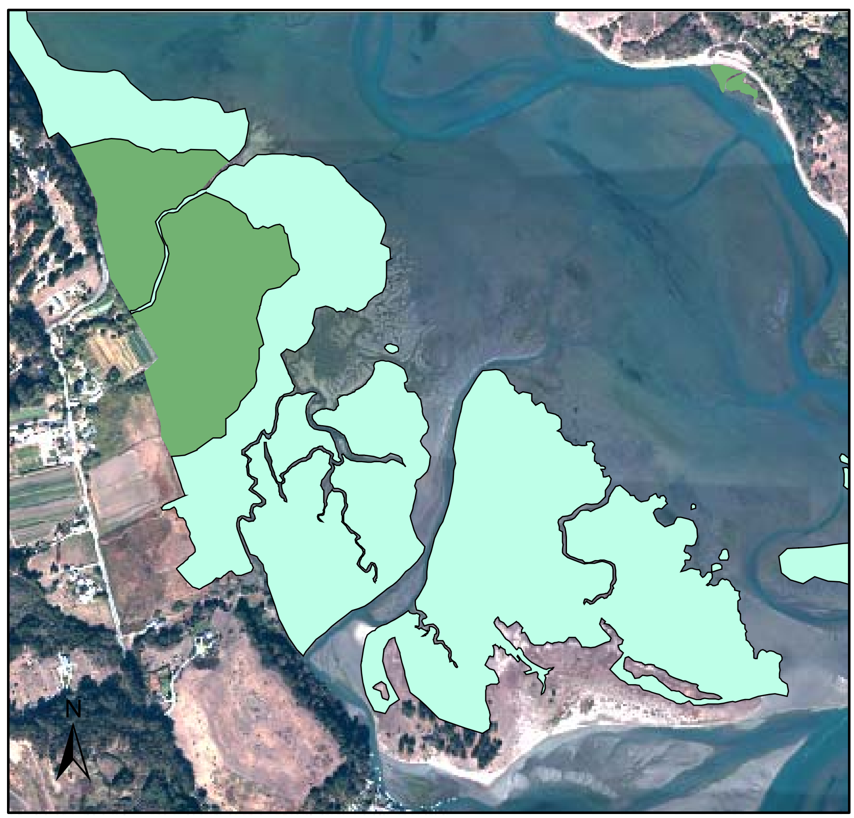
Geomorphic Features: distribution of salt marsh constrained by longitudinal axis of wind fetch



Affected by Anthropogenic Modification (Year 50)

Geomorphic Features: Expansion of fluvial delta into lagoon, lateral expansion of Kent Island proportional to that of fluvial delta, growth of area sheltered from wind fetch





Legend

Salt Marsh

Fluvial Delta

0 500 1,000 2,000 3,000 4,000 5,000 Feet

figure 6 - 1

Projecting the Future Evolution of Bolinas Lagoon

Marsh Expansion Due to the Progradation of Pine Gulch Creek Delta

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Table 6-1. Anthropogenic Activities and Their Effect on Tidal Prism

Activity	Change in Process	Change in Lagoon Form	Change in Tidal Prism
Construction of Seadrift	Permanently impounded about 90 acres of Bolinas Lagoon that were formerly subject to tidal action.	This has resulted in a permanent loss of tidal prism. Borrow channels temporarily offset about half of this reduction.	0.3 MCY loss
Creek Channelization	Increase in bedload delivery and formation of a fluvial delta at the mouth of Pine Gulch Creek.	This has resulted in a conversion of intertidal to supratidal habitat.	0.25 MCY loss
	Sheltering of wind waves between Kent Island and the Pine Gulch Creek delta allows for marsh expansion of about 75 acres beyond its 1854 value.	This has resulted in conversion of higher mudflat to tidal marsh.	0.25 MCY loss
Change in Wind Fetch	Protrusion of the Pine Gulch Creek delta and construction of Seadrift dikes in the lagoon interior has reduced the amount of mudflat exposed to significant wind wave agitation.	This has resulted in a conversion of lower mudflat to higher mudflat, although many remain below levels appropriate for marsh plant colonization.	0.3 MCY loss
Other effects	Placement of fill in the South Arm, along Highway 1, and at other locations.	Long-term loss of tidal prism.	0.1 MCY loss

7. MONITORING AND ADAPTIVE MANAGEMENT

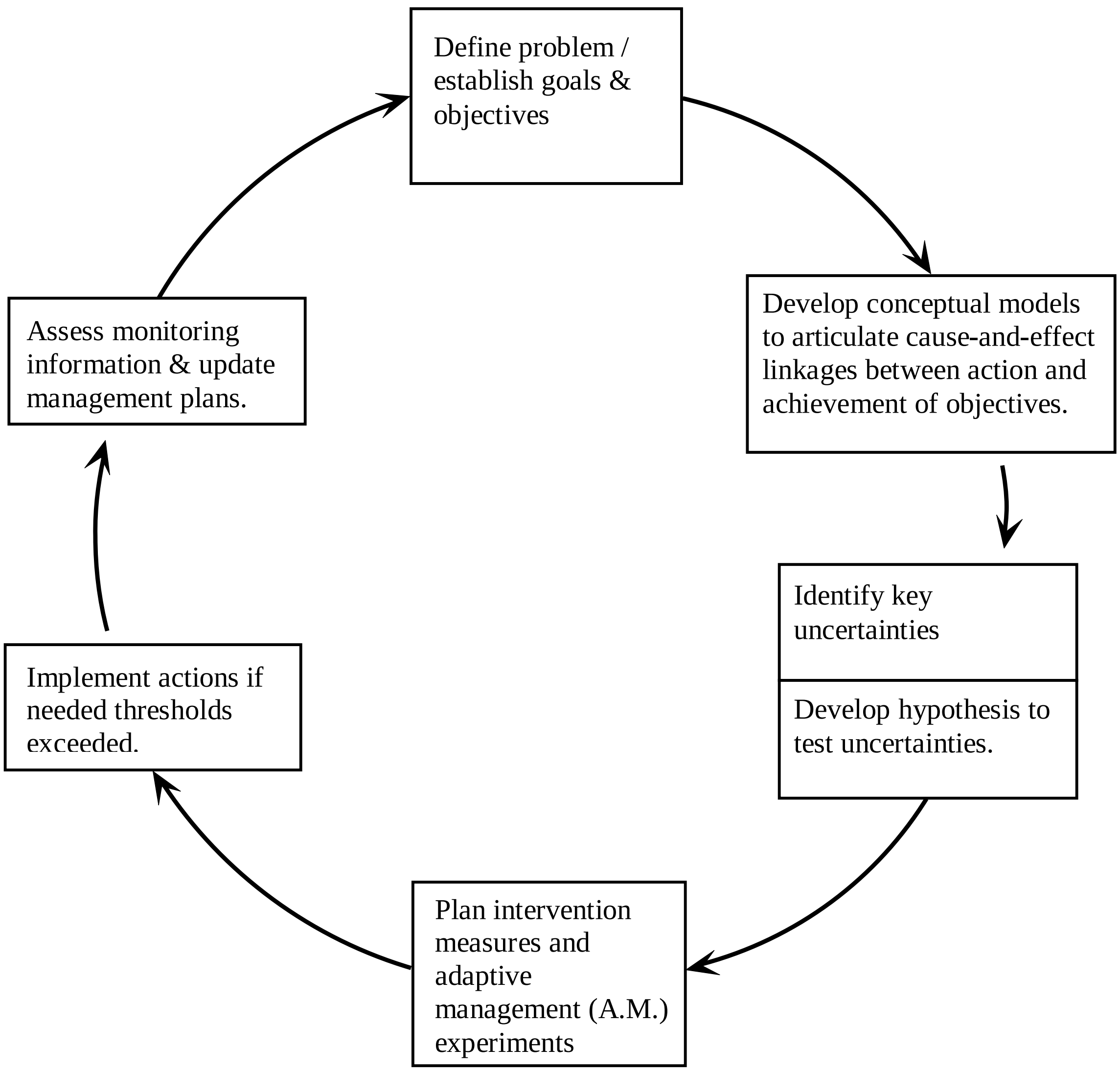
Although studies carried out as part of this project have increased our ability to explain how Bolinas Lagoon has evolved in the past and how it may change in the future, our understanding of ecosystem functions remains incomplete. As described below, feeding new information based on periodic monitoring and analysis back into the decision-making processes can help reduce these uncertainties. Monitoring can be used to test specific assumptions regarding future lagoon evolution and to examine the validity of the 50-year projection. If management actions are undertaken, then monitoring can also be used to assess the effects of intervention measures. This process of adaptive management increases the likelihood of achieving agreed-upon objectives, while reducing the potential for adversely affecting important existing resources of the lagoon.

7.1 MANAGING IN THE FACE OF UNCERTAINTY

An adaptive management plan establishes clear management goals and a structured decision-making framework. Within this framework management decisions and actions are based on explicit conceptual models of system function and monitoring of key physical and ecological variables. The adaptive management process acknowledges that uncertainties exist in our understanding of ecosystem functions and provides an operational framework for updating management plans based on improved understanding of ecosystem dynamics (Holling, 1978 and Walters, 1986).

As new insight on ecosystem functions emerges through periodic monitoring and analysis, this information is fed back into the planning and management process (Figure 7-1). Feedback loops between monitoring and management actions are specifically designed to improve the ability to discern the effects of management actions and choose appropriate intervention measures. Adaptive management allows for conceptual models, goals, objectives, and key indicators to be re-evaluated and, if needed, revised to reflect the most current understanding of how Bolinas Lagoon functions.

Figure 7-2 shows an operational framework for developing and implementing an adaptive management plan for Bolinas Lagoon. The plan should be administered by the MCOSD, with input from the Bolinas Lagoon Technical Advisory Committee (BLTAC). In addition to regular monitoring and specific experiments designed to reduce uncertainties in the key cause-and-effect linkages of conceptual models, the adaptive management plan consists of a series of pre-planned intervention measures. These actions are formulated to achieve specific management objectives. Management plans are continually updated as appropriate, based on new information regarding ecosystem functions emerges.



f igure 7-1

Projecting the Future Evolution of Bolinas Lagoon

The Adaptive Management Process

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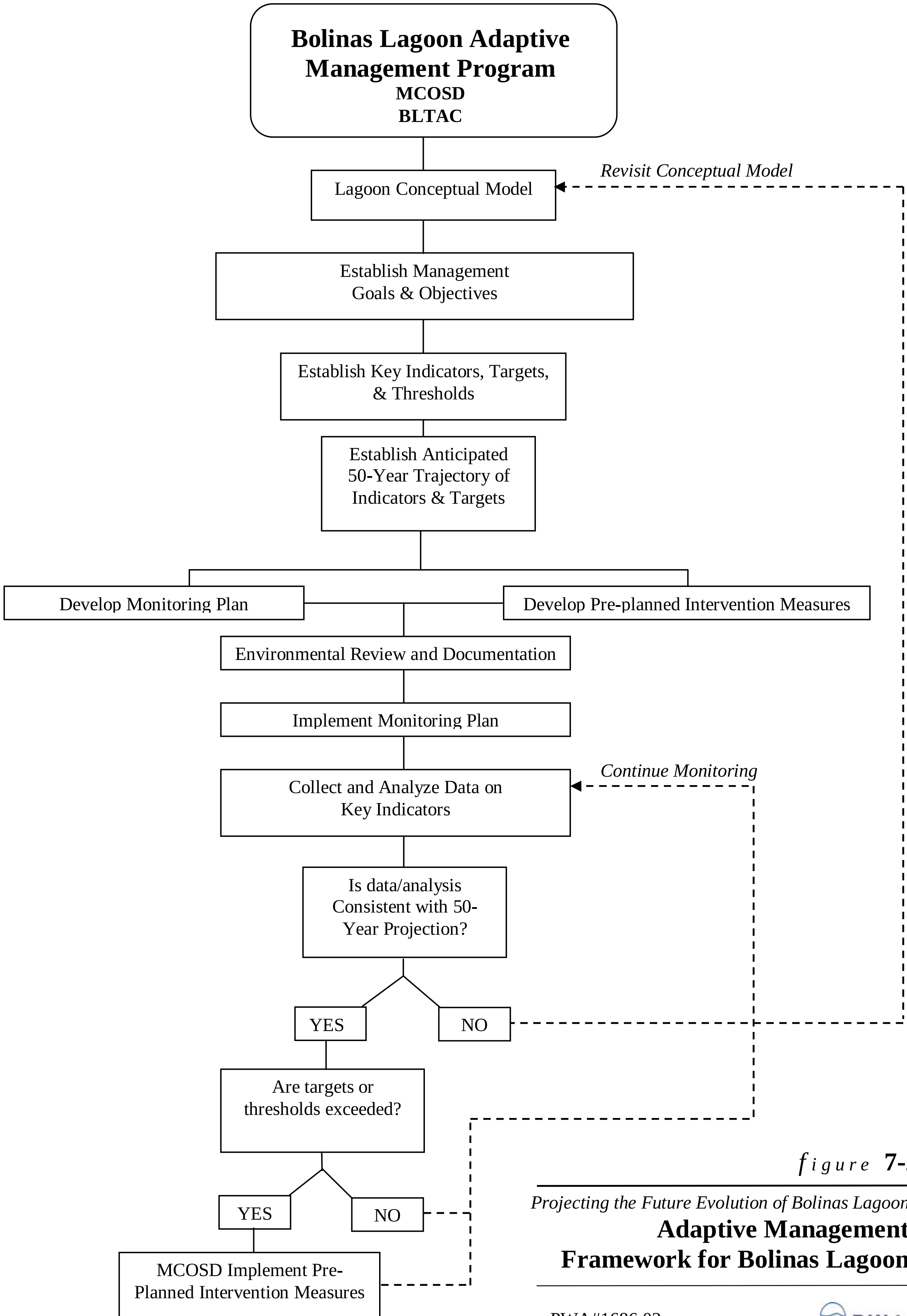

figure **7-2**

Projecting the Future Evolution of Bolinas Lagoon

Adaptive Management Framework for Bolinas Lagoon

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7.2 ESTABLISHING MANAGEMENT GOALS AND OBJECTIVES

Marin County first established a plan for use and protection of Bolinas Lagoon as a condition of the transfer of jurisdictional control from the State of California to the County. The *Bolinas Lagoon Plan* (1972) and *Bolinas Lagoon Resource Management Plan* (1981) were superceded by the *Bolinas Lagoon Management Plan Update* (1996), which considered information regarding the physical and ecological changes that were observed during the 1980s and 1990s. Management goals and objectives included in the *Bolinas Lagoon Management Plan Update* were developed by the MCOSD and the BLTAC, a technical committee formed in 1974 to offer advice and comments to the County on issues affecting the lagoon and its natural resources. The 1996 management plan update established the following broad goals and objectives:

Goal 1. Preserve and restore the ecological values of Bolinas Lagoon.

- Objective 1. Preserve the abundance and diversity of Lagoon life (especially native aquatic birds, marine mammals, fish, and marine plants and invertebrates).
- Objective 2. Preserve and enhance, over the long term, an ecological system including aquatic habitats (subtidal, intertidal, marsh, riparian, sand bar, and beach) that best protects the abundance and diversity of Lagoon life.
- Objective 3. Restore water quality and hydraulic functions that will decrease sedimentation and prevent the loss of rich estuarine habitats.

Goal 2. Consistent with Goal 1, maintain and enhance the opportunities for education, research, recreation, navigation, and aesthetic enjoyment of the Bolinas Lagoon.

- Objective 1. Promote education of the public about the ecological values of the lagoon and its watershed.
- Objective 2. Support research about the lagoon's physical and biological systems and human uses.
- Objective 3. Allow compatible recreational activities.
- Objective 4. Continue use of a limited area of the lagoon for small boat mooring.

Goal 3. Promote land use management in the lagoon's watershed consistent with preserving and restoring the ecological values of Bolinas Lagoon.

- Objective 1. Promote cooperative efforts to acquire and preserve lands of ecological significance to Bolinas Lagoon.
- Objective 2. Encourage and support sound watershed management practices.
- Objective 3. Encourage cooperative watershed improvement efforts.

As expressed in these goals, the over-arching management strategy is to allow for natural geomorphic and hydrologic processes to maintain the resources of Bolinas Lagoon (Goal 1, Objective 3). This is a recognition that development of habitats (Goal 1, Objective 2) and biological uses (Goal 1, Objective 1) rely on natural processes that drive the geomorphic evolution of the lagoon.

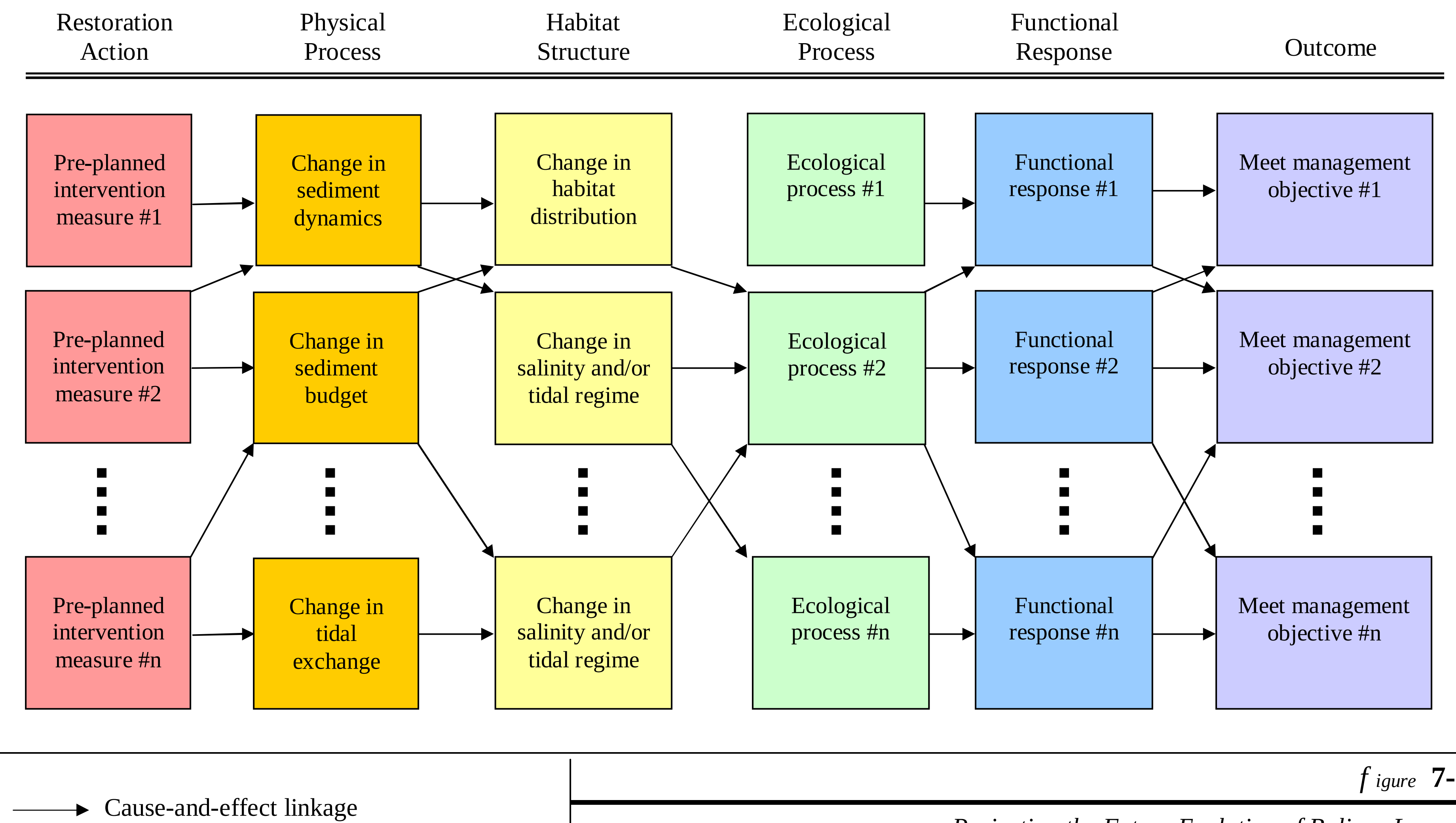
We recommend that the goals and objectives stated above be revisited, and possibly revised, based on the latest understanding of how Bolinas Lagoon functions and evolves. Additionally, management goals and objectives should be based on the following concepts of ecological integrity:

- Coastal lagoons, creeks, and beaches are dynamic evolving physical systems.
- At any given time, the lagoon landscape is an expression of its watershed, climate, tectonic, geomorphic and ecological history.
- Beach morphology is a function of the littoral processes – including longshore and offshore sand transport and episodic storm events – and sediment delivery from the watershed.
- Physical processes tend to drive the lagoon toward an inherent form. So long as natural physical processes are allowed to occur, the lagoon system can be self-correcting.
- Ecosystems are self-organizing communities that are responsive to the physical processes that occur within the lagoon.
- Species diversity and habitat resilience are natural attributes of self-organizing communities.
- Human induced changes interfere with the natural development of ecosystems through the introduction of sediment, pollutants, and invasive species.

7.3 MAKING MANAGEMENT PLANS OPERATIONAL

Broad goals need to be translated into specific management objectives for planning purposes, and indicators used to measure these objectives need to be identified. The paragraphs below define management objectives and key indicators more precisely, and how they are used to guide the planning process.

Management objectives. Objectives are specific means for achieving the stated management or project goals. Any proposed intervention or restoration actions should be designed to meet the explicit operational objectives. Note that certain objectives may be in direct conflict with each other (e.g. ecological and human use objectives), and there may not be one restoration alternative that is capable of achieving every objective. Therefore, various restoration alternatives can be developed with the intent of satisfying as many different objectives as possible, and then be compared to evaluate their relative ability to meet project objectives. Figure 7-3 provides a framework for this evaluation.



f igure **7-3**

Projecting the Future Evolution of Bolinas Lagoon

Using 'Operational' Conceptual Models to Establish Management Actions

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Key indicators. Selection of key indicators provides a simple method for measuring, either quantitatively or qualitatively, the degree to which each project objective is met. Key indicators are based on knowledge of the particular ecosystem, either through historical information prior to human disturbance or in relation to a “reference” system that exhibits the desired characteristics set by the management objectives. Once indicators have been selected, the next step is to determine acceptable and desirable levels for them. Note that certain indicators provided below may be too specific to be evaluated at the conceptual level. However, these indicators are still included because they may be important for planning future project phases and/or long-term monitoring and adaptive management.

Targets. Each key indicator will have a threshold target value or a range of target values specified, one limit being the tolerable level and the other being the desirable. Some target values are based on absolute criteria that are important in maintaining a desired ecosystem and other targets may be relative to a historic baseline or reference system with the desired characteristics. If the system crosses the threshold value or moves outside the specified range for a given indicator, remedial action might then be proposed to restore ecological integrity. We emphasize that the critical limits for these indicators may vary among wetland habitat types. Setting these critical limits would be the next step in the Project evaluation.

The plan should be based on an explicit conceptual model of Bolinas Lagoon in order to select appropriate physical and ecological indicators and to establish effective intervention measures that could be implemented, if needed, to return physical or ecological conditions to a desirable state. Based on the evaluation of purpose and need for intervention, we recommend developing a series of ‘operational’ conceptual models that describe how specific intervention actions can implemented to achieve each management objective (Figure 7-3).

Implementation of the Bolinas Lagoon adaptive management plan should consist of regular monitoring, analysis of this data, periodic revisions to the conceptual model, and implementation of pre-planned and appropriate intervention measures only if thresholds are exceeded. If target values are not exceeded, no action should be taken, and the monitoring program should continue. The analysis of monitoring data will also provide an opportunity to confirm or refute hypotheses established in the conceptual model and to assess the accuracy of the predicted Lagoon evolution.

7.4 SUGGESTED MONITORING AT BOLINAS LAGOON

Monitoring of physical and biological indicators is recommended to document whether or not shifts in morphologic units, habitats, and populations of plants and animals are occurring as projected, and to reduce gaps in our understanding of how the ecosystem of Bolinas Lagoon functions. Based on our understanding of the physical and ecological lagoon functions, we have identified the following key uncertainties that can potentially be addressed through continued monitoring:

- How will future declines in tidal prism affect the potential for inlet closure?
- Will the effects of wind waves over exposed portions of Bolinas Lagoon prevent marsh vegetation from establishing on presently unvegetated mudflats?
- Will Pine Gulch Creek delta continue to advance into the lagoon interior at its 20th century rate?
- How quickly will the rates of sediment accumulation and tidal prism loss decelerate as Bolinas Lagoon approaches a new equilibrium form?
- Are habitat changes and ecological functions changing as expected?

We recommend that the MCOSD identify individuals or institutions to collect, manage, and interpret the monitoring elements outlined below. Data management and interpretation are crucial to making monitoring data useful. We suggest that once monitoring data have been interpreted and reviewed, essential findings be presented to MCOSD and BLTAC. In addition to monitoring, we recommend that the management goals and objectives for Bolinas Lagoon be revisited, and possibly revised, based on the new information developed as part of the present study.

7.4.1 Monitoring Physical Elements

Given our understanding of the most important cause-and-effect linkages between physical processes and the ecological functions, we recommend regular monitoring to track changes in the following key uncertainties. The proposed monitoring is intended to confirm our projections of future habitat distribution and manage risks associated with possible inlet closure.

- **Key Indicators of Inlet Closure.** If the inlet is closed for any period of time, the potential for more drastic changes in salinity could occur. For example, if it is closed in the summer months, the lagoon is likely to become hypersaline as evaporation increases salinity levels above that of normal seawater. Lagoon systems that are closed in summer also undergo a rapid decrease in dissolved oxygen as dying organisms' use of the oxygen increases in the water column. Fish kills and a decrease in the diversity of benthic invertebrates is a likely outcome as has occurred in San Dieguito and Batiquitos Lagoon when they close in the summer. If the Bolinas Lagoon were to close in the winter, freshwater will build up behind the lagoon, flooding salt marsh areas and converting them to more brackish water wetlands. Mudflats will become flooded, reducing foraging habitat for migratory birds in the fall and/or spring. In some cases, marine organisms that require certain breeding cycles will be disrupted by the closure.

  Our analysis predicts that the lagoon will not close in the next 50 years; however, we recognize the ecological significance of maintaining an open connection to the ocean. Therefore, we recommend monitoring the lagoon to confirm that closure is not imminent due to the projected progressive decrease in tidal prism and the consequent increase in closure potential. Since the tidal range inside the lagoon and the size of the inlet are expected to change prior to closure, we recommend monitoring the following key indicators:

- *Tidal range inside Bolinas Lagoon.* Installation and maintenance of a continuously recording tide gage will allow long-term trends in tidal range to be established, and potentially provide an early sign of changes to inlet closure. Gradual increases in the mean low-water elevations inside Bolinas Lagoon could indicate a reduction in the effective tidal prism of the lagoon and signal a substantial reduction in inlet stability.

- *Changes to the size of the tidal inlet.* The size of the inlet continually varies in response to the wave climate and tide conditions. However, long-term reductions of the inlet could indicate significant increases in closure potential if these trends fall outside of the seasonal variability. Inspection of cross-sections collected at the inlet 'throat' each spring and fall could also help interpret tidal observations.

The proposed tide gauge installation and monitoring of the inlet cross section would inform management decisions in light of the existing uncertainties regarding closure potential. These uncertainties results from two sources: (1) the threshold value of the O'Brien stability index that actually induces closure, and (2) uncertainties in our projection of future tidal prism.

- **Equilibrium Mudflat Elevation.** Elevation transects collected from 1968-2004 suggest that mudflats exposed to the dominant winds reach a relative balance between erosive and depositonal processes. This balance is largely responsible for limiting future expansion of salt marsh and maintaining tidal prism values sufficient to keep an open connection to the ocean. Although monitoring data indicate that exposed mudflats remain below colonization elevations, the precise equilibrium elevation is uncertain. Furthermore, the ultimate equilibrium elevation of mudflats is crucial to the extent of future salt marsh and tidal prism (a 1-ft variance in elevation of the Year 50 Frequently Submerged Mudflats would result in about 0.5 MCY change in tidal prism).

  We recommend regular surveys of elevation transects to confirm that mudflats exposed to the dominant winds remain below colonization elevations, and that deposition and erosive processes are in relative balance. Collection of elevation data along a few key transects could provide other useful information as well, such as the rate at which Pine Gulch Creek continues to advance into the lagoon interior.

- **Net Sediment Accumulation and Tidal Prism Change.** The decadal bathymetric surveys from 1968 to 1998 provide a data set unique to coastal California, and allow for the cumulative effect of change across all of the geomorphic units to be assessed in the form of tidal prism and net sedimentation. We recommend continuing the practice of decadal surveys. This will allow for projections of future changes in tidal prism and net sedimentation to be confirmed.

In addition to the monitoring described above, we recommend that estimates of future sea level rise be reviewed and incorporated into our projections of future lagoon conditions as this information becomes available. Recent studies regarding ice sheet melt in Greenland and Antarctica may lead to the IPPC estimates of future sea level rise used in our analysis to be revised upward. We recommend the revised estimates of sea level rise be reviewed after their publication. If appropriate, this new information should be incorporated into the models of lagoon evolution and the 50-year projection updated.

7.4.2 Monitoring Biological Elements

Monitoring of biological indicators is recommended to document whether or not shifts in morphologic units and the associated ecological responses are occurring as projected. Monitoring should be conducted at 5-year intervals, and should focus on a few key species as indicators of system response. For example, in combination with measures of tidal range, much could be learned from a routine survey of the relative abundance and elevational distribution of alder, alkali bulrush, salt grass, pickleweed, and cordgrass. The proposed field work to relate plant species to tidal elevation or inundation regime could lead to the development of such practical indicators. However, some populations of mobile species of wildlife, including especially the Coho run in Pine Gulch and the migratory shorebirds and waterfowl that use the system, are obviously very important. Some of the indicators should be faunal, if a comprehensive assessment of system condition and response to management actions is to be developed.

Several biological indicators of ecosystem function are available at Bolinas Lagoon. Among them are vegetation, invertebrates, fish, birds, and harbor seals. Perhaps the best indicators are the populations of predators in the higher trophic levels. At Bolinas Lagoon, birds, such as egrets and herons, and harbor seals represent high trophic levels.

- **Habitat Extent and Composition.** To monitor gradual, long term changes to habitats, aerial mapping of wetland habitats and vegetation transect sampling are recommended. The six transects established and sampled by WRA biologists during spring 2004 can be monitored to measure changes in vertical habitat distribution, plant species elevation, and plant species composition.

  In addition, we recommend NWI and morphologic unit mapping to monitor changes in aerial extent of wetland types defined by hydroperiod, substrate type, and vegetation cover. Mapping should be conducted using aerial photographic interpretation. In order to detect changes in aerial extent of habitat types against Year 0 using aerial images, the images would have to be comparable. The images need to be standardized for time of tide, time of year, pixel resolution, spectra, and error of rectification, e.g., any apparent differences between the images.

- **Invertebrates.** Benthic invertebrates represent an important food source for numerous species of fish and birds at Bolinas Lagoon. Data collected from regular monitoring of invertebrate communities at designated sampling locations could indicate gradual changes in the distribution of morphological units in the lagoon. Such changes may have already resulted in the current decline in the Washington and gaper clams.

Monitoring should be conducted at sampling points established during previous surveys. Data from previous surveys can be used as a baseline with which comparisons on diversity and abundance can be made. In addition, it may be possible to determine if a correlation exists between changes in morphological units and invertebrate community structure, and changes in fish and bird communities.

- **Fish.** Fish are an important prey item for other fish, many bird species, and marine mammals. Commercial fishermen have noted declines in populations and individual size of some fish species in the lagoon over the past several decades. Such changes in fish community structure may be contributing to declines in some fish-eating diving birds (PRBO Conservation Science data). The California Department of Fish and Game conducted several fish community surveys in Bolinas Lagoon between 1994 and 2002. Data collected during these surveys generally support the claims of commercial fishermen, and provide valuable baseline information for future comparison.

  Data collected from regular monitoring of fish communities at designated sampling locations could indicate the effect of gradual changes in the distribution of morphological units in the lagoon. It is recommended that future monitoring of fish diversity and abundance use similar methodologies as those established by the California Department of Fish and Game.

- **Birds.** It is important to note that the majority of birds that occur at Bolinas Lagoon are seasonal, and that significant impacts to their abundance may occur hundreds or thousands of miles away. The effects of relatively minor shifts in mudflat elevation on shorebird diversity and abundance may be difficult to isolate from other possible causes. For example, significant annual variation in the abundance of several wintering waterfowl species occurs at Bolinas Lagoon (PRBO Conservation Science data). It has been documented that wintering numbers of some duck species vary considerably depending upon weather conditions on their breeding grounds in the northern plains or arctic tundra (Kaufman, 1996).

  PRBO has been collecting annual winter population data for several bird species representing a number of feeding guilds since the 1970's. These data provide an excellent baseline for future studies. It is recommended that these wintering populations continue to be closely monitored. If the Bolinas Lagoon populations show a decrease over time, and other populations remain stable, it could be assumed that some factor within the lagoon is affecting the local population. Because the majority of wintering birds visit the lagoon to feed, declines may be associated with decreases in prey abundance and/or availability. A rapid decline is not expected to occur if the shifts in morphologic units occur as projected; however, noticeable declines in the numbers of some bird species may represent a threshold of changes in prey abundance and availability for more specialized feeders, and/or could indicate that the shifts in the distribution of morphologic units are occurring more rapidly than expected.

- **Harbor Seals.** Harbor seal populations and habitat use have been well documented in Bolinas Lagoon. There is an increasing population trend for this species at Bolinas Lagoon. If the population decreases significantly over several years, it may indicate a reduction in the availability of haul-out sites and/or preferred prey.

- **Spartina altniflora.** Establishment of invasive Atlantic cordgrass (*Spartina alterniflora*) in Bolinas Lagoon would be a significant threat to native plant communities and habitats. It grows at higher and lower elevations than the native California cordgrass (*Spartina foliosa*), reducing mudflat and shorebird habitat and replacing pickleweed and other high marsh species. It can also alter tidal circulation by colonizing channel bottoms. In addition, it hybridizes with the native cordgrass and could lead to extirpation of the native species over time. Atlantic cordgrass was identified in 2003 Bolinas Lagoon by the San Francisco Estuary Invasive Spartina Project (ISP), a project of the California State Coastal Conservancy and eradicated by Marin County Open Space District and ISP. Reliable morphological characters are not presently known that can be used to positively identify hybrids of *S. alterniflora* and *S. foliosa*. ISP collects samples of suspected invasive cordgrass and conducts genetic testing to determine presence of hybrids with native *S. foliosa.* Ongoing monitoring for *S. alterniflora* in Bolinas Lagoon is conducted by Marin County Open Space District, Audubon Canyon Ranch and ISP. A monitoring plan for Bolinas Lagoon should be developed that includes reporting on the ongoing monitoring and invasive control efforts.

All biological indicators should be considered together locally and within a regional context to determine if population changes are associated with local conditions, or are the result of conditions unrelated to the lagoon. Comparison with studies conducted through other regional monitoring programs may help to interpret trends that are a result of broader drivers rather than local. For example, changes in fish abundance that resulted in decreasing numbers of egrets, herons, and harbor seals at Bolinas Lagoon may be significant if similar events were not being documented in other coastal lagoons and estuaries. Additional research could then be focused on whether the causes of the shifts were natural or anthropomorphic, and if intervention is necessary.

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APPENDIX A
FIELD STUDIES: ESTABLISHING BASELINE CONDITIONS

APPENDIX A
Biological Field Studies: Establishing Baseline Conditions

In order to evaluate the need for a management action associated with preserving and/or enhancing Bolinas Lagoon habitats and to gain a clearer understanding of implications related to possible adaptive management strategies, the shift in the ecological function due to habitat change over time must be understood. Previous analyses of habitat types within the lagoon were too broad and did not reflect the detail necessary for understanding the ecological shift in lagoon function. A clearer understanding of this shift in function can be achieved by examining the change in habitat quantity and diversity, related to lagoon sedimentation, over time.

With the goal of determining whether a significant change in the type, amount, and distribution of habitat has occurred, a characterization of the current mix of habitats was undertaken to address the significance of these ecological elements and to provide baseline conditions for future adaptive management actions.

A.1 FIELD METHODS

During Spring 2004, field surveys were conducted by WRA biologists in Bolinas Lagoon to characterize baseline (YR 0) conditions. The purpose of these studies was to address data gaps associated with existing Lagoon habitats and species. The goal of baseline characterization studies was to generate a more meaningful projection of potential habitat and species abundance and distribution that may be expected in YR 50. The following studies were conducted:

- Habitat Distribution and Composition
- Special status species surveys and habitat quality assessment
- Invertebrate sampling
- Eelgrass bed mapping

Six transect baselines were established at six non-random locations throughout the Lagoon to sample the following parameters: (1) spatial and vertical habitat distribution, (2) vegetation composition and percent cover, and (3) substrate texture. These parameters were recorded for each sample point along a transect baseline at the following locations across the Lagoon:

- Kent Island
- Pine Gulch Creek delta
- North Basin
- Eastern Shore adjacent to Highway One (two locations)
- South Arm near the mouth of Eskoot Creek

A.1.1 Wetland Habitat Distribution and Composition

A wetland habitat evaluation was conducted to characterize the current mix of habitats to determine whether a significant change in the type, amount, and distribution of habitat has occurred in relation to

Lagoon accretion, or is expected to occur over a 50-year trajectory. Habitat mapping and characterization studies were conducted to describe the types of habitats present and measure their horizontal and vertical extent. Lagoon habitats evaluated during mapping and characterization field studies include low-, mid-, and high-elevation salt marsh; brackish marsh; and riparian. It should be noted that habitat types evaluated during field studies are not ecologically discreet communities, but represent a continuum of conditions that exist across the tidal range.

A.1.1.1 Habitat Distribution

Spatial Distribution: Wetland Habitat Mapping and Classification

Classification. Wetland habitats were mapped and classified throughout the Lagoon, according to the USFWS Cowardin Wetland Classification System (1979). The hierarchical structure of this classification system is composed of three levels: System, Subsystem, and Class. There are four systems present in Bolinas Lagoon: Marine, Estuarine, Riverine, and Palustrine, each containing several subsystems. The Marine system consists of the open ocean overlying the continental shelf and its associated high-energy coastline. The Estuarine system is the most commonly mapped system in the Lagoon. This system consists of deepwater tidal habitats and adjacent tidal wetlands that are usually semienclosed by land but have open, partly obstructed, or sporadic access to the open ocean. The Riverine system includes all wetlands and freshwater habitats contained within a channel with water containing less than five ppt ocean-derived salinity. The Palustrine system includes all nontidal wetlands dominated by trees, shrubs, and emergent vegetation.

Systems and subsystems have similar hydrological, geomorphological, chemical, and biological mechanisms within each of their respective categories. Dominant plant communities and physiography and composition of the substrate describe the Class level. Water Regime Modifiers apply to Classes. This category considers specific hydrologic conditions that affect the periodicity and duration of inundation. Special Modifiers describe wetlands that have been created or highly modified by human activities. This includes wetlands that are diked or impounded, excavated, farmed, drained or ditched, grazed by cattle, filled with artificial substrate, or dammed by beavers. A diagram illustrating the Cowardin classification hierarchy is provided in Figure A-1. Once a wetland was evaluated and classified, it was assigned a mapping code developed by the National Wetlands Inventory (NWI), a division of USFWS. This code is derived from the USFWS Cowardin Wetland Classification System. A description of mapping codes is provided in Table A-1.

Mapping. Wetland boundaries were created by heads up digitizing, using multi-spectral ultra high-resolution ($1m^2$) ortho-imagery acquired in October of 2001 and two-foot contour data. Wetland boundaries and classification types were field-verified to achieve greater accuracy. Wetland polygons were classified according to a hierarchical structure that includes: system, subsystem, class, subclass, and water regime modifier. Each polygon was then assigned a corresponding NWI mapping code. A map of USFWS wetland types was produced, using the multi-spectral ortho-imagery as a backdrop.

Vertical Habitat Distribution

Each transect characterized the elevational range or vertical distribution of the following wetland habitats: riparian, fresh and/or brackish marsh, and high, mid, and low tidal marsh. The vertical distribution of habitat types was measured with a laser level; surveyed elevations were referenced to temporary (but stable) benchmarks and then referenced to local tidal datums, once they were reckoned. Vegetation surveys were conducted along transect baselines that ran from higher to lower elevation. The baseline was set up with 0 at the top of the slope, usually within a riparian zone, and a measuring tape was pulled out to the mudflat edge. The tape spanned across all habitat types present at each location.

Habitat boundary determinations were estimated based on topography and species composition during field sampling. Assemblages of certain key species denoted each habitat type. The upper limit of high marsh was delimited by the dominance of salt marsh species. For example, cord grass cover was highest in low marsh; pickleweed cover tended to be highest in mid and high marsh; and high marsh supported a mix of species and generally had the greatest diversity of species as compared to the other tidal marsh zones. With the exception of one location, sample points were established along the transect baseline at the upper, middle, and lower boundary of each habitat to characterize the ecotone or transitional zone between habitats and approximate mid-point of each habitat. The number of sample points varied from eleven to six, depending on the number of habitats present.

A.1.1.2 Habitat Composition

Plant Species Composition and Cover

Vegetation composition and cover was estimated within a circular plot with a five-meter radius at each sample point location along the transect baselines. Plants were identified to the species level. See Table A-2 for a list of species observed. Absolute cover was estimated for all plant species observed in each of four quadrants and recorded on a data sheet. All transect baselines were photo-documented at the time of data collection.

Substrate Texture

Soil samples were collected at select sample points representing low, mid, and high marsh. These samples were then sent out to a Cooper Testing Laboratory for particle size analyses. A sieve analysis was conducted that (particle size or gradation) included most sieve sizes down to #200 (75 microns). If the particle size distribution was below what the #200 sieve accommodated, then a hydrometer was run in addition to the sieves.

These field data were tabulated, summarized and analyzed; methods of data analyses are discussed below.

A.1.2 Botanical and Wildlife Surveys and Habitat Assessment

Special status species include those plants and wildlife species that have been formally listed, are proposed as endangered or threatened, or are candidates for such listing under the federal Endangered Species Act (ESA) or California Endangered Species Act (CESA). These Acts afford protection to both listed and proposed species. In addition, California Department of Fish and Game (CDFG) Species of Special Concern, which are species that face extirpation in California if current population and habitat trends continue, and U.S. Fish and Wildlife Service (USFWS) Species of Concern are considered special status species. Although California and USFWS Species of Concern generally have no special legal status, they are given special consideration under the California Environmental Quality Act (CEQA).

In addition to regulations for special status species, most birds in the United States, including non-status species, are protected by the Migratory Bird Treaty Act of 1918. Under this legislation, destroying active nests, eggs, and young is illegal. Plant species on California Native Plant Society (CNPS) Lists 1 and 2 are also considered special status plant species. Impacts to these species are considered significant according to the California Environmental Quality Act (CEQA). The CNPS List 3 and 4 plants have little or no protection under CEQA, but are included in this analysis for completeness. The survey and habitat assessment also included species of local concern as indicated by the USFWS list for the Bolinas USGS quad.

Surveys were previously conducted in the Lagoon that documented the occurrence of special status species within Bolinas Lagoon (DEIR 2002). However, distribution of special status species that are likely to occur within the Lagoon and their potential suitable habitat that they may use was not mapped or considered in the selection of alternatives for the proposed dredging project. WRA conducted more in-depth studies covering the occurrence and distribution of special status species in the lagoon to address this data gap. Literature and database searches were conducted to verify potential rare plant and wildlife species that may occur in the Lagoon and to update special status plant and wildlife species' listings for 2004. These sources included CNDDB, peer-reviewed journal articles, anecdotal birding records (internet list-serv sites), and unpublished biological reports pertinent to the Lagoon's biological resources. Using information collected during the literature search, WRA performed surveys and habitat assessments to evaluate suitability of the Lagoon to support potentially occurring special status species.

Special Status Plant Surveys

Compiling information generated in the background information search, a table of potentially occurring species, with their protection status, habitat requirements, and likelihood to occur in the Study Area was generated (Table A-3). It is important to note that surveys included only species known to occur in habitats similar to those found in the Lagoon: coastal salt marsh, coastal dune, freshwater marsh, and riparian. Several additional species came up during the literature search of the Bolinas quad that typically inhabit forest, woodland, chaparral, grassland, and coastal scrub habitats; these species have potential to occur, or are known to occur, in the vicinity of, but not within Bolinas Lagoon itself. A master list of all species observed throughout the Lagoon during field surveys is provided in Table A-2.

Due to the size of the surveyed area and complexity of habitat distributions, separate lists were compiled for four regions of the Lagoon: Kent Island, Pine Gulch Creek Delta, the North Basin/Eastern Shore, and the South Arm near the mouth of Eskoot Creek. These lists are provided in Table A-4.

Rare plant surveys corresponded to peak blooming periods for observing and accurately identifying rare plant species with potential to occur in the Lagoon. All plants encountered during the survey were identified, using The Jepson Manual (Hickman 1993), to the taxonomic level necessary to determine whether or not they were rare. The surveys followed the protocol for plant surveys described by Nelson (1987). One early season rare plant field survey was conducted on May 5, 2004. An additional late season rare plant survey took place on June 11, 2004.

Special Status Wildlife Surveys

The focus of the special status wildlife species assessment included review of documents and literature describing biological resources, and fieldwork in and surrounding Bolinas Lagoon. WRA also contacted local biologists regarding the status of waterbirds, shorebirds, snowy plovers and California red-legged frogs at the Lagoon. Fieldwork involved a preliminary evaluation of habitat suitability for special-status wildlife species expected to occur in the lagoon or in the immediate upland vicinity of the lagoon.

Potential occurrence of special status species in the Bolinas Lagoon area was evaluated by first determining which special status species occur in the vicinity of the Lagoon through a literature and database search (Table A-5). Database searches for known occurrences of special status species focused on Marin County. The following sources were reviewed to determine which special status wildlife species have been documented to occur in the vicinity of the Lagoon:

- California Natural Diversity Database records (CNDDB) (CDFG 2005)
- USFWS Quadrangle Species Lists (USFWS 2005)
- CDFG publication “California’s Wildlife, Volumes I-III” (Zeiner et al. 1990)
- CDFG publication “Amphibians and Reptile Species of Special Concern in California” (Jennings 2004)
- Bolinas Lagoon Draft Environmental Impact Statement/Report and Draft Feasibility Report, Bolinas Lagoon Ecosystem Restoration Project (U.S. Army Corps of Engineers and Marin County Open Space District

A site visit was conducted to search for suitable habitats within the Lagoon for those species identified as occurring within the vicinity. Potential for special status species to occur in the Lagoon was then evaluated according to the following criteria:

(1) <u>Not Present</u>. Habitat on and adjacent to the Lagoon is clearly unsuitable for the species requirements (foraging, breeding, cover, substrate, elevation, hydrology, plant community, site history, disturbance regime).

(2) Low Potential. Few of the habitat components meeting the species requirements are present, and/or the majority of habitat on and adjacent to the Lagoon is unsuitable or of very poor quality. The species is not likely to be found in the Lagoon.

(3) Moderate Potential. Some of the habitat components meeting the species requirements are present, and/or only some of the habitat on or adjacent to the Lagoon is unsuitable. The species has a moderate probability of being found in the Lagoon.

(4) High Potential. All of the habitat components meeting the species requirements are present and/or most of the habitat on or adjacent to the Lagoon is highly suitable. The species has a high probability of being found at the Lagoon.

(5) Present. Species is observed at the Lagoon or has been recorded (i.e. CNDDB, other reports) there recently.

Marin County was searched for relevant CNDDB occurrence records. Table A-5 presents the special status wildlife species with a potential to occur within the Lagoon, their habitat requirements, and a rating of potential for occurrence.

Field surveys also included daytime and nighttime protocol-level California red-legged frog surveys. These surveys were conducted in streams that flow into the Lagoon, including: Pine Gulch, Lewis Gulch, Wilkins Gulch, Pike County Gulch, Audubon Canyon Creek, Volunteer Canyon Gulch, Morses Gulch, McKinnen Gulch, and Stinson Gulch. Aquatic habitat adjacent (east and west) to Highway 1 was surveyed; Pine Gulch and Lewis Gulch were surveyed from the Bolinas/Fairfax road to their outlet in the Lagoon. No California red-legged frogs were observed during these surveys.

Invertebrate Sampling

Nineteen invertebrate samples were collected from various locations throughout the Lagoon. Elevation and GPS data were also collected at each sampling location. These samples were sent to an aquatic ecologist for identification and estimation of relative abundance of species present at varying lagoon locations and elevations. These data were summarized and analyzed and presented on graphs (Figures A-2 through A-4).

Eelgrass Bed Mapping

Prior to performing the field survey, aerial photographs and bathymetric maps of the Lagoon were examined to gain a large- scale perspective of potential eelgrass abundance and distribution. An in-water aerial eelgrass survey was performed from a kayak during a daylight low tide on August 4, 2004. The time of survey coincided with the peak growth period for eelgrass in the San Francisco Bay area. Subtidal channels and shallows were traversed along transects running approximately north to south to determine presence or absence of eelgrass. Areas identified as suitable for eelgrass growth, based on review of available data, were carefully searched. A sub-meter accuracy Global Positioning System (GPS) unit was on board the kayak during the survey to map the location of any eelgrass beds that may have been observed.

A.2 DATA ANALYSIS METHODS

Field data collected along six transects were summarized and analyzed. These data included plant and invertebrate species' composition and elevations, sediment texture (percent sand content) in high, mid, and low marsh habitats, and distance between sample points (length of each sampled habitat type). These were tabulated and analyzed according to the following methods:

Species vs. Elevation

Target plant and invertebrate species' elevation ranges were plotted for the all six sample sites. The elevation median and range (ft) of each plant species was plotted on a chart in Excel. Tidal datums were added to both charts.

Species Frequency vs. Elevation

To gain a more meaningful interpretation of the species-elevation correlation, the frequency of each target species at a particular elevation was also plotted. Frequency refers to the number of times a species or taxon was sampled at a particular elevation. Horizontal histograms were created for each plant species (17 plant species) and each invertebrate taxon (10 categories) showing their distribution across elevation. The frequencies of each species and taxon in each elevation bin was then plotted on vertical area graphs. All graphing was done using SigmaPlot 9.0. Tidal datums were added to all fitted line plots.

Transect Slope

Scatterplots of elevation vs. distance (length of transect) were created for each transect using both MINITAB (version 14) and SigmaPlot (version 9.0). A linear regression of elevation on distance was done for each transect (MINITAB). A regression line was fitted to the data of each transect. The slope of each transect was taken from the regression equation for each transect and converted to a percentage. Tidal datums were added to all fitted line plots.

Texture vs. Distance

A grouped bar graph was created in SigmaPlot 9.0. Percent sand in each transect was plotted against distance from the inlet and each transect was divided into habitat (high, mid, and low marsh). Separate graphs (scatterplots and bar graphs) with regression lines were also created for each of the three habitat types.

A.3. FIELD MONITORING RESULTS

A.3.1 Habitat Transect Sampling

The elevational distribution, slope, and composition of habitat types in the lagoon was characterized by transect sampling at six locations throughout the Lagoon.

Habitat Elevation and Slope

Elevations at which various habitat types were observed and slopes of sampled habitat transects varied across the lagoon. The East Shore of the lagoon is situated along the main channel of Bolinas Lagoon and is relatively steeply sloped, and exposed to wind-wave action that continuously erodes mudflats and salt marsh. Subsequently, tidal marsh exists as a narrow fringe in this region of the lagoon. Habitat transitions are abrupt and the number and amount of distinct habitat types is lower than other lagoon locations. On the other hand, the North and Western Shore of the lagoon support a gradually sloped, broad marsh plain that is sheltered from wind-wave action. Gradual habitat transition were observed in these areas, supporting well developed riparian, brackish, and salt marsh habitat zones.

The following section describes the surveyed habitats in terms measured elevation ranges and slope. The width and elevation of habitat types for each of six transects was measured using GPS and a laser level. Maps illustrating transect layouts are provided as Figure A-5. Table A-6 contains elevation ranges of each observed habitat type at six lagoon locations. These data are plotted on a graph provided as Figure A-6. Transect slopes are plotted on graphs in Figure A-7.

Habitat boundary determinations were estimated based on topography and species composition during field sampling. The division between mid and high marsh was not as sharp as other habitat transitions. High marsh often had overall higher species richness and a greater proportion of saltgrass, jaumea, and alkali heath as compared with the mid marsh zone. Areas identified as mid marsh occurred at all sample site locations throughout the lagoon. The high marsh-low marsh boundary was delineated by a decline in species richness, i.e. a dominance of pickleweed and a visual break in topography. The lower boundary of mid marsh was determined by the edge of cordgrass, a dominant species in low marsh. Areas identified as cordgrass dominated marsh occurred at the lowest end of the transects, situated between mid marsh and frequently exposed mudflats.

North Basin (Transect 1). This area is represented on Figure 5-7 as a transitional morphological unit and supported a complex of freshwater and tidally influenced habitats along the northern shore of the lagoon. Sampled elevation ranged from 9.81 ft NAVD88 at the upper end of the riparian zone to 3.98 ft at the low marsh/mudflat interface. Measured slope of the habitat transect was –0.54%. A narrow fringe of brackish marsh, situated in a transitional zone between riparian and tidal marsh habitats, was dominated by alkali bulrush (*Scirpus maritimus*). The high marsh occurred within a narrow elevation band, from 5.81 to 5.83 ft NAVD88, and was dominated by saltgrass (*Distichlis spicata)*. Mid marsh, dominated by pickleweed, extended down to 4.84 ft, and low elevation, cordgrass-dominated marsh extended down to 3.98 ft NAVD88.

Pine Gulch Creek Delta (Transect 2). The mouth of Pine Gulch Creek is situated on a fluvial delta and supports riparian, brackish and salt marsh habitats, as illustrated on PWA's map of morphological units and habitats (Figure 5-7.) Sampled habitat elevations ranged from 10.79 ft NAVD88 at the upper riparian boundary to 5.02 ft at the mudflat edge. Measured slope of the habitat transect was –0.45%, this area had the lowest slope of all six sampled sites. Riparian vegetation extended down to 7.12 feet; brackish marsh, dominated by Baltic rush (*Juncus balticus*) and coastal cinquefoil (*Potentilla anserina* ssp. *pacifica*) extended to 6.24 ft; and high marsh, supporting predominantly saltgrass and alkali heath (*Frankenia salina*) was measured down to 5.26 ft. With the exception of Kent Island, this site was unique in that it did not support a cordgrass-dominated low elevation marsh. Pickleweed dominated marsh extended down to the edge of unvegetated mudflats. Pine Gulch Creek Delta had the highest low marsh/mudflat interface of all sampled sites, measured at 4.94 ft.

Kent Island (Transect 8). Kent Island is a flood tide shoal supporting a broad salt marsh plain along its northern and eastern portions, situated at the mouth of Bolinas Lagoon. Unlike other sampled areas, Kent Island did not have freshwater source to create a transitional marsh zone. The transect spanned from coastal dune at its upper edge of 6.49 ft NAVD88 to sandy intertidal flats at 4.58 ft. Measured slope of the habitat transect was –0.50%. The area identified as high marsh supported a relatively diverse mix of saltgrass, alkali heath, arrow grass (*Triglochin concinnum*), pickleweed, fleshy jaumea (*Jaumea carnosa*), and sea lavender (*Limonium californicum*). Low elevation marsh, measured below 4.77 ft NAVD88, supported both cordgrass and pickleweed.

East Shore (Transect 4 and Transect 5). On the east shore of the lagoon along Highway 1, narrow tidal marsh fringe was sampled along small fluvial deltas situated along the main channel of the lagoon, Sampled areas along the east side of the lagoon along Highway 1 were relatively steeply sloped comparison with other sampled areas. Measured slopes were –0.75% (4) and –1.64% (5). Riparian habitat of these areas extended from just below MHW elevation to 6.53 ft NAVD88 (Transect 4) and 4.63 ft (Transect 5). These areas did not support areas identified as high marsh. The lowest low marsh/mudflat interface was measured at Transect #4, just above MSL (3.26 ft NAVD88) at 3.08 ft NAVD88. Transect #5 along the lagoon's East Shore did not support an area identified as low marsh, likely due to exposure to erosive forces of continuous water movement.

South Arm (Transect 6). The south end of Bolinas Lagoon is predominantly salt marsh plain dissected by several narrow channels with limited mudflat area. Unlike other lagoon transect locations that ran along a gradient from higher to lower elevation habitats, this region of the lagoon had undulating topography, as shown on the slope graph in Figure A-7. Riparian habitat was sampled at both ends of the transect where freshwater entered the Lagoon from hillside seeps. This area did not support distinct transitions between high, mid, and low marsh along a consistent elevational gradient. Narrow bands of alkali bulrush (*Scirpus maritimus*)-dominated brackish marsh, saltgrass and pickleweed dominated high to mid marsh, and cordgrass-dominated low marsh along channels were sampled in between.

Key Plant Species Elevations

Key or dominant species were identified from the plant composition data collected during field surveys in Spring 2004. Key species were commonly observed species that usually occurred in more than one habitat type, but were dominant within a particular habitat type. For example, willows tended to dominate riparian habitat, and monotypic stands of cordgrass were commonly observed in low elevation salt marsh. To illustrate the general elevational range of key species at the six sample sites, elevation values were plotted on a graph (Figure A-8). A separate graph was plotted to determine the frequency each species occurs at a particular elevation (Figure A-9). The results of these analyses are as follows:

The elevation distribution of plant species within Bolinas Lagoon corresponds to ecological gradients influenced by salinity, length of tidal inundation, and other abiotic factors. A typical species elevation model for San Francisco Bay tidal marshes would include cordgrass in low marsh, transitioning to pickleweed in mid elevation marsh, to saltgrass, alkali heath, and sea lavender in high marsh zones. Within the lagoon, several salt marsh species were observed at elevations that did not match expected species zonation patterns. For example, pickleweed, typically a mid to high marsh inhabitant, sometimes occurred in low marsh zones in Bolinas Lagoon. In addition, the elevation ranges of plant species sampled at six separate locations overlapped significantly. This finding of variable and overlapping plant elevations coincided with results from an unpublished plant elevation study in the lagoon, conducted by a graduate student at the University of California, Berkeley (Schmidt, unpubl.).

Figure A-8 shows the elevational range of plant species plotted for each of six sample sites in the lagoon. Cordgrass (*Spartina foliosa*) occurred at the lowest elevation of all the plant species (as low as 3.08 ft NAVD88) and is the only species to extend down to the MSL tidal datum. Arroyo willow occurs in the highest elevation of all the plant species (10.86 ft), though ranges of red alder and marsh parsley both extend up to 10.79 ft. Arroyo willow also has the broadest elevation range (6.23 ft, from 4.63 to 10.86 ft) salt marsh dodder (*Cuscuta salina* var. *major*) has the most limited elevation range (0.3 ft, from 5.94 to 6.24 ft). The median elevation for most species is between 4.50 ft and 6.50 ft. Red alder, marsh parsley, salt marsh dodder, and coastal cinquefoil (*Potentilla anserina* var. *pacifica*) were the only sampled species that occurred at elevations entirely above MHHW.

Figure A-9 shows the frequency at which each target plant species occurred at a particular elevation. The only species to occur below an elevation of 4 ft NAVD88 are *Spartina foliosa* and *Salicornia virginica*. Each transect ends at approximately 4 ft in low marsh habitat, which is a typical habitat for both species. Most species occur at elevations between 5-8 ft (mid marsh habitat). Species occurring at high marsh/riparian elevations (above 10 ft) include *Alnus rubra*, *Oenanthe sarmentosa*, and *Salix lasiolepis*. Many species that are present at elevations above and below 8ft are absent at 8 ft. These include: *Grindelia stricta*, *Distichlis spicata*, *Jaumea carnosa*, *Limonium californicum*, and *Scirpus maritimus.* The majority of the species have the highest frequency near the MHW and MHHW tidal datums.

Sediment Texture and Distance from the Inlet

Sediment texture was plotted against the distance from the lagoon inlet for all six transects in Figure A-10. Sediment texture was also plotted against habitat type in Figure A-11. Results of analyses show that in low marsh and mid-marsh habitats, there is a distinct trend between percent sand content and distance from the inlet. Percent sand generally decreases further from the inlet.

In high marsh, the trend is less detectable. There is a slight trend of percent sand decreasing further from inlet. This slope is so close to 0 that it's not reasonable to say that there is a relationship between percent sand and distance (p=0.16). Apart from the higher percent sand along the eastern shore of the lagoon at Transect #5, there is not a significant difference in percent sand at 1000 ft, 2000 ft, and 3000 ft.

It was determined that percent sand content decreased overall with distance from the lagoon inlet. Not surprisingly, based on our understanding of the dominant ocean source, the highest sand content was measured at Kent Island, and the lowest was at the North Basin.

A.3.2 Wetland Habitat Mapping

NWI wetland habitat mapping and classification efforts resulted in an exhaustive inventory of wetland resources present in the Bolinas Lagoon. Field biologists mapped 1500 acres of the lagoon and classified 31 wetland types, when displayed at the special modifier level used in the classification system. A map of these wetlands and key describing the categories is provided as Figure A-12 and Table A-1.

Physical processes control the distribution and abundance of habitat types in the Lagoon, which in turn control the distribution and abundance of indicator species. On this premise, PWA and WRA developed a consistent habitat typology to integrate physical and biological models so that geomorphic units were synonymous with major habitat types. This habitat typology was expressed as geomorphic units that would show expected responses of habitats to changes in elevation and hydroperiod during the 50-year trajectory. However, it should be noted each geomorphic unit is composed of several USFWS habitat types that were mapped and classified based on the system (estuarine, marine, or palustrine), substrate type, and duration/periodicity of inundation.

A.3.3 Invertebrate Sampling

Figure A-2 shows the observed elevational range of taxonomic groups of invertebrates plotted collected from 19 sites within in the lagoon. A map of these locations is provided as Figure A-13. Polychaetes, oligochaetes and the California horn snail are present at the lowest elevations (extending down to -11.03 ft). Polychaetes, other gastropods, and other crustacea are also present at the highest elevations (extending to 4.8 ft) though the upper range limit of all the sampled estuarine invertebrate taxa is around 4 ft. Polychaetes have the broadest elevation range (15.8 ft, from 4.8 to -11.03 ft). Other crustacea and the ghost shrimp each had only one occurrence. The median value for most invertebrates is between 2 and 4 ft.

Figure A-4 shows the frequency at which each key invertebrate taxonomic group or species occurred at a particular elevation. The highest frequencies for most invertebrates occurs around 4 ft. (near the MSL tidal datum). An exception to this is arthropods, which is are abundant between 0-2 ft. This group is the most abundant of all the groups of invertebrates, with 249 individuals occurring at 0.9 ft. Five groups have a secondary peak in frequency between 0-2 ft including Polychaeata, Oligochaeta, Nemertea, other gastropods, and clams. Polychaetes, Oligochaetes, and California horn snail are present down to the lowest elevations. Individuals in these groups are present to a depth of -11.03 ft. Polychaetes have the broadest range, extending from 4.8 ft down to -11.03 ft. The only invertebrates present at the MHW tidal datum are crabs. All other invertebrates occur below the MHW tidal datum.

A.3.4 Special Status Species Surveys

Plants

Of 27 potentially occurring special status plant species in Bolinas Lagoon, two special status plant species were found during late spring and early summer surveys that coincided with peak blooming periods of these species. Table A-3 list potentially occurring species that were surveyed for in Spring 2004. During the survey conducted on June 11, 2004, a Point Reyes bird's-beak (*Cordylanthus maritimus* ssp. *palustris*) population on the north side of Kent Island was censused and mapped using GPS. This is one of the largest single populations of Point Reyes bird's-beak in California. This species is afforded special protection as a Federal Species of Concern and a CNPS 1B species. A map of bird's beak occurrences is provided as Figure A-13. Although not observed during surveys conducted by WRA, two populations of Point Reyes bird's beak were noted along the eastern shoreline of Bolinas Lagoon at the McKinnan and Morses Gulch delta that were identified in 2002-2003 rare plant surveys by NPS biologists (D. Fong, pers. comm.). In addition, three species recognized as Species of Local Concern on the USFWS Bolinas USGS quad list were also observed during surveys: cordgrass throughout the Lagoon and California saltbrush (*Atriplex californica*) Kent Island, and johnny-nip (*Castilleja ambigua* ssp. *ambigua*) on Kent Island and Pine Gulch Creek delta.

Wildlife

Several special status wildlife species are known to occur at Bolinas Lagoon. Table A-5 list potentially occurring species that were surveyed for in Spring 2004. Federal-listed species that have been documented in the area include California brown pelican, western snowy plover, California red-legged frog, coho salmon, and steelhead. The California black rail is a state-listed species that has been observed in suitable tidal marsh habitat at the lagoon.

The California brown pelican does not nest in the lagoon; however, it forages for fish in sub-tidal channels and over frequently submerged mudflat.

The western snowy plover, which depends on sandy areas for breeding, historically nested on the beach at the tip of the Stinson Beach sand spit (MCOSD 1996) and on the sand beach of Kent Island (USACOE and MCOSD 2002).

California black rail has been documented to occur near the mouths of Pine Gulch Creek and Audubon Canyon (Evens, et al. 1986). The tidal wetlands in these and other areas of the lagoon provide suitable habitat for this species.

Although the California clapper rail has not been seen in the Lagoon for many years (G. Page, pers. comm.), a potential long-term benefit of projected tidal marsh succession in Bolinas Lagoon is the range re-expansion of the California clapper rail. Soon after Pacific cordgrass established in southern Tomales Bay, the first clapper rails were detected after decades of absence. Bolinas Lagoon may function as a stepping-stone population between Richardson Bay and Point Reyes clapper rail populations, and could be significant for its recovery (P. Baye, pers. comm.).

California red-legged frogs (CRLF) have been observed in the vicinity of the lagoon (USACOE and MCOSD 2002). A breeding location has been noted by NPS biologists in the seasonal wetland at the confluence of the lagoon and Wilkin's gulch. (D. Fong, pers. comm.). This species typically requires deep, perennial sources of fresh water for breeding. Tributaries and wetlands surrounding the lagoon provide suitable habitat for this amphibian.

Anadromous salmonids pass through the lagoon en route to many streams in the watershed, where they spawn. During a 1996 survey conducted by CDFG, steelhead were observed in Pine Gulch Creek. Anecdotal information suggests that coho salmon may spawn in Pine Gulch Creek (Bolinas Lagoon Foundation 2003).

The mosaic of habitats that are found in Bolinas Lagoon also provides suitable conditions for other special status wildlife species, including CDFG Species of Special Concern and USFWS Species of Concern. Several bat species likely forage over the lagoon. Many special status raptors, shorebirds, passerines, fish, and invertebrates potentially occur at Bolinas Lagoon.

Although most of these species are present only during a portion of their life cycle (breeding, foraging, and/or migration), the lagoon provides critical resources for survival. For example, special status shorebirds migrating along the Pacific Coast to and from Arctic breeding grounds include the lagoon as one of several locations to rest and feed.

A.3.5 Other Botanical Surveys

<u>Invasive Species</u>

It was noted during field surveys that five invasive plant species on Cal IPC List A were present in the lagoon: European beach grass (*Ammophila arenaria*), scotch broom (*Cytisus scoparius*), and iceplant (*Carpobrotus edulis*), cape ivy (*Delairea odorata*) and Himalayan blackberry (*Rubus discolor*). These species are documented as aggressive invaders that displace natives and disrupt natural habitats, posing a threat to the natural biodiversity of Bolinas Lagoon. Invasion by non-native plant species may increase the rate of sediment accretion or dune expansion, resulting in more rapid habitat change and reduce the quality of native habitats.

The accelerated accumulation of sand along the windward side of Kent Island has created a disturbed regime that is favorable for the establishment of non-native invasive plant species, namely European beach grass, scotch broom, and iceplant. The incursion of these exotic species likely indicates that this area is undergoing rapid change that has resulted in disturbance to native plant populations. European beachgrass, in particular, is an aggressive colonizer of beach areas that forms a dense mat of grass and rhizomes, unlike any of the native dunemat species. The beachgrass captures sand, decreasing natural sand movement, and causing the dunes to increase in height. Succession ensues toward colonization by other exotic plant species, until the integrity of the ecosystem is threatened.

Cape ivy and Himalayan blackberry were observed in riparian areas along Pine Gulch and the North Basin, and within small willow patches along the Eastern Shore. These plants are also known to spread rapidly, threatening the diversity of riparian areas along the lagoon.

<u>Eelgrass Beds</u>

One habitat type that has been in decline and may have disappeared based upon results of recent surveys, is eelgrass beds. Eelgrass beds were previously limited to subtidal channels near the mouth of the lagoon, but were not detected in August 2004 survey conducted during a daytime low tide (DEIR 20002). Eelgrass beds are important habitat for subtidal fish and are used by herring for egg laying and their lost, if sustained in the future, is significant. As a habitat that could be most affected by the loss of tidal prism, the distribution over time could also be an indicator of the health of the lagoon, particularly in subtidal areas. For example, in Batiquitos lagoon in southern California, eelgrass was eliminated once the lagoon had closed due to sedimentation, but recovered rapidly once the restoration project to restore the tidal inlet was completed.

Table A-1 Key to National Wetland Inventory Mapping Codes

NWI CODE	System	Subsystem	Class	SubClass	Water Regime Modifier	Special Modifier
E1UB2L	Estuarine	Subtidal	Unconsolidated Bottom	Sand	Subtidal	
E1UB3L	Estuarine	Subtidal	Unconsolidated Bottom	Mud	Subtidal	
E1US3N	Estuarine	Subtidal	Unconsolidated Shore	Mud	Regularly Exposed	
E2EM/US3N	Estuarine	Intertidal	Emergent/Unconsolidated Shore	Mud	Regularly Exposed	
E2EMN	Estuarine	Intertidal	Emergent	n/a	Regularly Exposed	
E2EMPh	Estuarine	Intertidal	Emergent	n/a	Irregularly Flooded--high marsh	
E2EMPm	Estuarine	Intertidal	Emergent	n/a	Irregularly Flooded--mid-marsh	
E2EMPmh	Estuarine	Intertidal	Emergent	n/a	Irregularly Flooded--mid-marsh	diked/impounded
E2RS2N	Estuarine	Intertidal	Rocky Shore	Rubble	Regularly Exposed	
E2UB2/AB1N	Estuarine	Intertidal	Unconsolidated Bottom/Aquatic Bed	Sand/Algal	Regularly Exposed	
E2US2N	Estuarine	Intertidal	Unconsolidated Shore	Sand	Regularly Exposed	
E2US2Pm	Estuarine	Intertidal	Unconsolidated Shore	Sand	Irregularly Flooded--mid-marsh	
E2US3M	Estuarine	Intertidal	Unconsolidated Shore	Mud	Irregularly Exposed	
E2US3N	Estuarine	Intertidal	Unconsolidated Shore	Mud	Regularly Exposed	
M2US2PN	Marine	Intertidal	Unconsolidated Shore	Sand		
M2US2Ph	Marine	Intertidal	Unconsolidated Shore	Sand	Irregularly Flooded--high marsh/above MHHW	
PEMB2	Palustrine	n/a	Emergent	n/a	Seasonally Saturated	
PEMB2h	Palustrine	n/a	Emergent	n/a	Seasonally Saturated	diked/impounded
PEMC2	Palustrine	n/a	Emergent	n/a	Seasonally Flooded/Seasonally Saturated	
PEMF	Palustrine	n/a	Emergent	n/a	Semipermanently Flooded	
PFOB2	Palustrine	n/a	Forested	n/a	Seasonally Saturated	
PFOC2	Palustrine	n/a	Forested	n/a	Seasnally Flooded/Seasonally Saturated	
PFOF	Palustrine	n/a	Forested	n/a	Semipermanently Flooded	
PSBF	Palustrine	n/a	Streambed	n/a	Semipermanently Flooded	
PSS/FOC1	Palustrine	n/a	Scrub-Shrub/Forested	n/a	Seasonally Flooded/Well Drained	
PSS/FOG	Palustrine	n/a	Scrub-Shrub/Forested	n/a	Intermittently Exposed	
PSSB2	Palustrine	n/a	Scrub-Shrub	n/a	Seasonally Saturated	
PSSB3	Palustrine	n/a	Scrub-Shrub	n/a	Permanently Saturated	
PSSC1	Palustrine	n/a	Scrub-Shrub	n/a	Seasonally Flooded/Well Drained	
PSSC2	Palustrine	n/a	Scrub-Shrub	n/a	Seasonally Flooded/Seasonally Saturated	
PSSC3	Palustrine	n/a	Scrub-Shrub	n/a	Seasonally Flooded/Permanently Saturated	
PSSF	Palustrine	n/a	Scrub-Shrub	n/a	Semipermanently Flooded	

* Based upon USFWS Classification of Wetlands and Deepwater Habitats of the United States (Cowardin et al. 1979)

Table A-2. Master list of all plant species observed during 2004 field surveys.

SCIENTIFIC NAME	COMMON NAME
Acer negundo	box elder
Aira caryophyllea	silver hairgrass
Alnus rubra	red alder
Ambrosia chamissonis	beach-bur
Ammophila arenaria	European beach grass
Anagallis arvensis	Scarlet pimpernel
Artemisia pycnocephala	beach wormwood
Athyrium filix-femina var. *cyclosorum*	lady fern
Atriplex californica	California saltbrush
Atriplex leucophylla	seascale
Atriplex triangularis	spearscale
Avena fatua	wild oats
Bromus diandrus	ripgut brome
Cakile maritima	sea rocket
Carpobrotus edulis	iceplant
Castilleja ambigua ssp. ambigua	johnny-nip
Cirsium vulgare	bull thistle
Claytonia perfoliata	miner's lettuce
Conium maculatum	poison hemlock
Cordylanthus maritimus ssp. palustris	Point Reyes bird's-beak
Cotula coronopifolia	brass buttons
Cuscuta salina var. major	dodder
Cyperus eragrostis	tall flatsedge
Cytisus scoparius	scotch broom
Delairea odorata	Cape ivy

SCIENTIFIC NAME	COMMON NAME
Distichlis spicata	saltgrass
Equisetum arvense	horsetail
Festuca rubra	red fescue
Foeniculum vulgare	sweet fennel
Frankenia salina	alkali heath
Galium aparine	common bedstraw
Grindelia stricta var. platyphylla	marsh gumplant
Heracleum lanatum	cow parsnip
Holcus lanatus	velvet grass
Jaumea carnosa	marsh jaumea
Juncus balticus	Baltic rush
Juncus effusus var. brunneus	bog rush
Juncus lesueurii	dune rush
Lactuca serriola	prickly wild lettuce
Leymus x. *vancouveriensis*	dune wild-rye
Limonium californicum	western marsh-rosemary
Lotus corniculatus	bird's foot trefoil
Melilotus indica	sour clover
Melica torreyana	Torrey's melicgrass
Mimulus guttatus	monkeyflower
Myosotis discolor	forget-me-not
Oenanthe sarmentosa	water parsely
Oenothera elata ssp. hookeri	primrose
Phalaris arundinacea	reed canarygrass
Plantago maritima	alkali plantain
Plantago major	common plantain

SCIENTIFIC NAME	COMMON NAME
Plantago coronopus	cut-leaf plantain
Poa annua	annual bluegrass
Polypogon monspeliensis	rabbitsfoot grass
Potentilla anserina ssp. pacifica	silverweed
Ranunculus californicus	California buttercup
Ranunculus muricatus	spiney buttercup
Raphanus sativus	wild radish
Rubus parviflorus	thimbleberry
Rubus ursinus	Pacific blackberry
Rubus discolor	Himalayan blackberry
Rubus spectabilis	salmon berry
Rumex crispus	curly dock
Salicornia virginica	pickleweed
Salix lucida ssp. lasiandra	yellow willow
Salix lasiolepis	arroyo willow
Sambucus racemosa	red elderberry
Scirpus californicus	California tule
Scirpus maritimus	prairie rush
Scirpus pungens	three-square
Scrophularia californica	bee-plant
Smilacina racemosa	large false-Solomon's-seal
Sonchus asper	Prickly sow thistle
Sonchus oleraceus	common sow-thistle
Spartina foliosa	cordgrass
Spergularia macrotheca	sticky sandspurry
Spergularia rubra	red sandspurry

SCIENTIFIC NAME	COMMON NAME
Stachys ajugoides var. ajugoides	Ajuga hedge nettle
Stachys chamissonis	coastal hedgenettle
Toxicodendron diversilobum	poison oak
Tropaeolum majus	nasturtium
Triglochin concinna var. *concinna*	arrow-grass
Urtica dioica	thistle
Vinca major	greater periwinkle
Vulpia bromoides	small fescue

Table A-3. Special status plant species that may occur or are known to occur in Bolinas Lagoon. List compiled from USFWS Official Species Lists for Bolinas USGS Quads (2004), and searches of Bolinas USGS Quad in the California Department of Fish and Game (CDFG) Natural Diversity Data Base (2004) and the California Native Plant Society (CNPS) electronic inventory (2004).

SPECIES	STATUS*	BLOOMING PERIOD	HABITAT	POTENTIAL FOR OCCURRENCE
Alopecurus aequalis var. *Sonomensis* Sonoma alopecurus	FE, List 1B	May -July	Marshes and swamps, (freshwater), riparian scrub. 5-36 M.	**Not found**. Species not observed during May or June surveys.
Astragalus nuttallii var. *virgatus* Nuttall's milk-vetch	SLC	Jan-Nov	Open bluffs, dunes, sandy areas	**Not found**. Species not observed during May or June surveys.
Astragalus pycnostachyus var. *pycnostachyus* costal marsh milk-vetch	List 1B	Apr-Oct	Coastal dunes, coastal salt marshes. 0-30 M.	**Not found**. Species not observed during May or June surveys.
Atriplex californica California saltbrush	SLC	March- July	Generally in alkaline, saline soils, wetlands, or marshes.	**Present**. Observed during May and June surveys.
Campanula californica swamp harebell	List 1B	June-Oct	Bogs and fens, closed-cone coniferous forest, coastal prairie, meadows, freshwater marsh, coast coniferous forest. 1-405 M.	**Not found**. Species not observed during June survey.
Carex lyngbyei Lyngbye's sedge	List 2	May-Aug	Marshes and swamps (brackish or freshwater). 0-10 m.	**Not found**. Species not observed during May or June surveys.
Castilleja ambigua spp. *humboldtiensis* Humboldt Bay owl's clover	List 1B	April-Aug	Coastal salt marsh. Known only from Humboldt and Marin counties. 0-3 M.	**Not found**. Species not observed during May or June surveys.
Castilleja ambigua ssp. *ambigua* salt marsh owl's clover	SLC	April - July	Wetland habitat.	**Present**. Species observed on Kent Island and Pine Gulch Creek delta during May survey.

Table A-4. Lists of plant species observed in four regions of the Lagoon during 2004 rare plant surveys.

KENT ISLAND

SCIENTIFIC NAME	COMMON NAME
Coastal Dune	
Aira caryophyllea	silver hairgrass
Ambrosia chamissonis	beach-bur
Ammophila arenaria	European beach grass
Anagallis arvensis	scarlet pimpernel
Artemisia pycnocephala	coastal sage-wort
Atriplex leucophylla	seascale
Atriplex triangularis	spearscale
Atriplex californica	California saltbrush
Avena fatua	wild oats
Bromus diandrus	ripgut brome
Cakile maritima	sea rocket
Carpobrotus edulis	iceplant
Castilleja ambigua ssp. ambigua	johnny-nip
Conium maculatum	poison hemlock
Cytisus scoparius	scotch broom
Festuca rubra	red fescue
Juncus lesueurii	dune rush
Leymus mollis	dune wild-rye
Lotus corniculatus	bird's foot trefoil
Melilotus indica	sour clover
Oenothera elata ssp. *hookeri*	evening primrose
Plantago coronopus	cut-leaf plantain

SCIENTIFIC NAME	COMMON NAME
Polypogon monspeliensis	rabbitsfoot grass
Raphanus sativus	wild radish
Rumex crispus	curly dock
Toxicodendron diversilobum	poison oak
Vulpia myruros	small fescue
High Salt Marsh	
Cordylanthus maritimus ssp. *palustris*	Point Reyes bird's-beak
Cotula coronopifolia	brass buttons
Distichlis spicata	saltgrass
Frankenia salina	alkali heath
Grindelia stricta var. platyphylla	marsh gumplant
Jaumea carnosa	marsh jaumea
Lactuca serriola	prickly wild lettuce
Limonium californicum	western marsh-rosemary
Plantago maritima	Alkali plantain
Salicornia virginica	pickleweed
Scirpus pungens	three-square
Scirpus maritimus	prairie rush
Sonchus oleraceus	common sow-thistle
Spergularia macrotheca	sticky sandspurry
Spergularia rubra	red sandspurry
Triglochin concinna var. *concinna*	arrow-grass
Mid Salt Marsh	
Frankenia salina	alkali heath
Jaumea carnosa	marsh jaumea
Limonium californicum	western marsh-rosemary

SCIENTIFIC NAME	COMMON NAME
Polypogon monspeliensis	rabbitsfoot grass
Raphanus sativus	wild radish
Rumex crispus	curly dock
Salicornia virginica	pickleweed
Triglochin concinna var. *concinna*	arrow-grass
Low Salt Marsh	
Salicornia virginica	pickleweed
Spartina foliosa	cordgrass

PINE GULCH CREEK DELTA:

SCIENTIFIC NAME	COMMON NAME
Riparian	
Acer negundo	box elder
Alnus rubra	red alder
Anagallis arvensis	scarlet pimpernel
Athyrium filix-femina var. *cyclosorum*	lady fern
Cirsium vulgare	bull thistle
Claytonia perfoliata	miner’s lettuce
Conium maculatum	poison hemlock
Delairea oderata	Cape ivy
Foeniculum vulgare	sweet fennel
Galium aparine	common bedstraw
Holcus lanatus	velvet grass
Juncus effusus var. brunneus	bog rush
Melica torreyana	Torrey’s melicgrass

SCIENTIFIC NAME	COMMON NAME
Myosotis discolor	forget-me-not
Oenanthe sarmentosa	water parsely
Plantago major	common plantain
Poa annua	annual bluegrass
Potentilla anserina	silverweed
Ranunculus californicus	California buttercup
Ranunculus muricatus	spiney buttercup
Raphanus sativus	wild radish
Rubus discolor	Himalayan blackberry
Rubus parviflorus	thimbleberry
Rubus spectabilis	salmon berry
Rubus ursinus	Pacific blackberry
Salix lasiolepis	arroyo willow
Salix lucida ssp. lasiandra	yellow willow
Sambucus racemosa	red elderberry
Scrophularia californica	bee-plant
Smilacina racemosa	large false-solomon's-seal
Sonchus asper	prickley sow-thistle
Stachys chamissonis	coastal hedgenettle
Tropaeolum majus	nasturtium
Urtica dioica	nettle
Vinca major	greater periwinkle
Freshwater Emergent Marsh	
Cyperus eragrostis	tall flatsedge
Equisetum arvense	common horsetail
Holcus lanatus	velvet grass

SCIENTIFIC NAME	COMMON NAME
Juncus effusus	bog rush
Mimulus guttatus	monkey flower
Oenanthe sarmentosa	water parsely
Phalaris arundinacea	reed canarygrass
Ranunculus californica	California buttercup
Rubus discolor	Himalayan blackberry
Stachys ajugoides var. ajugoides	Ajuga hedge nettle
Buffer/Brackish Marsh	
Atriplex triangularis	spearscale
Conium maculatum	poison hemlock
Cotula coronopifolia	brass buttons
Cuscuta salina	dodder
Distichlis spicata	saltgrass
Frankenia salina	alkali heath
Grindelia stricta var. platyphylla	marsh gumplant
Juncus balticus	baltic rush
Potentilla anserina	silverweek
Rumex sp.	curly dock
Salicornia virginica	pickelweed
Scirpus pungens	three-square
Scirpus maritimus	prairie rush
Spergularia rubra	red sandspurry
High Marsh	
Castilleja ambigua ssp. *ambigua*	johnny-nip
Cotula coronopifolia	brass buttons
Distichlis spicata	saltgrass

SCIENTIFIC NAME	COMMON NAME
Frankenia salina	alkali heath
Jaumea carnosa	marsh jaumea
Salicornia virginica	pickleweed
Mid Marsh	
Distichlis spicata	saltgrass
Frankenia salina	alkali heath
Jaumea carnosa	marsh jaumea
Limonium californicum	western marsh-rosemary
Salicornia virginica	pickleweed
Spartina foliosa	cordgrass
Low Marsh	
Jaumea carnosa	marsh jaumea
Salicornia virginica	pickleweed
Spartina foliosa	cordgrass

NORTH BASIN/EASTERN SHORE

SCIENTIFIC NAME	COMMON NAME
Riparian	
Acer negundo	box elder
Alnus rubra	red alder
Anagallis arvensis	scarlet pimpernel
Athyrium filix-femina var. *cyclosorum*	lady fern
Cirsium vulgare	bull thistle
Claytonia perfoliata	miner’s lettuce
Conium maculatum	poison hemlock
Delairea odorata	Cape ivy
Foeniculum vulgare	sweet fennel
Galium aparine	common bedstraw
Holcus lanatus	velvet grass
Juncus effusus var. brunneus	bog rush
Melica torreyana	Torrey’s melicgrass
Myosotis discolor	forget-me-not
Tropaeolum majus	nasturtium
Oenanthe sarmentosa	water parsely
Plantago major	common plantain
Poa annua	annual bluegrass
Potentilla anserina	silverweed
Ranunculus californica	California buttercup
Ranunculus muricatus	spiney buttercup
Raphanus sativus	wild radish
Rubus discolor	Himalayan blackberry
Rubus parviflorus	thimbleberry

SCIENTIFIC NAME	COMMON NAME
Rubus spectabilis	salmon berry
Rubus ursinus	Pacific blackberry
Salix lasiolepis	arroyo willow
Salix lucida ssp. lasiandra	yellow willow
Sambucus racemosa	red elderberry
Scrophularia californica	bee-plant
Smilacina racemosa	large false-solomon's-seal
Sonchus asper	common sow-thistle
Stachys chamissonis	coastal hedgenettle
Urtica dioica	nettle
Vinca major	greater periwinkle
Brackish Marsh/Riparian Interface	
Alnus rubra	red alder
Delairea odorata	Cape ivy
Distichlis spicata	saltgrass
Grindelia stricta var. platyphylla	marsh gumplant
Heracleum lanatum	cow parsnip
Juncus balticus	Baltic rush
Rumex crispus	curly dock
Salicornia virginica	pickleweed
Salix lasiolepis	arroyo willow
Scirpus maritimus	prairie rush
Vinca major	greater periwinkle
High Marsh	
Atriplex triangularis	spearscale
Distichlis spicata	saltgrass

SCIENTIFIC NAME	COMMON NAME
Frankenia salina	alkali heath
Jaumea carnosa	marsh jaumea
Juncus balticus	Baltic rush
Salicornia virginica	pickleweed
Scirpus martimus	prairie rush
Triglochin concinna var. *concinna*	arrow-grass
Mid Marsh	
Distichlis spicata	saltgrass
Frankenia salina	alkali heath
Jaumea carnosa	marsh jaumea
Limonium californicum	western marsh-rosemary
Salicornia virginica	pickleweed
Spartina foliosa	cordgrass
Low Marsh	
Jaumea carnosa	marsh jaumea
Salicornia virginica	pickleweed
Spartina foliosa	cordgrass

SOUTH ARM OF LAGOON (NEAR MOUTH OF ESKOOT CREEK):

SCIENTIFIC NAME	COMMON NAME
Riparian/Roadside	
Conium maculatum	poison hemlock
Potentilla anserina	silverweed
Salix lasiolepis	arroyo willow
Sambucus racemosa	red elderberry
Toxicodendron diversilobum	poison oak
Brackish Marsh/Riparian Interface	
Juncus balticus	Baltic rush
Jaumea carnosa	marsh jaumea
Salicornia virginica	pickleweed
Salix lasiolepis	arroyo willow
Scirpus californicus	California tule
Scirpus maritimus	prairie rush
High (-mid) marsh	
Cuscuta salina var. *major*	dodder
Distichlis spicata	saltgrass
Frankenia salina	alkali heath
Grindelia stricta var. platyphylla	marsh gumplant
Jaumea carnosa	marsh jaumea
Potentilla anserina ssp. *pacifica*	silverweed
Salicornia virginica	pickleweed
Scirpus martimus	prairie rush
Triglochin concinna var. *concinna*	arrow-grass
Mid marsh	
Distichlis spicata	saltgrass

SCIENTIFIC NAME	COMMON NAME
Frankenia salina	alkali heath
Jaumea carnosa	marsh jaumea
Limonium californicum	western marsh-rosemary
Salicornia virginica	pickleweed
Triglochin concinna var. *concinna*	arrow-grass
Low marsh	
Jaumea carnosa	marsh jaumea
Salicornia virginica	pickleweed
Spartina foliosa	cordgrass

Table A-5. Special status wildlife species that may occur, or are known to occur in habitats similar to those found in the Lagoon. List compiled from USFWS Species lists (USFWS 2004), and CNDDB (CDFG 2004) for the USGS Bolinas Quadrangle.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
Mammals			
long-eared myotis *Myotis evotis*	FSC	Primarily a forest associated species. Day roosts in hollow trees, under exfoliating bark, rock outcrop crevices and buildings. Other roosts include caves, mines and under bridges.	**Low Potential.** Widespread but uncommon species in California. No known occurrences in vicinity though suitable habitat is available in nearby forest habitat.
fringed myotis *Myotis thysanodes*	FSC	Associated with a wide variety of habitats including mixed coniferous-deciduous forest and redwood/sequoia groves. Buildings, mines and large snags are important day and night roosts.	**Low Potential.** Widespread but uncommon species in California. No known occurrences in vicinity though suitable habitat is available in nearby forest habitat.
long-legged myotis *Myotis volans*	FSC	Generally associated with woodlands and forested habitats. Large hollow trees, rock crevices and buildings are important day roosts. Other roosts include caves, mines and buildings.	**Low Potential.** Species is common in California in woodland and forest habitats above 1200m. Suitable habitat available in nearby woodland/forest habitat though no known occurrences in vicinity.
Yuma myotis *Myotis yumanensis*	FSC, CSC	Known for its ability to survive in urbanized environments. Also found in heavily forested settings. Day roosts in buildings, trees, mines, caves, bridges and rock crevices. Night roosts associated with man-made structures.	**Moderate Potential.** Common and widespread in California. May forage in open forest and woodland habitat in vicinity.
pallid bat *Antrozous pallidus*	CSC	Found in deserts, grasslands, shrublands, woodlands, and forests. Most common in open, dry habitats with rocky areas for roosting. Roosts must protect bats from high temperatures. Very sensitive to disturbance of roosting sites.	**High Potential** Closest occurrence at Olema Creek in riparian vegetation dominated by alders. Similar habitat available at Pine Gulch, northern tip of lagoon, and ..

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
Townsend's western big-eared bat *Euderma maculatum*	FSC, CSC	Primarily found in rural settings in a wide variety of habitats including oak woodlands and mixed coniferous-deciduous forest. Day roosts highly associated with caves and mines. Very sensitive to human disturbance.	**High Potential**. Two known roosting occurrences in the vicinity of Olema. May roost in woodland habitat adjacent to Lagoon.
Pt. Reyes mountain beaver *Aplodontia rufa phaea*	FSC, CSC	Occurs near springs or seepages in densely vegetated riparian and scrub areas in the vicinity of Pt Reyes peninsula. Population status unknown.	**Low Potential.** Formerly occurring throughout Pt. Reyes National Seashore. Most populations are now thought to be extirpated.
Pt. Reyes jumping mouse *Zapus trinotatus orarius*	FSC, CSC	Occurs in riparian areas, grasslands, and wet meadows of Pt. Reyes peninsula. Population status unknown.	**Low Potential**. Suitable habitat available in Pine Gulch riparian area. Population status uncertain.
Steller sea-lion *Eumetopia jubatus*	FT	Prefers offshore haul-out and breeding sites with unrestricted access to water, near aquatic food supply in areas of minimal human disturbance.	**Not Present.** No records of species occurrence in Lagoon (which has extensive records for marine mammals).
southern sea otter *Enhydra lutris nereis*	FT, CFP	Formerly resident along entire California Coast. Small populations now known from San Mateo County south to Santa Barbara County. Prefer kelp forests within 1 ½ miles of shore.	**Not Present.** No records existing of species occurrence in Lagoon (which holds extensive records for marine mammals).
Birds			
common loon *Gavia immer*	FSC, CSC	Winter in estuarine and subtidal marine habitats along the California coast, San Francisco Bay.	**Present.** Known to winter in Bolinas Lagoon.
ashy storm petrel *Oceanodroma homochroa*	FSC, CSC	Breed on Farallon Islands off of Sonoma Coast.	**Low Potential.** May occur as vagrant, suitable nesting habitat not available.
California brown pelican *Pelecanus occidentalis californicus*	FE, SE, CFP	Found in estuarine, marine subtidal, and marine pelagic waters along the coast. Nest on rocky or low brushy slopes of undisturbed islands.	**Present.** Documented to forage in Lagoon; nesting habitat not available.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
double-crested cormorant *Phalacrocorax auritus*	CSC	Nests along coast on sequestered islets, usually on ground with sloping surface or in tall trees along lake margins.	**Present.** Documented to forage in Lagoon.
great egret (rookery) Ardea alba		Colonial nester in large trees. Rookery sites located near marshes, tide-flats, irrigated pastures, and margins of rivers and lakes.	**Present.** Rookery site at Audobon Canyon Ranch, directly adjacent to northeast portion of Lagoon. Frequently observed foraging in Lagoon.
snowy egret (rookery) *Egretta thula*		Widespread along shores of coastal estuaries, fresh and saline emergent wetlands, ponds, slow-moving rivers, irrigation ditches, and wet fields. Feeds primarily on small fish, crustaceans and large insects.	**Present.** Rookery site at Audobon Canyon Ranch, directly adjacent to northeast portion of Lagoon. Frequently observed foraging in Lagoon.
black-crowned night heron (rookery) *Nycticorax nyticorax*		Colonial nester, usually in trees, occasionally in tule patches. Rookery sites located adjacent to foraging areas: lake margins, mud-bordered bays, marshy spots.	**Present.** Documented to forage throughout Lagoon. No documented rookeries in vicinity of Lagoon
great blue heron (rookery) *Ardea herodias*		Colonial nester in tall trees, cliffsides, and sequestered spots on marshes. Found in close proximity to foraging areas (rivers and streams, tide-flats, wet meadows.)	**Present.** Rookery at Audubon Canyon Ranch as well as in vicinity of Inverness, Olema, and the east and north arm of Drakes Estero.
Harlequin duck *Histrionicus histrionicus*	FSC, CSC	Found in marine waters along rocky shore during non-breeding season. Nests in inland streams.	**Low Potential.** Inland stream habitat available for breeding but species is quite rare. Not known to breed in vicinity.
white-tailed kite *Elanus leucurus*	FSC, CFP	Year-long resident of coastal and valley lowlands; rarely found away from agricultural areas. Preys on small diurnal mammals and occasional birds, insects, reptiles, and amphibians.	**Low Potential.** Suitable breeding and foraging habitat is available in the vicinity but species is not likely to utilize lagoon habitat. May occur as transient.
osprey *Pandion haliaetus*	CSC	Nests along ocean shores, bays, freshwater lakes and larger streams in treetops.	**Present.** Nest along Inverness Ridge and observed foraging over Bolinas Lagoon.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
bald eagle *Haliaeetus leucocephalus*	FPD, FT, SE, CFP	Requires large bodies of water, or free-flowing rivers with abundant fish adjacent snags or other perches. Nests in large, old-growth, or dominant live tree with open branchwork.	**Not Present.** No records exist of occurrence in Pt. Reyes vicinity.
northern harrier Circus cyaneus	CSC	Frequents meadows, grasslands, rangelands, fresh and saltwater emergent wetlands throughout California. Nests in shrubby vegetation on ground.	**High Potential.** Suitable foraging habitat available in saltmarsh areas. Known to forage and breeds in vicinity
ferruginous hawk *Buteo regalis*	FSC, CSC	Frequents open grasslands, sagebrush flats, desert scrub, low foothills surrounding valleys and fringes of pinyon-juniper habitats.	**Low Potential**. Uncommon winter resident and migrant at lower elevations. May occur as transient.
American peregrine falcon *Falco peregrinus anatum*	FD, SE, CFP	Winters throughout Central Valley. Requires protected cliffs and ledges for cover. Feeds on a variety of birds, and some mammals, insects, and fish.	**High Potential.** Anecdotal evidence of occurrence at Lagoon. Suitable foraging and nesting habitat available.
black rail *Laterallus jamaicensis coturniculus*	FSC, ST, CFP	Rarely seen resident of saline, brackish, and fresh emergent wetlands in the San Francisco Bay area. Nest in dense stands of pickleweed	**Present.** Observed at coves in Bolinas Lagoon at the mouth of Audubon Canyon, Pike County Gulch, as well as suitable marsh habitat in the vicinity of Pt. Reyes National Seashore.
California clapper rail *Rallus longirostris obsoletus*	FE, SE	Found in tidal salt marshes of the San Francisco Bay. Require mudlfats for foraging and dense vegetation on higher ground for nesting.	**Present.** 1975 observation in Bolinas Lagoon, location unclear
western snowy plover *Charadrius alexandrinus nivosus*	FT, CSC	Found on sandy beaches, salt pond levees and shores of large alkali lakes. Need sandy gravelly or friable soils for nesting.	**Present.** Nests on Bolinas Lagoon spit, Point Reyes Beach, Drake's Beach spit, Limantour spit.
black oystercatcher *Haematopus bachmani*s	FSC	Permanent resident on rocky shores of marine habitats along much of the California coast. Forages in rocky intertidal areas and breeds on undisturbed, rocky, open ocean shores.	**Not Present.** Rocky intertidal shores not present within Bolinas Lagoon.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
whimbrel *Numenius phaeopus*	FSC	Spring migrant at the Central California Coast. Forages on rocky intertidal, sandy beach marine habitats, and intertidal mudflats of estuarine habitats.	**Present.**. Documented to occur by PRBO. Suitable foraging habitat available, may occur as spring migrant.
long-billed curlew *Numenius americanus*	FSC, CSC	Winters in large coastal estuaries, upland herbaceous areas, and croplands. Breeds in northeastern California in wet meadow habitat.	**Present.** Observed foraging in tidal mudflats of Lagoon. Winter visitor.
marbled godwit *Limosa fedoa*	FSC	Migrant and winter visitor along California Coast. Most common on estuarine mudflats but also occurs on sandy beaches, open shores, saline emergent wetlands, and adjacent wet upland fields.	**Present.** Observed foraging in tidal mudflats of Lagoon. Winter visitor.
black turnstone *Arenaria melanocephala*	FSC	Winter visitor along California Coast. Common to abundant on rocky shores of marine habitats, prefers rugged, rocky, intertidal coasts but also occurs on sandy beaches and estuarine mudflats.	**Low Potential.** May occur as winter visitor to forage on the mudflats of the Lagoon.
red knot *Calidris canutus*	FSC	Fall and spring migrant in coastal estuarine habitats. Prefers estuarine sand or mud flats.	**High Potential.** May occur as spring or fall migrant to forage in mudflats of the Lagoon.
California least tern *Sterna antillarum browni*	CSC	Nests along the coast from San Francisco Bay South to Northern Baja California. Colonial breeder on bare or sparsely vegetated flat substrates: sand beaches, alkali flats, land fills, or paved areas.	**Not Present.** No known nesting records of species in Lagoon
black skimmer *Rynchops niger*	CSC	Nests on gravel bars, low islets, and sandy beaches in unvegetated sites.	**Moderate Potential**. No records of nesting colony at lagoon but may occur to forage as transient.
marbled murrelet *Brachyramphus marmoratus*	FT, SE	Breed in old-growth redwood stands containing platform-like branches along the coast.	**Low Potential.** Old growth redwood forest not available for nesting adjacent to lagoon. May occur as transients to forage, rest.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
tufted puffin *Fratercula cirrhata*	CSC	Uncommon species that nests on islands and coastal cliffs. Breeding colony on Farallon Islands.	**Low Potential.** May occur to forage in Lagoon, suitable nesting habitat not available.
western burrowing owl *Athene cunicularia hypugea*	FSC, CSC	Frequents open grasslands and shrublands with perches and burrows. Preys upon insects, small mammals, reptiles, birds, and carrion. Nests and roosts in old burrows of small mammals.	**Low Potential.** Uncommon species in region. May occur in grassland
northern spotted owl *Strix occidentalis caurina*	FT	Rely on large patches of old growth forest for hunting, roosting, nesting.	**Low Potential.** Breeding population located at nearby Bolinas Ridge. Not likely to utilize the Lagoon or adjacent area for roosting, nesting, or hunting.
Vaux's swift *Chaetura vauxi*	FSC, CSC	Forages high in the air over most terrain and habitats but prefers rivers/lakes. Requires large hollow trees for nesting.	**Present.** Documented nesting occurrence in chimney just north of Bolinas Lagoon.
black swift *Cypseloides niger*	FSC, CSC	Nests in riparian jungles of willow, often mixed with cottonwoods with thick lower story.	**Moderate Potential.** Suitable habitat available at Pine Gulch Creek. Documented to occur at Pt. Reyes National Seashore.
rufous hummingbird *Selasphorus rufus*	FSC	Found in a wide variety of habitats that provide nectar-producing flowers. A common migrant and uncommon summer resident of California.	**High Potential.** Suitable nesting and foraging habitat available in upland areas adjacent to lagoon.
Allen's hummingbird *Selasphorus sasin*	FSC	Breeds in sparse and open woodlands, coastal redwoods, and sparse to dense scrub habitats. Distribution highly dependent on abundance of nectar sources.	**High Potential.** Suitable nesting and foraging habitat available in upland areas adjacent to lagoon.
olive-sided flycatcher *Contopus cooperi*	FSC	Most often found in montane conifer forests where tall trees overlook canyons, meadows, lakes or other open terrain	**Present.** Observed singing in willow adjacent to lagoon during May 2004 assessment. Suitable breeding and foraging habitat available in upland riparian areas.
little willow flycatcher *Empidonax traillii brewsteri*	FSC, SE	Most numerous where extensive thickets of low, dense willows edge on wet meadows, ponds, or backwaters. Winter migrant.	**Low Potential.** May occur as winter migrant. Willow riparian habitat available adjacent to Lagoon.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
purple martin *Progne subis*	CSC	Inhabits woodlands, low elevation coniferous forest. Nest in old woodpecker cavities and human-made structures.	**High Potential.** May occur as transient or nest in woodland habitat adjacent to the lagoon.
bank swallow *Riparia riparia*	FSC, ST	Migrant in riparian and other lowland habitats in western California. Nests in riparian areas with vertical cliffs and bands with fine-textured or sandy soils in which to nest.	**High Potential.** May occur as migrant to forage over lagoon and adjacent upland areas.
California thrasher *Toxostoma redivivum*	FSC	Common resident of foothills and lowlands in cismontane California. Occupies moderate to dense chaparral habitats and extensive thickets in young or open valley foothill riparian habitat.	**High Potential.** Suitable chaparral habitat available in upland habitat adjacent to lagoon.
loggerhead shrike *Lanius ludovicianus*	FSC, CSC	Prefers open habitats with scattered shrubs, trees, posts, utility lines from which to forage for large insects. Nest well concealed above ground in densely-foliaged shrub or tree.	**Low Potential**. Typical open grassland habitat is not present.
yellow warbler *Dendroica petechia brewsteri*	CSC	Nests in riparian stands of willows, cottonwoods, aspens, sycamores, and alders. Also nests in montane shrubbery in open conifer forests.	**Low Potential.** Suitable breedinghabitat available in riparian habitat adjacent to Lagoon. Species decline has made it relatively uncommon. PRBO data indicates that the species is not breeding in Pine Gulch. Documented breeder at Olema Marsh.
hermit warbler *Dendroica occidentalis*	FSC	Frequents mature stands of conifers with open to dense canopy for breeding.	**Low Potential**. May rarely occur in transitional habitat during migration.
saltmarsh common yellowthroat *Geothlypis trichas sinuosa*	FSC, CSC	Frequents low, dense vegetation near water including fresh to saline emergent wetlands. Brushy habitats used in migration. Forages among wetland herbs and shrubs for insects primarily.	**Present.** Commonly observed species in wetlands in the vicinity. May occupy salt marsh and riparian habitats.
San Pablo song sparrow *Melospiza melodia samuelis*	FSC	Found in saline emergent wetlands of San Pablo Bay. Require low, dense vegetation for cover and nesting.	**Not Present.** Study Area is outside of species range.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
tricolored blackbird *Agelaius tricolor*	FSC, CSC	Usually nests over or near freshwater in dense cattails, tules, or thickets of willow, blackberry, wild rose or other tall herbs.	**Low Potential**. Typical freshwater emergent vegetation is not present. Foraging habitat (grassland, pasture) is not present.
Reptiles and Amphibians			
western pond turtle *Clemmys marmorata*	FSC, CSC	Occurs in perennial ponds, lakes, rivers and streams with suitable basking habitat (mud banks, mats of floating vegetation, partially submerged logs) and submerged shelter.	**Low Potential**. Typically associated with freshwater habitats.
California horned lizard *Phrynosoma coronatum frontale*	FSC, CSC	Occurs in valley-foothill hardwood, conifer and riparian habitats, as well as in pine-cypress juniper and annual grass habitats. Prefers sand areas, washes, flood plains and wind-blown deposits.	**Not Present**. Typical habitat is not present in the Bolinas Lagoon area.
California red-legged frog *Rana aurora draytonii*	FT, CSC	Associated with quiet perennial to intermittent ponds, stream pools and wetlands. Prefers shorelines with extensive vegetation. Documented to disperse through upland habitats after rains.	**Present.** Known to occur in Pt. Reyes National Seashore vicinity, including Pine Gulch Creek.
northern red-legged frog *Rana aurora aurora*	FSC	Found in humid forests, woodlands, grasslands, and streamsides with plant cover. Most common in lowlands or foothills. Breeds in permanent water sources.	**Not Present.** Species not known to occur in Pt. Reyes vicinity.
foothill yellow-legged frog *Rana boylii*	FSC, CSC	Found in or near rocky streams in a variety of habitats. Feed on both aquatic and terrestrial invertebrates.	**Moderate Potential**. Pine Gulch Creek may provide suitable habitat conditions; not associated with saline habitats.
Fishes			
Pacific lamprey *Lampetra tridentata*	FSC	Anadromous fish found in the Sacramento-San Joaquin estuary and river system. Spawn in riffle areas with strong current in cool streams. Adults occur in bay and ocean waters.	**High Potential**. CDFG surveys during 1994-96 found lamprey ammocoetes in Pine Gulch Creek.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
green sturgeon *Acipenser medirostris*	FSC, CSC	Anadromous fish that spawns in Sacramento river. Feeds in estuaries and bays, including San Francisco Bay.	**Low Potential**. May rarely occur in Bolinas Lagoon. Not encountered during CDFG surveys.
coho salmon-central CA coast ESU *Oncorhynchus kisutch*	FT, SE	Require beds of loose, silt-free, coarse gravel for spawning. Also need cover, cool water and sufficent oxygen.	**Present.** Anecdotal reports suggest that Pine Gulch Creek supported runs of this species. Not encountered during CDFG surveys 1994-96. Also occurs in Lagunitas Creek drainage, Redwood Creek Watershed.
steelhead-central CA coast ESU *Oncorhynchus mykiss*	FT	From Russian River south to Soquel Creek and Pajaro River. Also San Francisco and San Pablo Bay Basins.	**Present**. Documented to occur in Pine Gulch Creek during CDFG surveys 1994-96.
California coastal chinook salmon *Oncorhynchus tshawytscha*	FT, SE, NMFS	Spawn in coastal streams at temps. from 4-14C. Prefer beds of loose, silt-free, coarse gravel and cover nearby for adults.	**Low Potential**. Not documented to occur in Pine Gulch Creek.
Tomales roach *Lavinia symmetricus ssp. 2*	CSC	Found in small, warm intermittent streams in the Tomales Bay watershed. Habitat generalists.	**Not Present**. Known from tributaries to Tomales Bay. Roach documented in Pine Gulch Creek are likely the Sacramento-San Joaquin subspecies.
tidewater goby *Eucyclogovius newberryi*	FE, CSC	Found in the brackish waters of coastal lagoons, marshes, creeks, and estuaries. Unique among fishes of the Pacific coast, gobies are restricted to waters of low salinity in coastal wetlands. They feed along the bottom, preferring clean, shallow, slow-moving waters.	**Low Potential**. Suitable habitat available in Bolinas Lagoon though no known occurrences despite biological survey efforts.
Invertebrates			
black abalone *Haliotes cracherodii*	FC, NMFS	Mid to low rocky tidal areas.	**Not Present.** Suitable rocky tidal areas not available within Lagoon.
Peninsula coast range shoulderband snail *Helminthoglypta nickliniana awania*	FSC	Known only from granite headlands at Pt. Reyes Peninsula. Inhabits coastal scrub and weedy pastures. Uniquely adapted to high winds, salt fog, and variable precipitation	**Not Present**. 1972 occurrence in Pt. Reyes National Seashore vicinity.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
mimic tryonia (California brackish-water snail) *Tryonia imitator*	none	Inhabits coastal lagoons, estuaries and salt marshes from Sonoma Co. south to San Diego Co. Able to withstand a wide range of salinities.	**Moderate Potential.** Suitable habitat available in Bolinas Lagoon though no records exist of occurrence.
California freshwater shrimp *Syncaris pacifica*	FE, SE	Endemic to Marin, Napa, and Sonoma Cos. Found in shallow pools away from streamflow in low gradient streams where riparian cover is moderate to heavy.	**Low Potential.** Uncommon species though observed at Lagunitas Creek and Olema Creek.
Tomales isopod *Caecidotea tomalensis*		Inhabits localized fresh-water ponds or streams with still or near-still water.	**High Potential**. 1984 observation in Audubon Canyon Ranch (Volunteer Canyon) tributary to Bolinas Lagoon.
Ricksecker's water scavenger beetle *Hydrochara rickseckeri*	FSC	Aquatic, known from the San Francisco Bay area.	**High Potential**. 1940 record from the vicinity of Bolinas.
bumblebee scarab beetle *Lichnanthe ursina*	FSC	Inhabits coastal sand dunes from Sonoma Co. south to San Mateo Co. . Usually flies close to sand surface near the crest of dunes.	**Low Potential**. Observed along shoreline near Inverness, 1980; however, dune habitat is limited in Bolinas Lagoon..
sandy beach tiger beetle *Cicindela hirticollis gravida*	FSC	Occurs along non-brackish areas of coast.	**Moderate Potential**. Suitable habitat may be present along shoals near mouth of lagoon.
Opler's longhorn moth *Adela oplerella*	FSC	Occurs in the inner coast ranges in Marin to Oakland. Inhabits serpentine grassland; larval foodplant is *Platystemon californicus*	**Not present.** Serpentine grassland habitat not available within Bolinas Lagoon Study Area.
Myrtle's silverspot butterfly *Speyeria zerene myrtleae*	FE	Restricted to the foggy coastal dunes/hills of the Point Reyes peninsula. Larval foodplant thought to be *Viola adunca.*	**Low Potential**. Larval host plant is not likely present in Bolinas Lagoon area. Observed as recently as 2003 in the vicinity of North Beach and Drake's Estero.
Marin elfin butterfly *Incisalia mossii*	FSC	Rocky outcrops, woody canyons, cliffs.	**Low Potential**. Typical habitat is not present in Bolinas Lagoon.
Point Reyes blue butterfly *Icaricia icarioides parapheres*	FSC	Confined to the Pt. Reyes Peninsula. Occurs in stable sand dunes with *Lupinus arboreus and L. varicolor.*	**Low Potential**. 1974 record from Point Reyes Dunes. Suitable habitat limited in Bolinas Lagoon.

SPECIES	STATUS*	HABITAT	POTENTIAL FOR OCCURRENCE
monarch butterfly *Danaus plexippus*	none	Winter roost sites located in wind-protected tree groves with nectar and water sources nearby.	**Low Potential**. Roost trees are not likely present in Bolinas Lagoon. Documented to roost throughout Bolinas, Pt. Reyes National Seashore, Tennessee Valley, Muir Beach, Fort Barry Military Reservation.

*** Key to status codes:**
Status codes used above are:
FE - Federal Endangered
FT - Federal Threatened
FC - Federal Candidate
FPD - Federal Proposed Delisted
FSC - United States Fish and Wildlife Service Federal Species of Concern
NMFS - Species under the Jurisdiction of the National Marine Fisheries Service
SE - State Endangered
CSC - CDFG Species of Special Concern, CSC (Draft) - 4 April 2001 Draft
CDFG Species of Special Concern
CFP - California Fully Protected Species
SLC - Species of Local Concern
None - No status given but rookery sites are monitored by CDFG
List 1B - CNPS 1B List, Endangered, Threatened, or Rare in California
List 2- CNPS List 2 Plants are rare, threatened, or endangered in California, but more common elsewhere

Table A-6. Sampled habitat elevation ranges at six field sites in Bolinas Lagoon.

Location	Transect #	Habitat	Elevation Range (ft)(NAVD88)
North Basin	1	Riparian	6.33 - 9.81
North Basin	1	Brackish Marsh	5.83 - 6.33
North Basin	1	High Marsh	5.31 - 5.83
North Basin	1	Mid Marsh	4.64 - 5.31
North Basin	1	Low Marsh	3.98 – 4.64
Pine Gulch Creek Delta	2	Riparian	7.12 - 10.79
Pine Gulch Creek Delta	2	Brackish Marsh	6.24 - 7.12
Pine Gulch Creek Delta	2	High Marsh	5.26 - 6.24
Pine Gulch Creek Delta	2	Mid Marsh	5.02 - 5.26
Pine Gulch Creek Delta	2	Low Marsh	4.94 - 5.02
East Shore along Highway 1	4	Riparian	6.53 - 6.93
East Shore along Highway 1	4	Brackish Marsh	4.39 - 6.53
East Shore along Highway 1	4	High Marsh	N/A
East Shore along Highway 1	4	Mid Marsh	3.99 - 4.39
East Shore along Highway 1	4	Low Marsh	3.08 - 3.99
East Shore along Highway 1	5	Riparian	4.63 - 10.86
East Shore along Highway 1	5	Brackish Marsh	4.61 - 4.63
East Shore along Highway 1	5	High Marsh	N/A
East Shore along Highway 1	5	Mid Marsh	4.48 - 4.61
East Shore along Highway 1	5	Low Marsh	N/A
South Arm	6	Riparian	9.25 - 35.73 (west side) 4.74 - 8.34 (east side)
South Arm	6	Brackish Marsh	5.09 - 9.25
South Arm	6	High Marsh	5.15 - 5.94
South Arm	6	Mid Marsh	4.91 - 5.15
South Arm	6	Low Marsh	4.91 - 5.09
Kent Island	8	Riparian	N/A
Kent Island	8	Brackish Marsh	N/A
Kent Island	8	High Marsh	5.24 - 6.49
Kent Island	8	Mid Marsh	4.77 – 5.24
Kent Island	8	Low Marsh	4.58 -4.77

Figure A-1. WETLANDS AND DEEPWATER HABITATS CLASSIFICATION

M - MARINE

SUBSYSTEM: 1 - SUBTIDAL

CLASS / Subclass

- RB – ROCK BOTTOM
  - 1 Bedrock
  - 2 Rubble
- UB – UNCONSOLIDATED BOTTOM
  - 1 Cobble-Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic
- AB – AQUATIC BED
  - 1 Algal
  - 3 Rooted Vascular
  - 5 *Unknown Submergent*
- RF - REEF
  - 1 Coral
  - 3 Worm
- OW - *OPEN WATER/ Unknown Bottom*

SUBSYSTEM: 2 - INTERTIDAL

CLASS / Subclass

- AB – AQUATIC BED
  - 1 Algal
  - 3 Rooted Vascular
  - 5 *Unknown Submergent*
- RF– REEF
  - 1 Coral
  - 3 Worm
- RS – ROCKY SHORE
  - 1 Bedrock
  - 2 Rubble
- US - UNCONSOLIDATED SHORE
  - 1 Cobble-Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic

E - ESTUARINE

SUBSYSTEM: 1 - SUBTIDAL

CLASS / Subclass

- RB - ROCK BOTTOM
  - 1 Bedrock
  - 2. Rubble
- UB – UNCONSOLIDATED BOTTOM
  - 1 Cobble-Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic
- AB – AQUATIC BED
  - 1 Algal
  - 3 Rooted Vascular
  - 4 Floating Vascular
  - 5 *Unknown Submergent*
  - 6 *Unknown Surface*
- RF – REEF
  - 1 Mollusc
  - 2 Worm
- OW - *OPEN WATER/ Unknown Bottom*

SUBSYSTEM: 2 - INTERTIDAL

CLASS / Subclass

- AB – AQUATIC BED
  - 1 Algal
  - 3 Rooted Vascular
  - 4 Floating Vascular
  - 5 *Unknown Submergent*
  - 6 *Unknown Surface*
- RF– REEF
  - 1 Mollusc
  - 2 Worm
- SB – STREAMBED
  - 1 Cobble Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic
- RS - ROCKY SHORE
  - 1 Bedrock
  - 2 Rubble
- US – UNCONSOLIDATED SHORE
  - 1 Cobble-Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic
- EM -EMERGENT
  - 1 Persistent
  - 2 Nonpersistent
- SS – SCRUB-SHRUB
  - 1 Broad-Leaved Deciduous
  - 2 Needle-Leaved Deciduous
  - 3 Broad-Leaved Evergreen
  - 4 Needle-Leaved Evergreen
  - 5 Dead
  - 6 *Deciduous*
  - 7 *Evergreen*
- FO – FORESTED
  - 1 Broad-Leaved Deciduous
  - 2 Needle-Leaved Deciduous
  - 3 Broad-Leaved Evergreen
  - 4 Needle-Leaved Evergreen
  - 5 Dead
  - 6 *Deciduous*
  - 7 *Evergreen*

R - RIVERINE

SUBSYSTEM: 1 – TIDAL, 2 – LOWER PERENNIAL, 3 – UPPER PERENNIAL, 4 – INTERMITTENT, 5 – *UNKNOWN PERENNIAL*

CLASS / Subclass

- RB – ROCK BOTTOM
  - 1 Bedrock
  - 2 Rubble
- UB – UNCONSOLIDATED BOTTOM
  - 1 Cobble-Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic
- *SB – STREAMBED
  - 1 Bedrock
  - 2 Rubble
  - 3 Cobble Gravel
  - 4 Sand
  - 5 Mud
  - 6 Organic
  - 7 Vegetated
- AB – AQUATIC BED
  - 1 Algal
  - 2 Aquatic Moss
  - 3 Rooted Vascular
  - 4 Floating Vascular
  - 5 *Unknown Submergent*
  - 6 *Unknown Surface*
- RS – ROCKY SHORE
  - 1 Bedrock
  - 2 Rubble
- US – UNCONSOLIDATED SHORE
  - 1 Cobble-Gravel
  - 2 Sand
  - 3 Mud
  - 4 Organic
  - 5 Vegetated
- **EM – EMERGENT
  - 2 Nonpersistent
- OW – *OPEN WATER/ Unknown Bottom*

* STREAMBED is limited to TIDAL and INTERMITTENT SUBSYSTEMS, and comprises the only CLASS in the INTERMITTENT SUBSYSTEM.
** EMERGENT is limited to TIDAL and LOWER PERENNIAL SUBSYSTEMS.

Classification of Wetlands and Deepwater Habitats of the United States
Cowardin ET AL. 1979 as modified for National Wetland Inventory Mapping Convention

Figure A-1. WETLANDS AND DEEPWATER HABITATS CLASSIFICATION

SYSTEM **L- LACUSTRINE**

SUBSYSTEM: **1 - LIMNETIC**

CLASS	RB – ROCK BOTTOM	UB – UNCONSOLIDATED BOTTOM	AB – AQUATIC BED	OW – *OPEN WATER/ Unknown Bottom*
Subclass	1 Bedrock 2. Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic	1 Algal 2 Aquatic Moss 3 Rooted Vascular 4 Floating Vascular 5 *Unknown Submergent* 6 *Unknown Surface*	

SUBSYSTEM: **2 - LITTORAL**

CLASS	RB – ROCK BOTTOM	UB – UNCONSOLIDATED BOTTOM	AB – AQUATIC BED	RS – ROCKY SHORE	US – UNCONSOLIDATED SHORE	EM – EMERGENT	OW – *OPEN WATER/ Unknown Bottom*
Subclass	1 Bedrock 2. Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic	1 Algal 2 Aquatic Moss 3 Rooted Vascular 4 Floating Vascular 5 *Unknown Submergent* 6 *Unknown Surface*	1 Bedrock 2. Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic 5 Vegetated	2 Nonpersistent	

SYSTEM **P - PALUSTRINE**

CLASS	RB – ROCK BOTTOM	UB – UNCONSOLIDATED BOTTOM	AB – AQUATIC BED	US – UNCONSOLIDATED SHORE	ML – MOSS-LICHEN	EM – EMERGENT	SS – SCRUB-SHRUB	FO – FORESTED	OW – *OPEN WATER/ Unknown Bottom*
Subclass	1 Bedrock 2. Rubble	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic	1 Algal 2 Aquatic Moss 3 Rooted Vascular 4 Floating Vascular 5 *Unknown Submergent* 6 *Unknown Surface*	1 Cobble-Gravel 2 Sand 3 Mud 4 Organic 5 Vegetated	1 Moss 2 Lichen	1 Persistent 2 Nonpersistent	1 Broad-Leaved Deciduous 2 Needle-Leaved Deciduous 3 Broad-Leaved Evergreen 4 Needle-Leaved Evergreen 5 Dead 6 *Deciduous* 7 *Evergreen*	1 Broad-Leaved Deciduous 2 Needle-Leaved Deciduous 3 Broad-Leaved Evergreen 4 Needle-Leaved Evergreen 5 Dead 6 *Deciduous* 7 *Evergreen*	

MODIFIERS

In order to more adequately describe the wetland and deepwater habitats one or more of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy. The farmed modifier may also be applied to the ecological system.

WATER REGIME				WATER CHEMISTRY			SOIL	SPECIAL MODIFIERS	
Non-Tidal		**Tidal**		**Coastal Halinity**	**Inland Salinity**	**pH Modifiers for all Fresh Water**			
A Temporarily Flooded B Saturated C Seasonally Flooded D *Seasonally Flooded/ Well Drained* E *Seasonally Flooded/ Saturated* F Semipermanently Flooded G Intermittently Exposed	H Permanently Flooded J Intermittently Flooded K Artificially Flooded W Intermittently Flooded/Temporary Y Saturated/Semipermanent/ Seasonal Z Intermittently Exposed/Permanent U *Unknown*	K *Artificially Flooded* L Subtidal M Irregularly Exposed N Regularly Exposed P Irregularly Flooded	*S Temporary-Tidal *R Seasonal-Tidal *T Semipermanent-Tidal *V Permanent-Tidal U *Unknown* *These water regimes are only used in tidally influenced, freshwater systems.	1 Hyperhaline 2 Euthaline 3 Mixohaline *(Brackish)* 4 Polyhaline 5 Mesohaline 6 Oligohaline 0 Fresh	7 Hypersaline 8 Eusaline 9 Mixosaline 0 Fresh	a Acid t Circumneutral i Alkaline	g Organic n Mineral	b *Beaver* d *Partially Drained/Ditched* f Farmed	h *Diked/Impounded* r Artificial Substrate s *Spoil* x Excavated

NOTE: 1. Italicized terms were added for mapping by the National Wetlands Inventory program.

2. Additional Water Regime Modifiers Added by WRA:

a. C1: Seasonally Flooded/Well Drained
b. C2: Seasonally Flooded/Seasonally Saturated
c. C3: Seasonally Flooded/Perm. Saturated
d. B1: Seasonally Saturated/Well Drained
e. B2: Seasonally Saturated
f. B3: Perm. Saturated
g. Ph: Irregularly Flooded/high marsh above MHHW
h. Pm: Irregularly Flooded/mid marsh between MHW and MHHW
i. N refers to low marsh or non-vegetated mudflats below MHW

Figure A-2. Bolinas Lagoon Invertebrate Sample Elevations

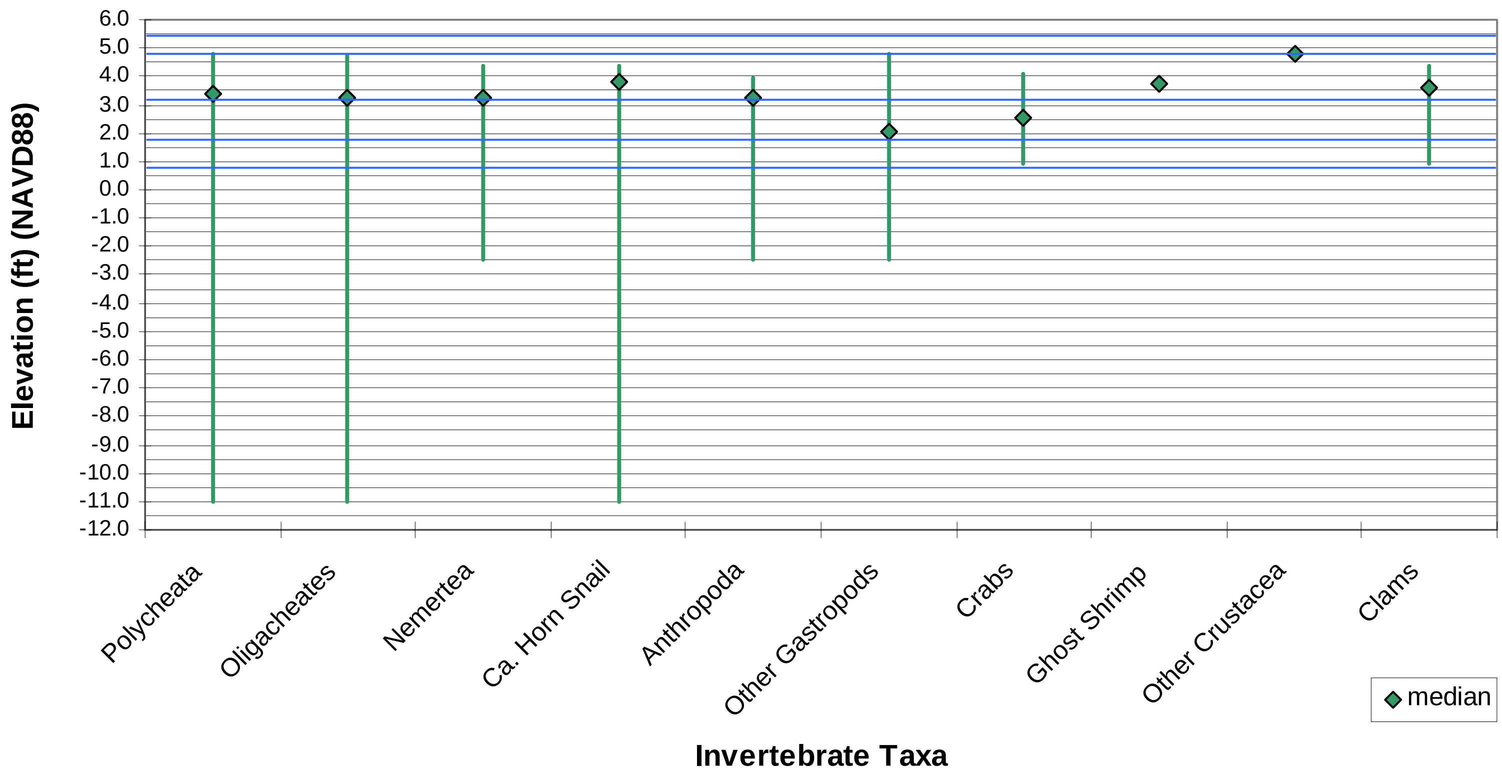


Figure A-3.
Overview of Invertebrate
Sample Locations

Bolinas Lagoon, California

wra
ENVIRONMENTAL CONSULTANTS
Map By: Gabe Olson

Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transects\TRG Memo\Fig7_InvertMap.mxd

Figure A-4a. Frequency of invertebrate occurrence at a particular elevation.

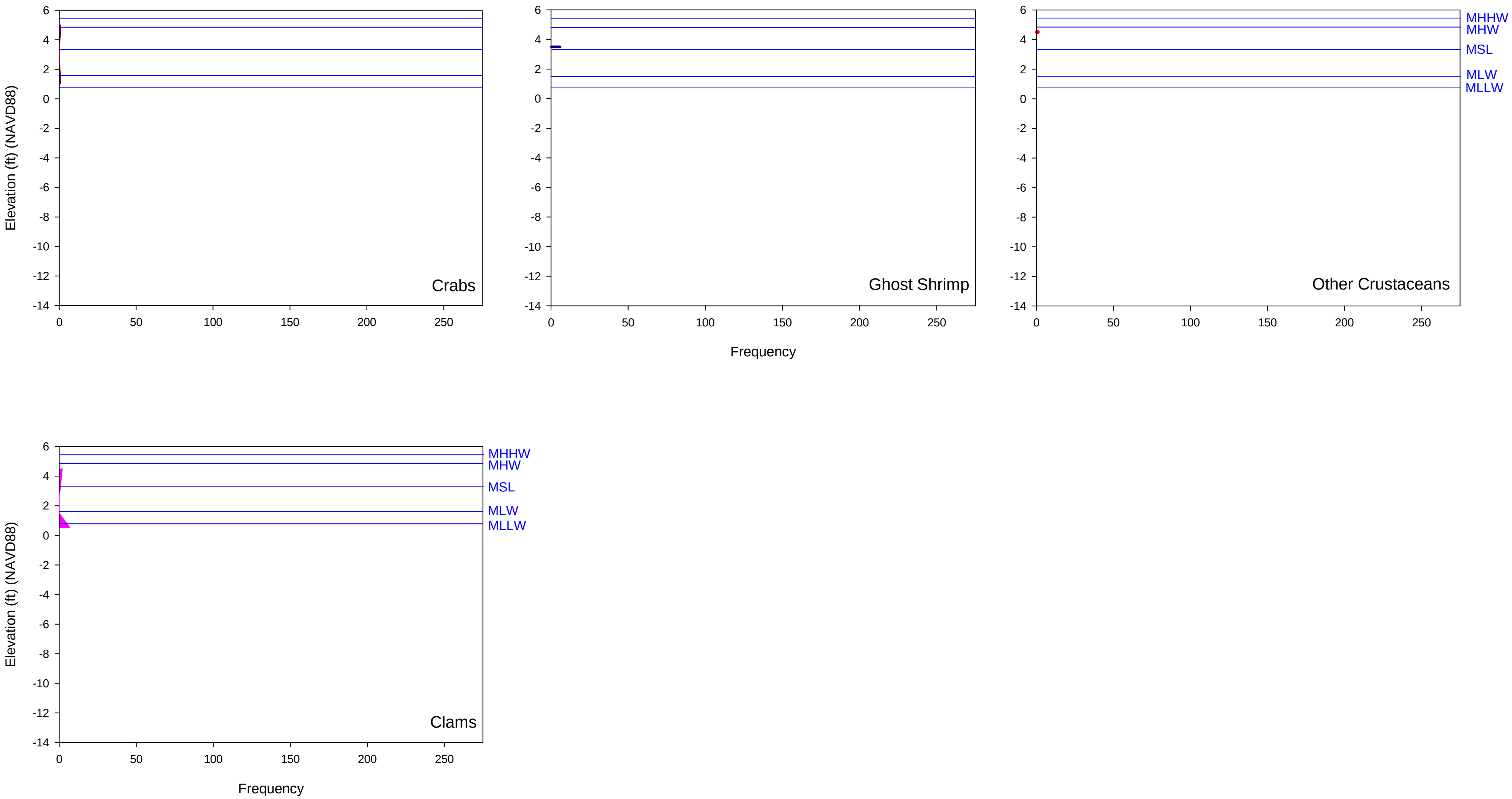
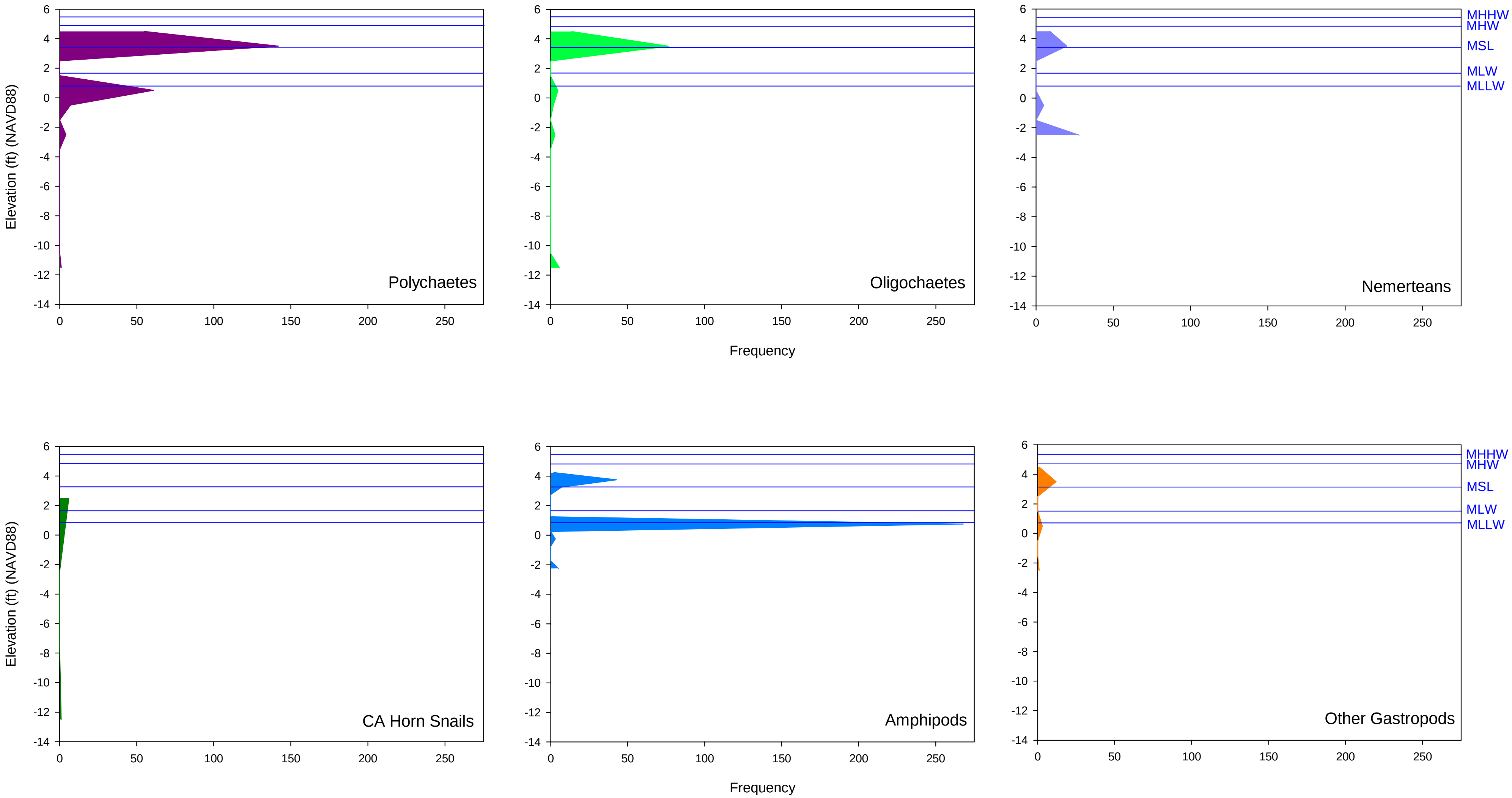


Figure A-4b. Frequency of invertebrate occurrence at a particular elevation.



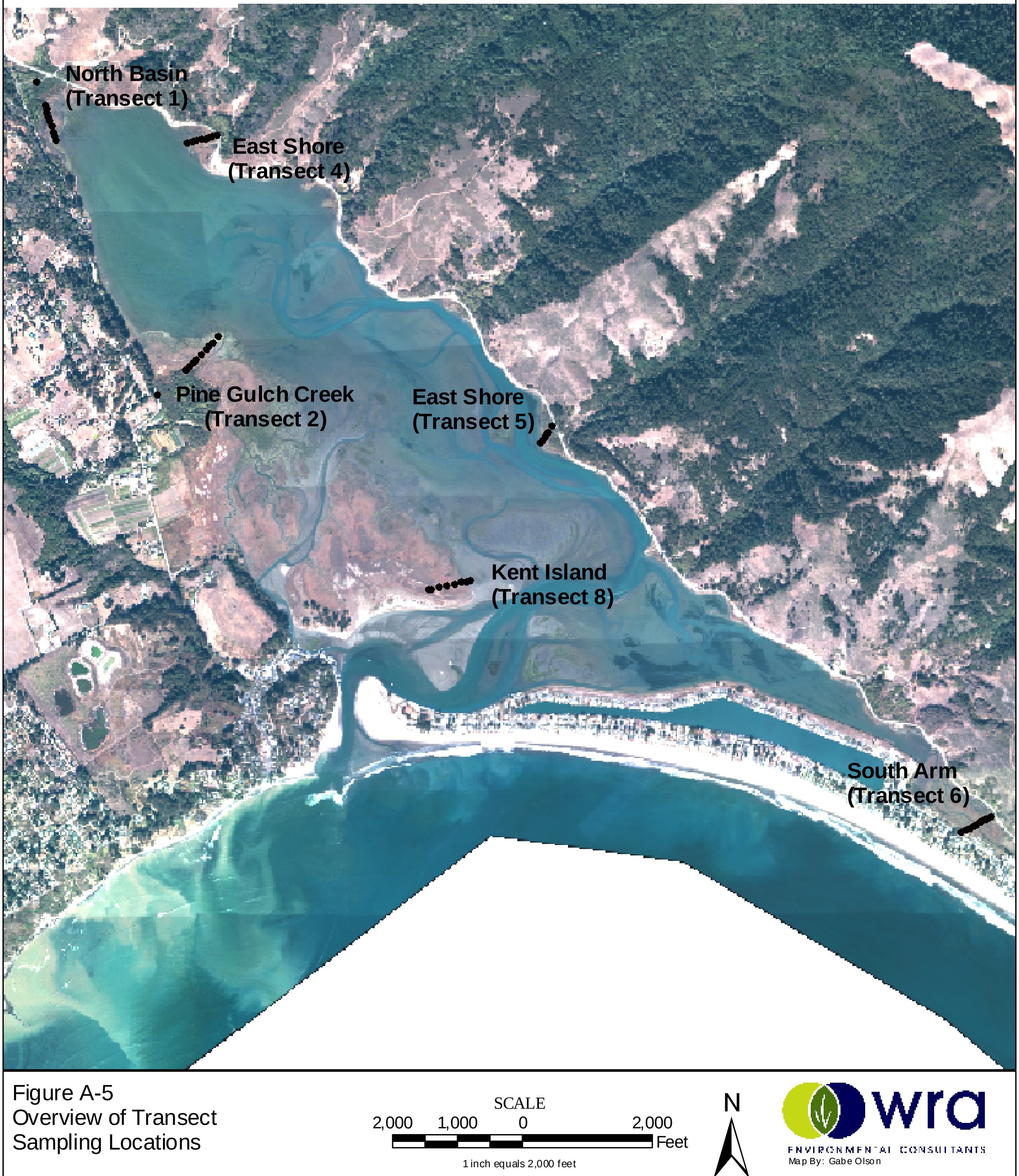


Figure A-5
Overview of Transect
Sampling Locations

Bolinas Lagoon, California

wra
ENVIRONMENTAL CONSULTANTS
Map By: Gabe Olson

Filepath: I:\Acad2000 files\13029\gis\Arcmap\TRG Memo\Fig1_Overview.mxd

Figure A-5a. Layout of Transect 1 at the North Basin

Bolinas, California

Vertical Datum: NAVD88

SCALE

150 75 0 150 Feet

1 inch equals 0 feet

N

wra

ENVIRONMENTAL CONSULTANTS

Map By: Gabe Olson
Basemap: USGS Topo Quad: Olivehurst
Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transect Figures\Fig 5-5a.mxd

Figure A-5b. Layout of Transect 2 at Pine Gulch Creek delta

Bolinas, California

Vertical Datum: NAVD88

SCALE

150 75 0 150 Feet

1 inch equals 0 feet

N

ENVIRONMENTAL CONSULTANTS

Map By: Gabe Olson
Basemap: USGS Topo Quad: Olivehurst
Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transect Figures\Fig 5-5b.mxd

Figure A-5c. Layout of Transect 4 along Eastern Shore

Bolinas, California

Vertical Datum: NAVD88

SCALE
150 75 0 150
Feet
1 inch equals 0 feet

N

wra
ENVIRONMENTAL CONSULTANTS

Map By: Gabe Olson
Basemap: USGS Topo Quad: Olivehurst
Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transect Figures\Fig 5-5c.mxd

Figure A-5d. Layout of Transect 5 along Eastern Shore

Bolinas, California

Vertical Datum: NAVD88

SCALE

150 75 0 150 Feet

1 inch equals 0 feet

N

wra ENVIRONMENTAL CONSULTANTS

Map By: Gabe Olson
Basemap: USGS Topo Quad: Olivehurst
Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transect Figures\Fig 5-5d.mxd

Figure A-5e. Layout of Transect 6 at South Arm

Bolinas, California

Vertical Datum: NAVD88

SCALE
150 75 0 150 Feet
1 inch equals 0 feet

N

wra ENVIRONMENTAL CONSULTANTS
Map By: Gabe Olson
Basemap: USGS Topo Quad: Olivehurst
Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transect Figures\Fig 5-5e.mxd

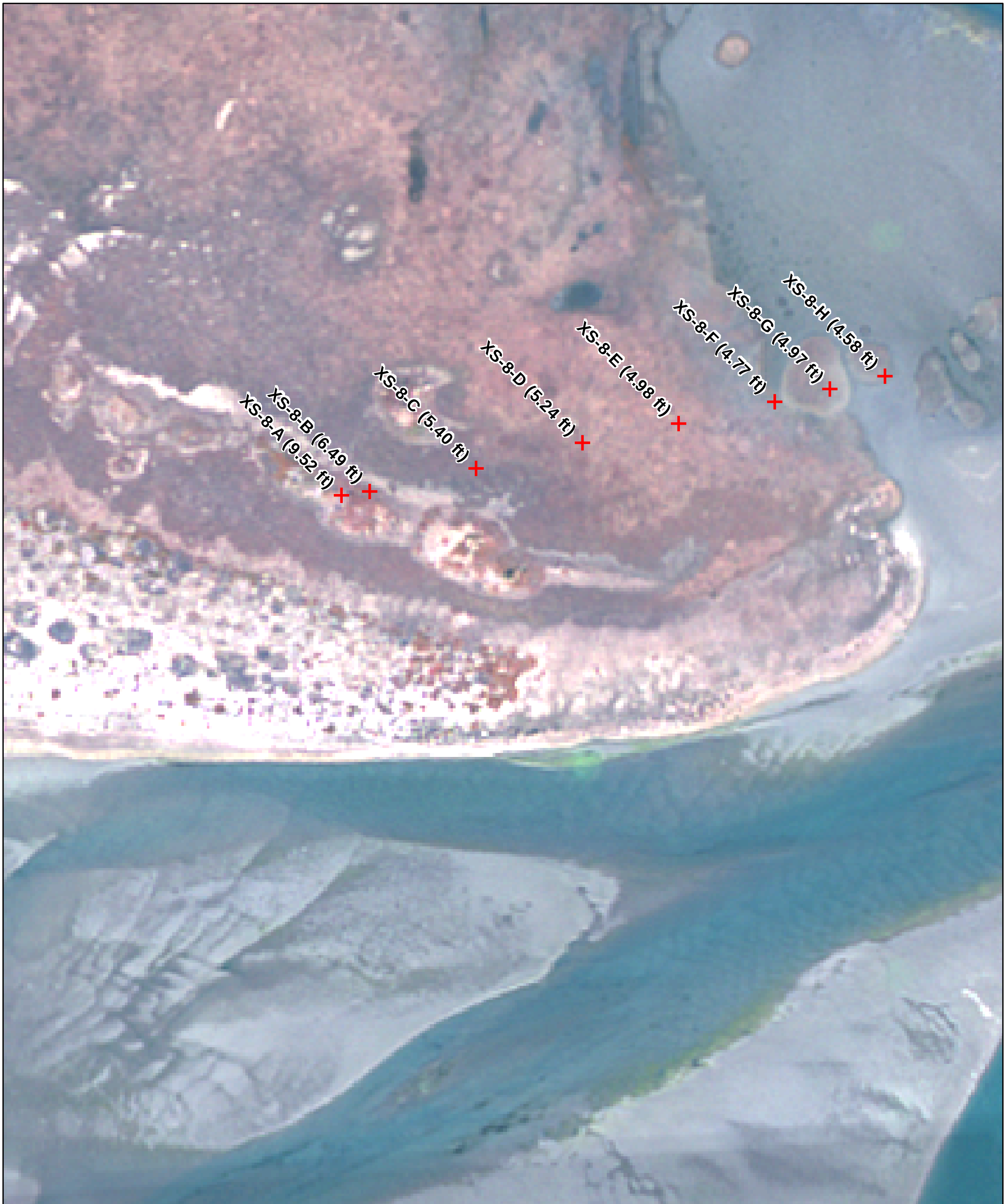


Figure A-5f. Layout of Transect on Kent Island

Bolinas, California

Vertical Datum: NAVD88

SCALE

150 75 0 150 Feet

1 inch equals 0 feet

N

wra ENVIRONMENTAL CONSULTANTS

Map By: Gabe Olson
Basemap: USGS Topo Quad: Olivehurst
Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transect Figures\Fig 5-5f.mxd

Figure A-6. Sampled Habitat Elevations in Bolinas Lagoon

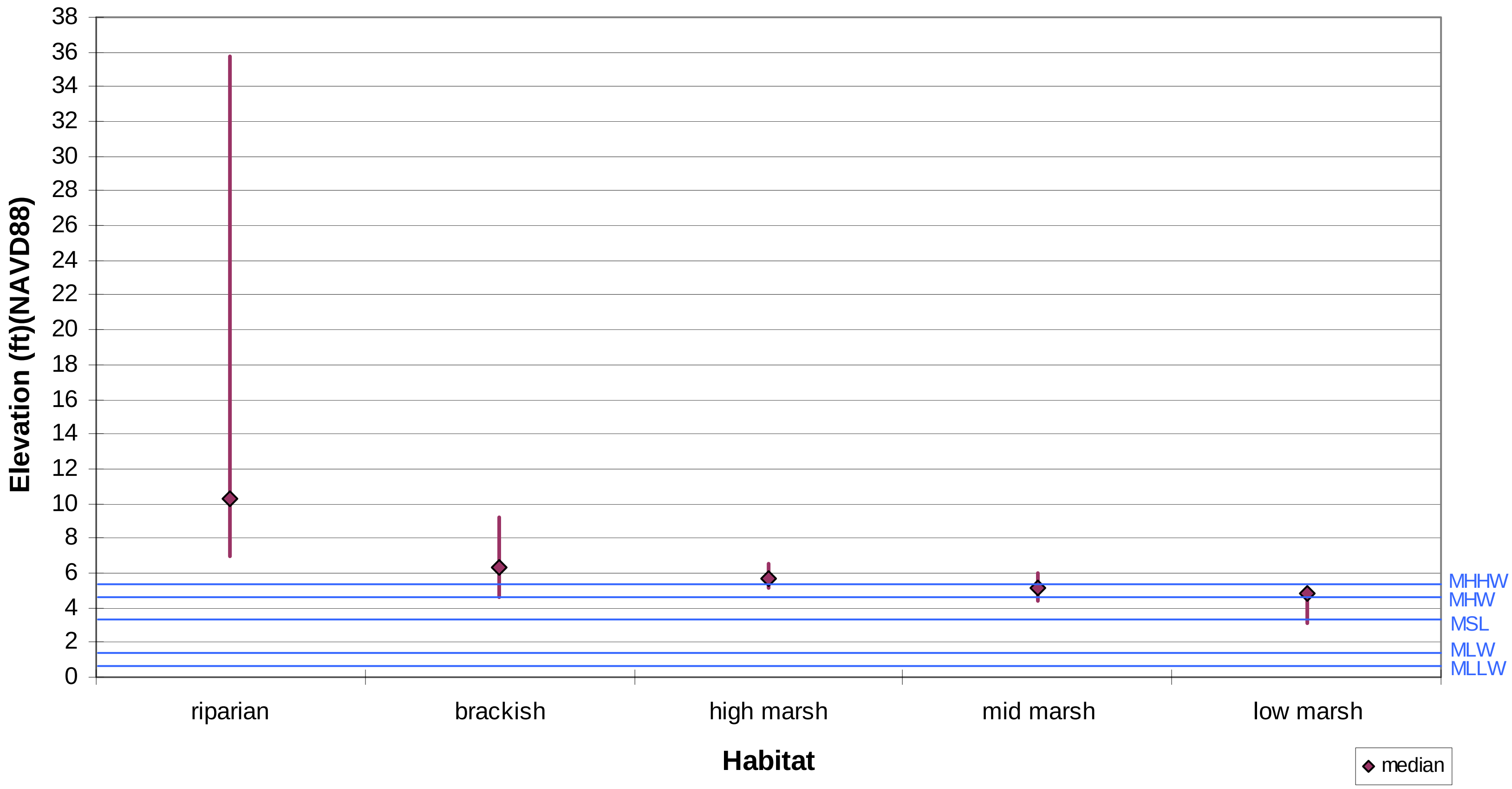
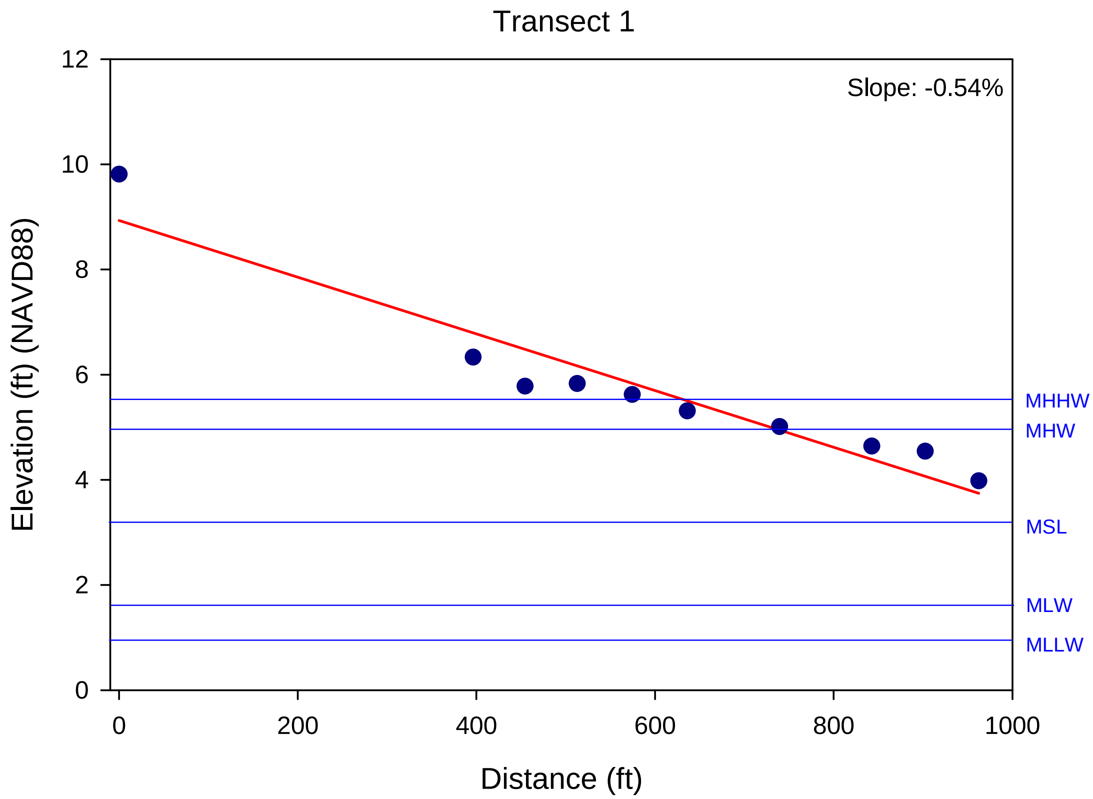


Figure A-7. Transect slopes (elevation vs. distance from 0 ft. to end point).



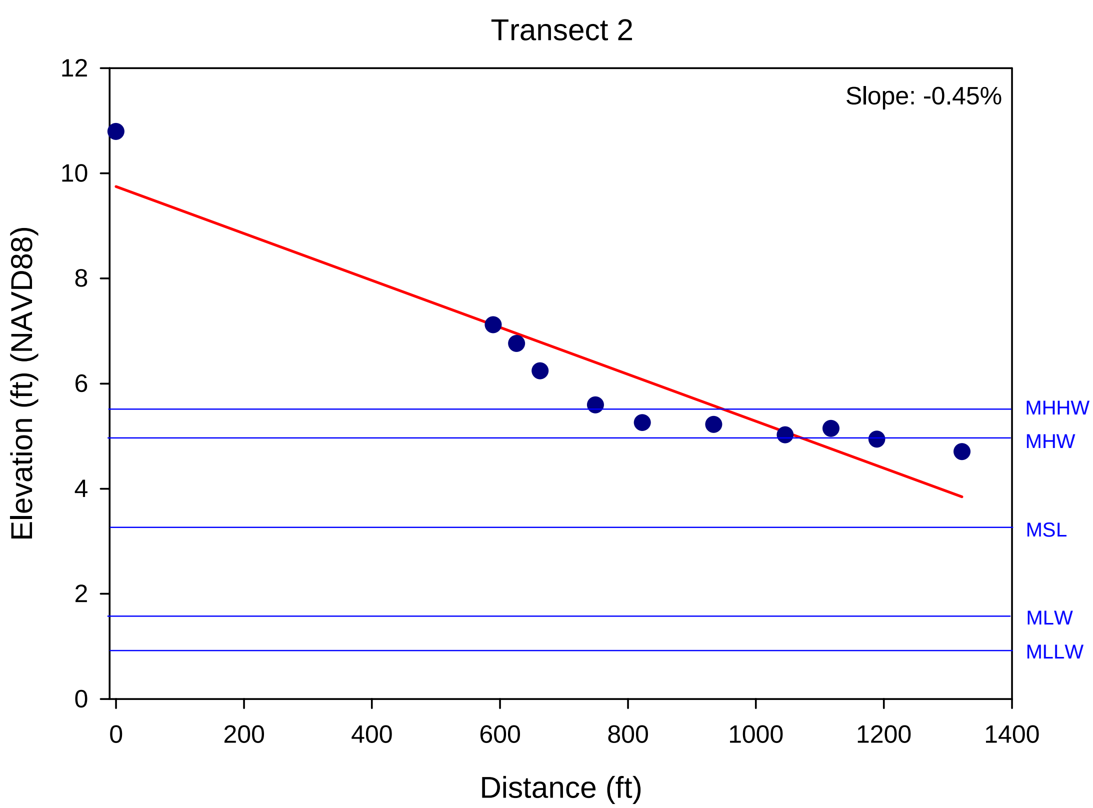
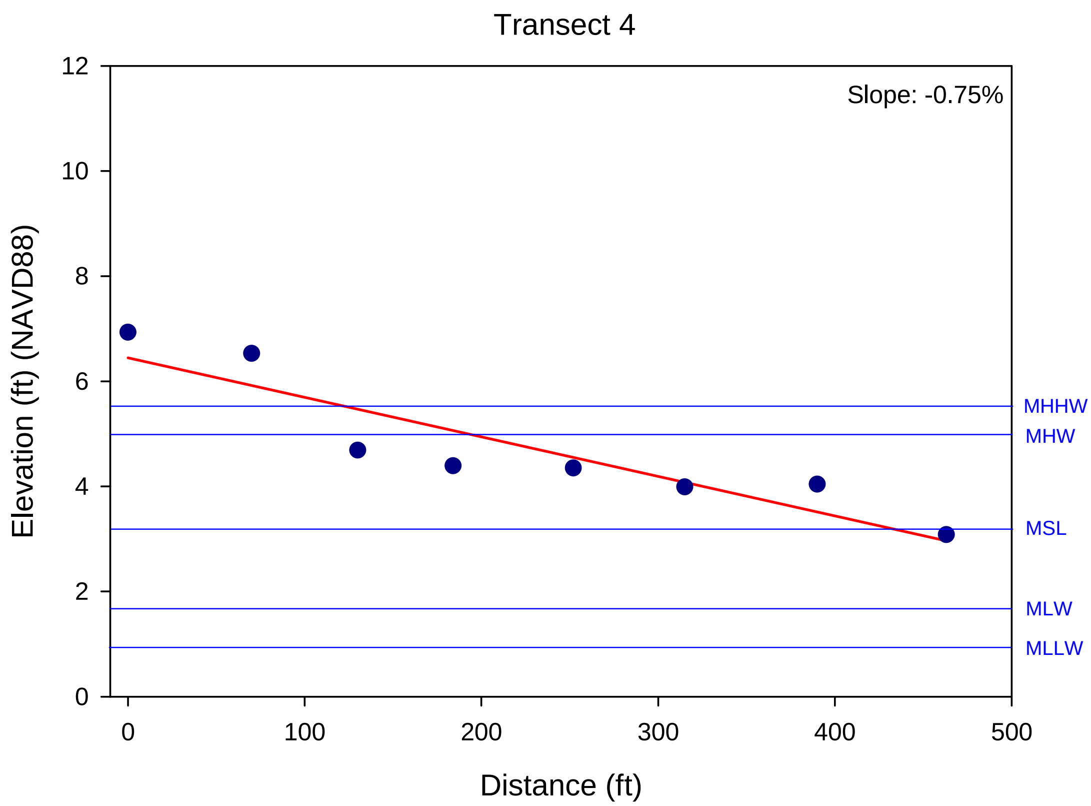


Figure A-7. Transect slopes (elevation vs. distance from 0 ft. to end point).



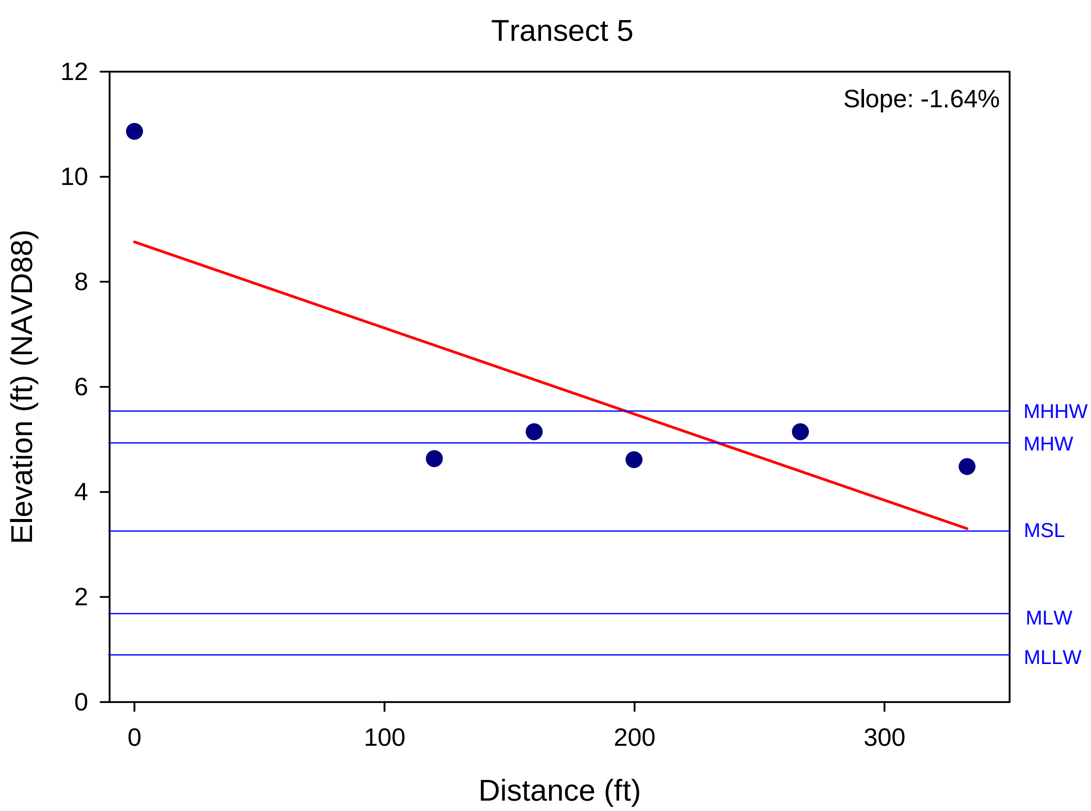
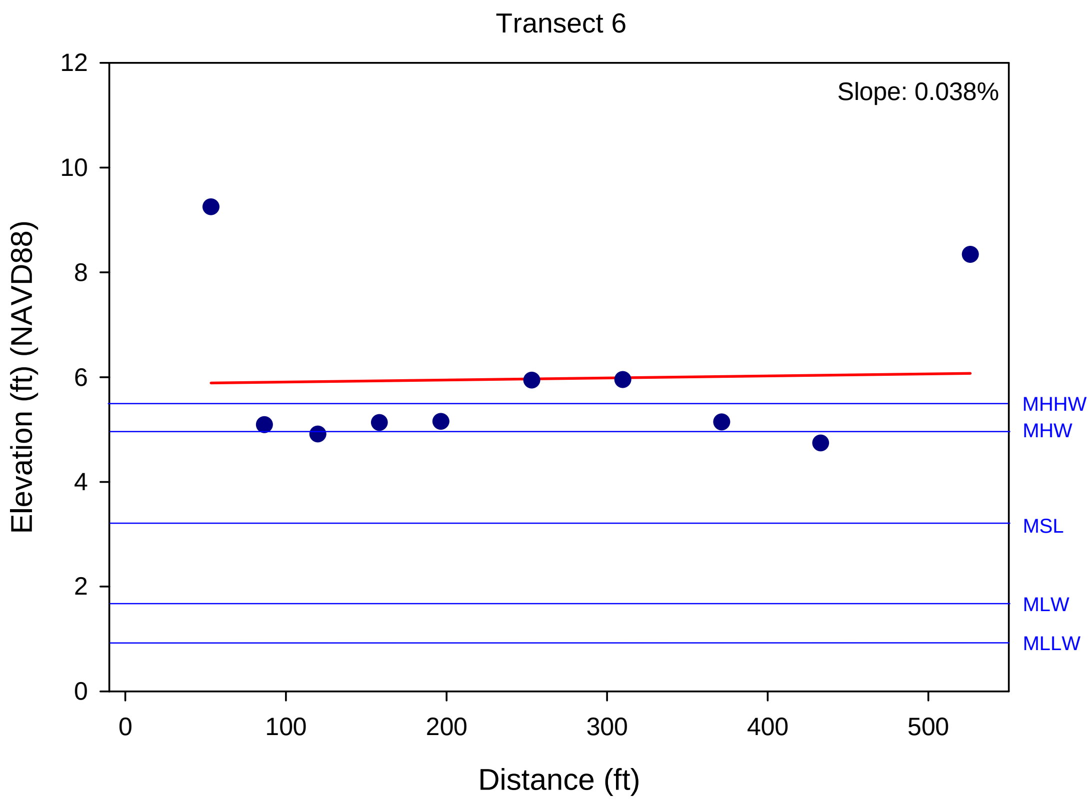


Figure A-7. Transect slopes (elevation vs. distance from 0 ft. to end point).



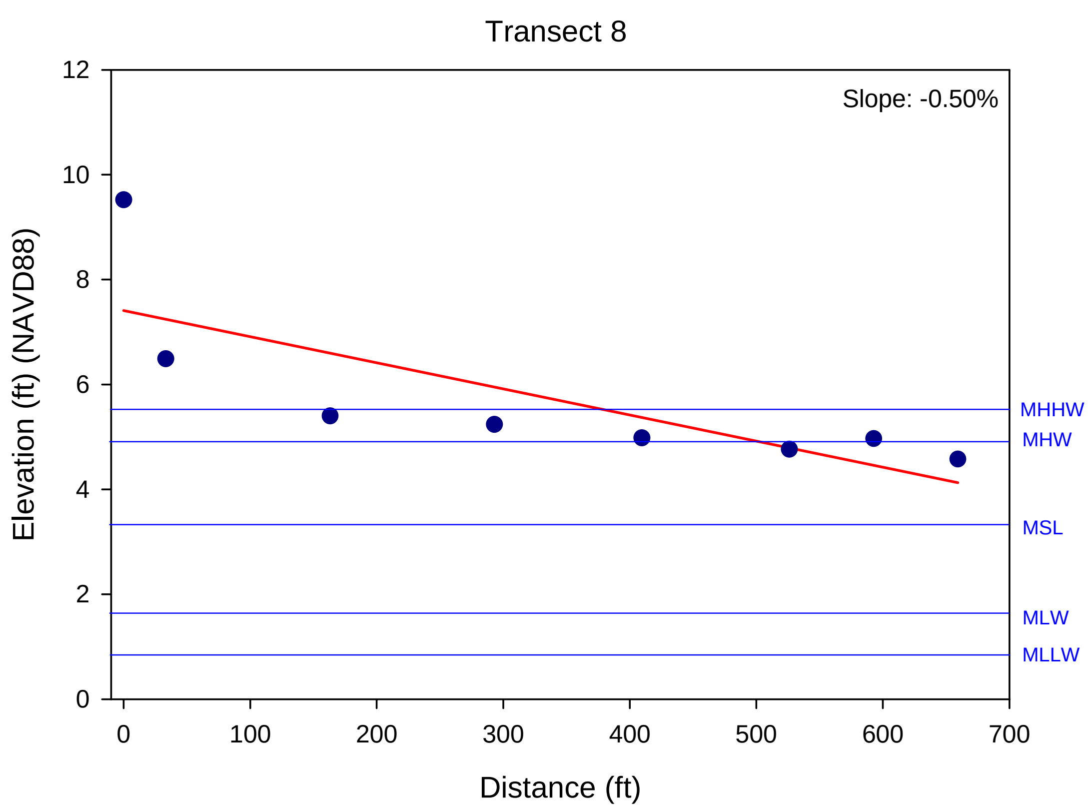


Figure A-8. Sampled plant species elevations at Bolinas Lagoon

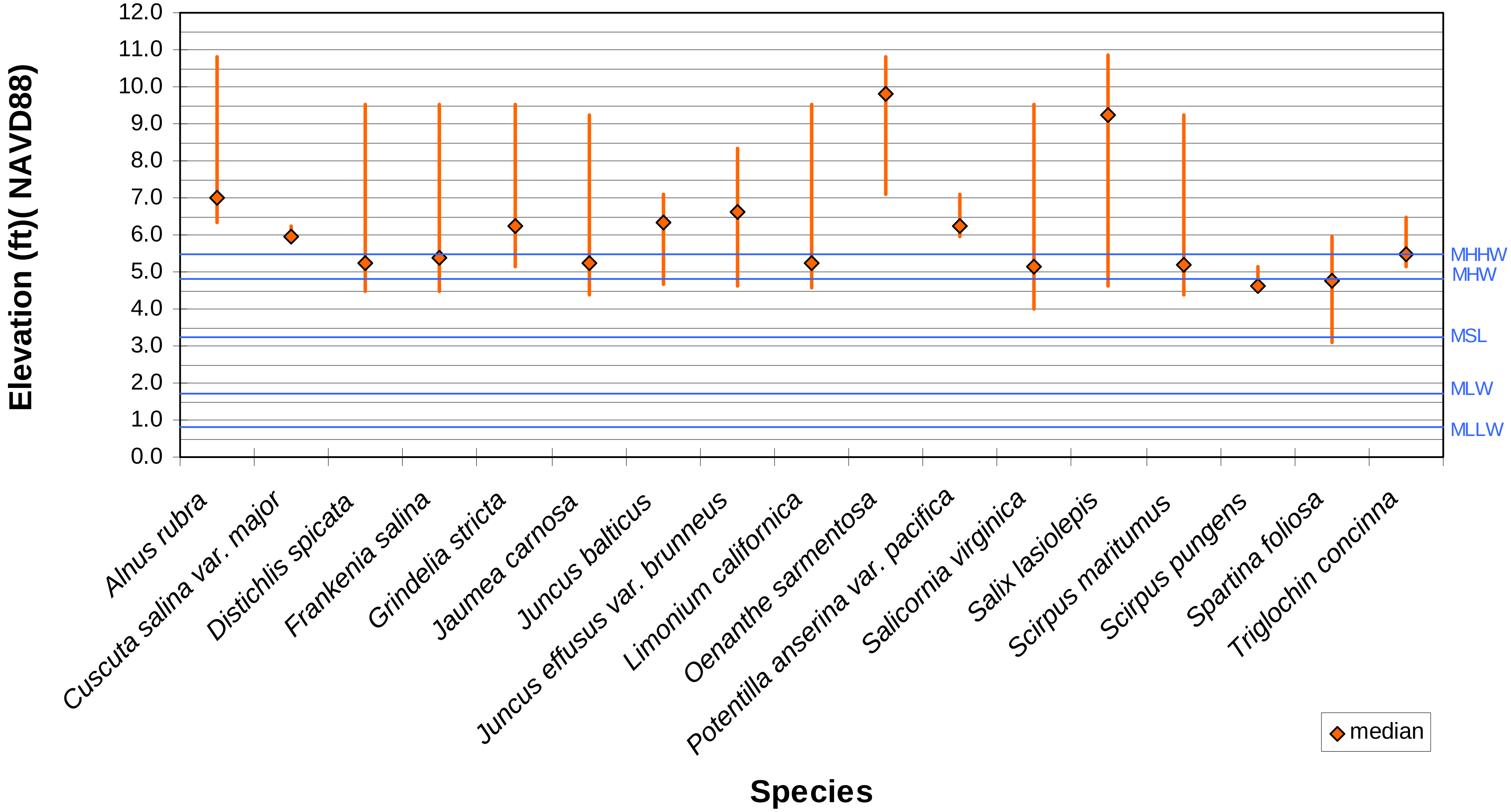


Figure A-9a. Frequency of plant species occurrence at a particular elevation.

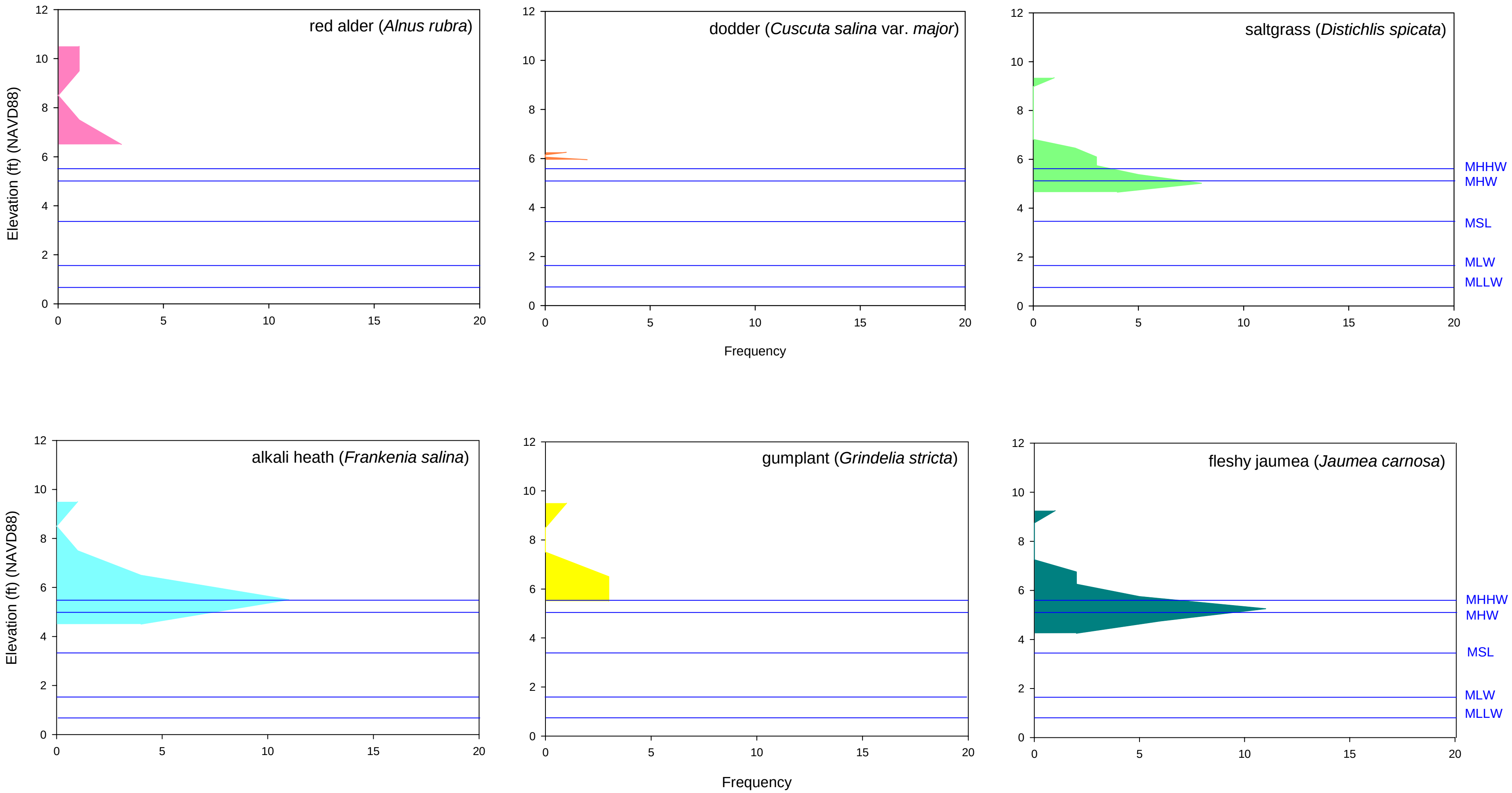


Figure A-9b. Frequency of plant species occurrence at a particular elevation.

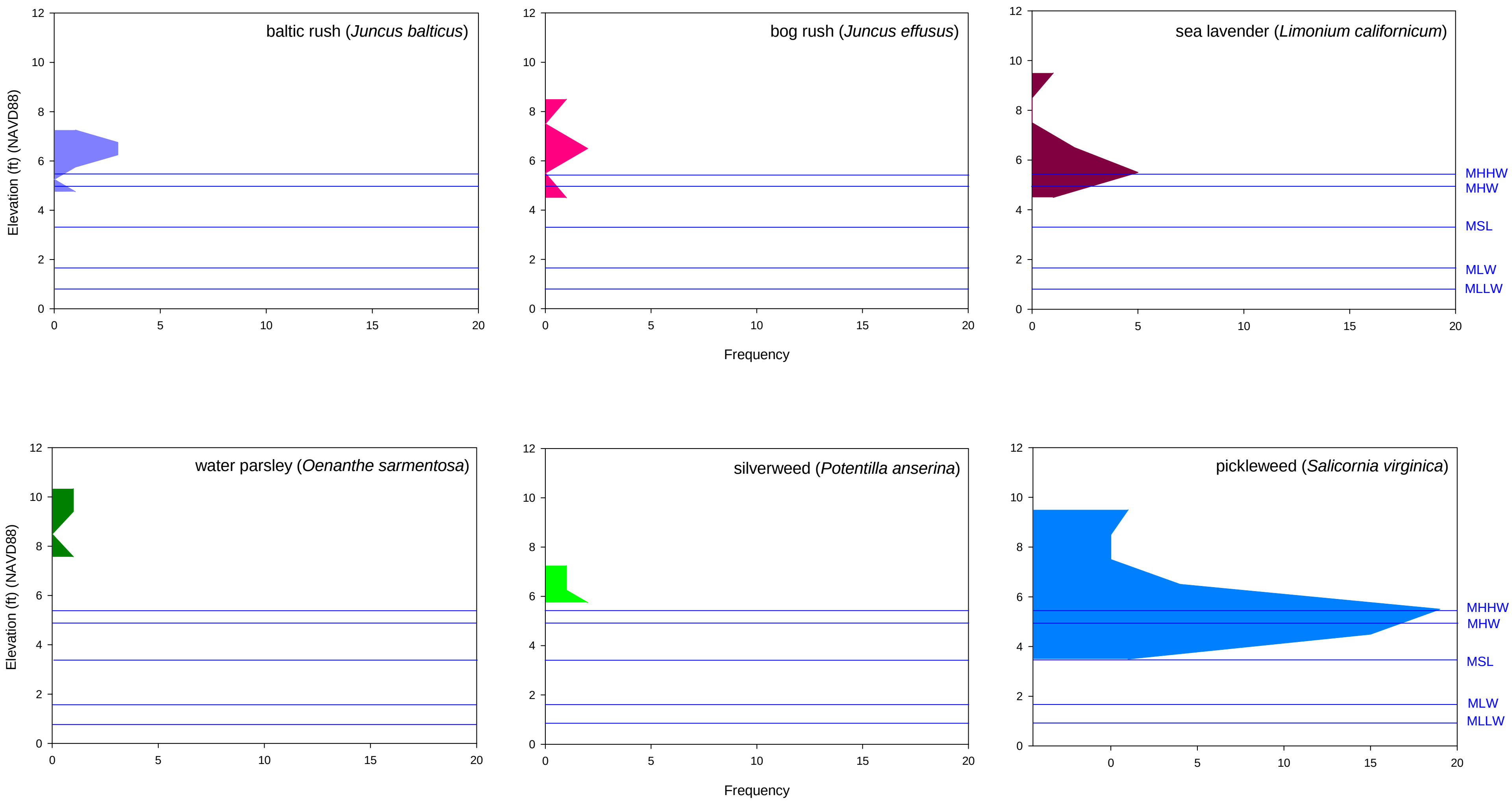


Figure A-9c. Frequency of plant species occurrence at a particular elevation.

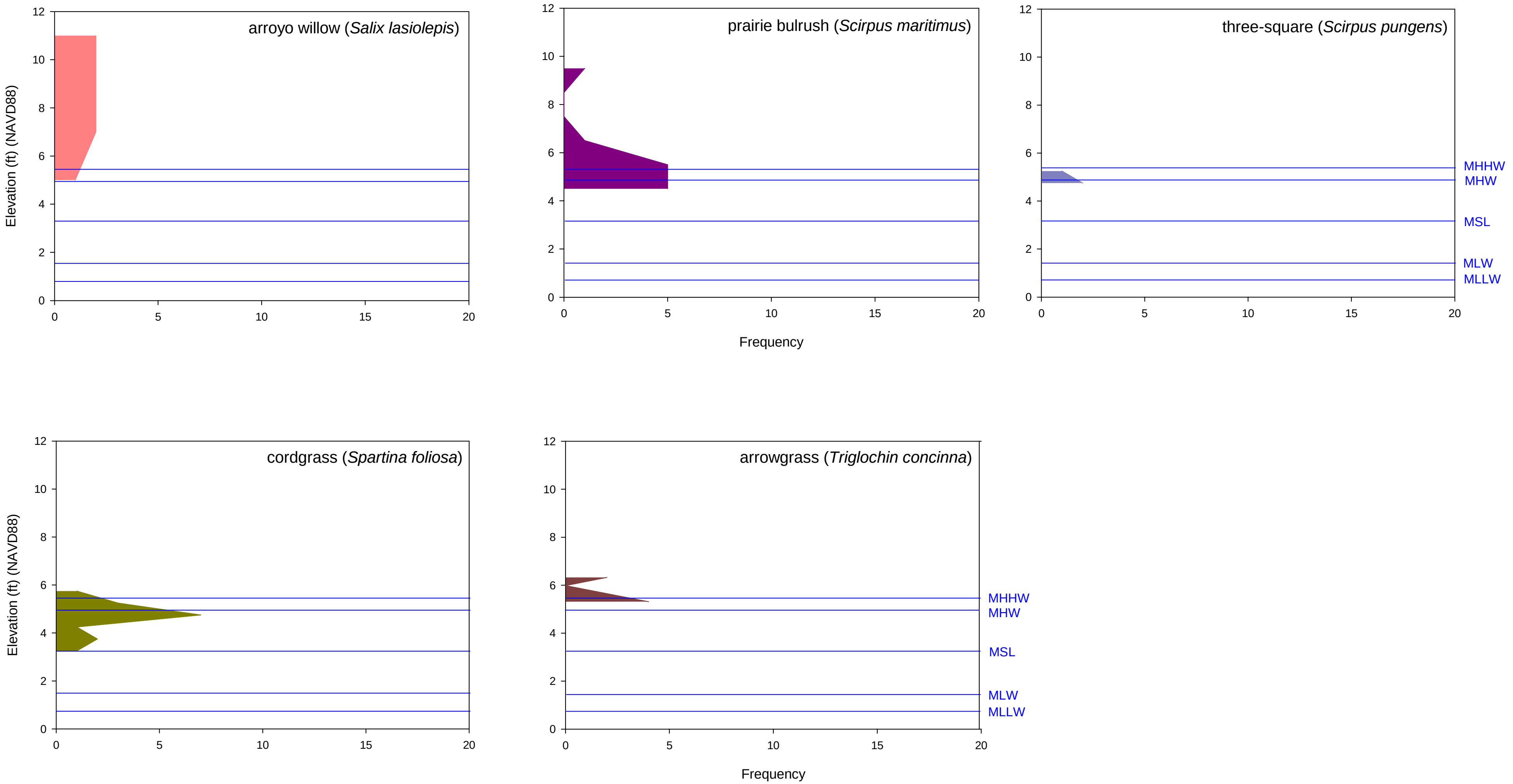


Figure A-10. Substrate texture vs. distance from inlet by transect number.

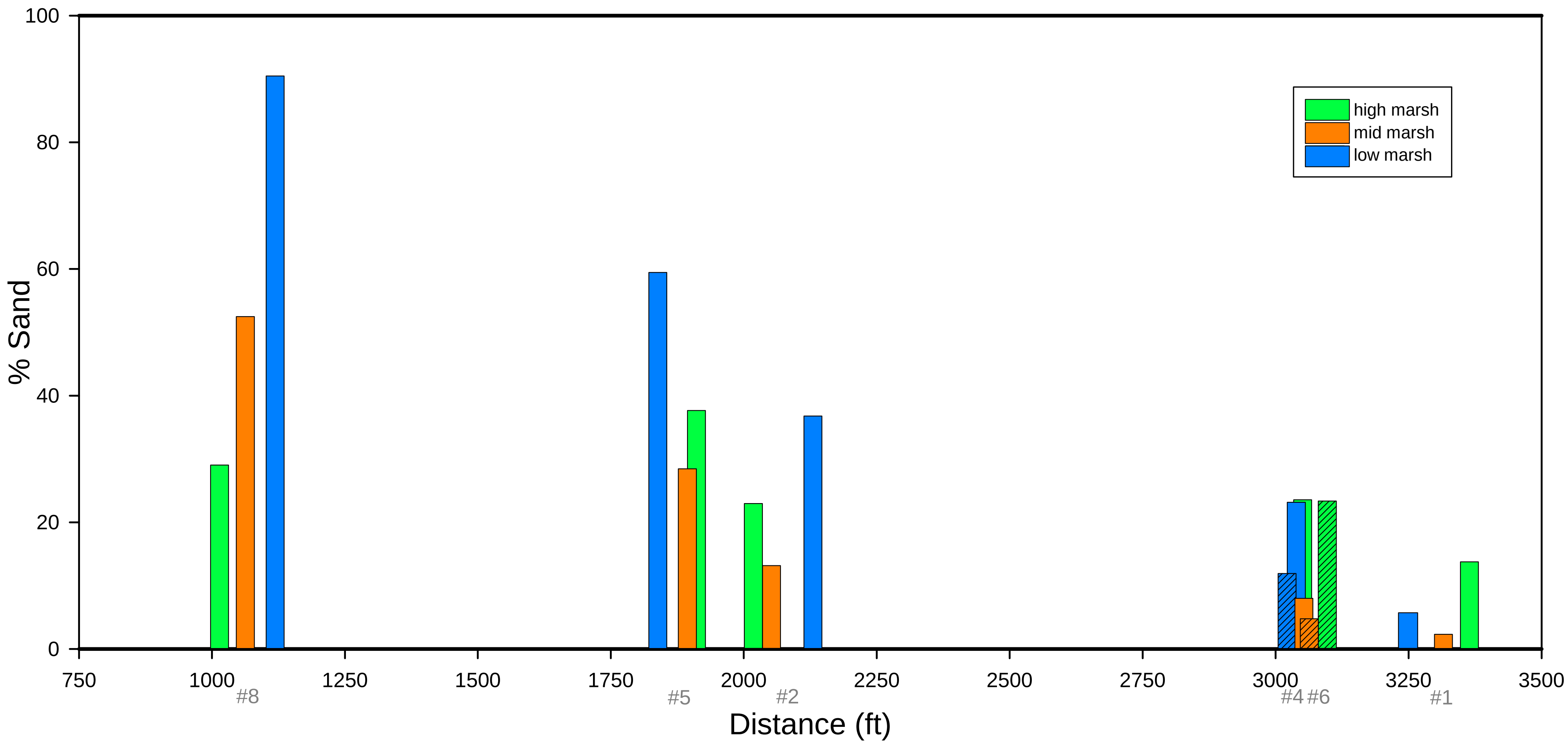
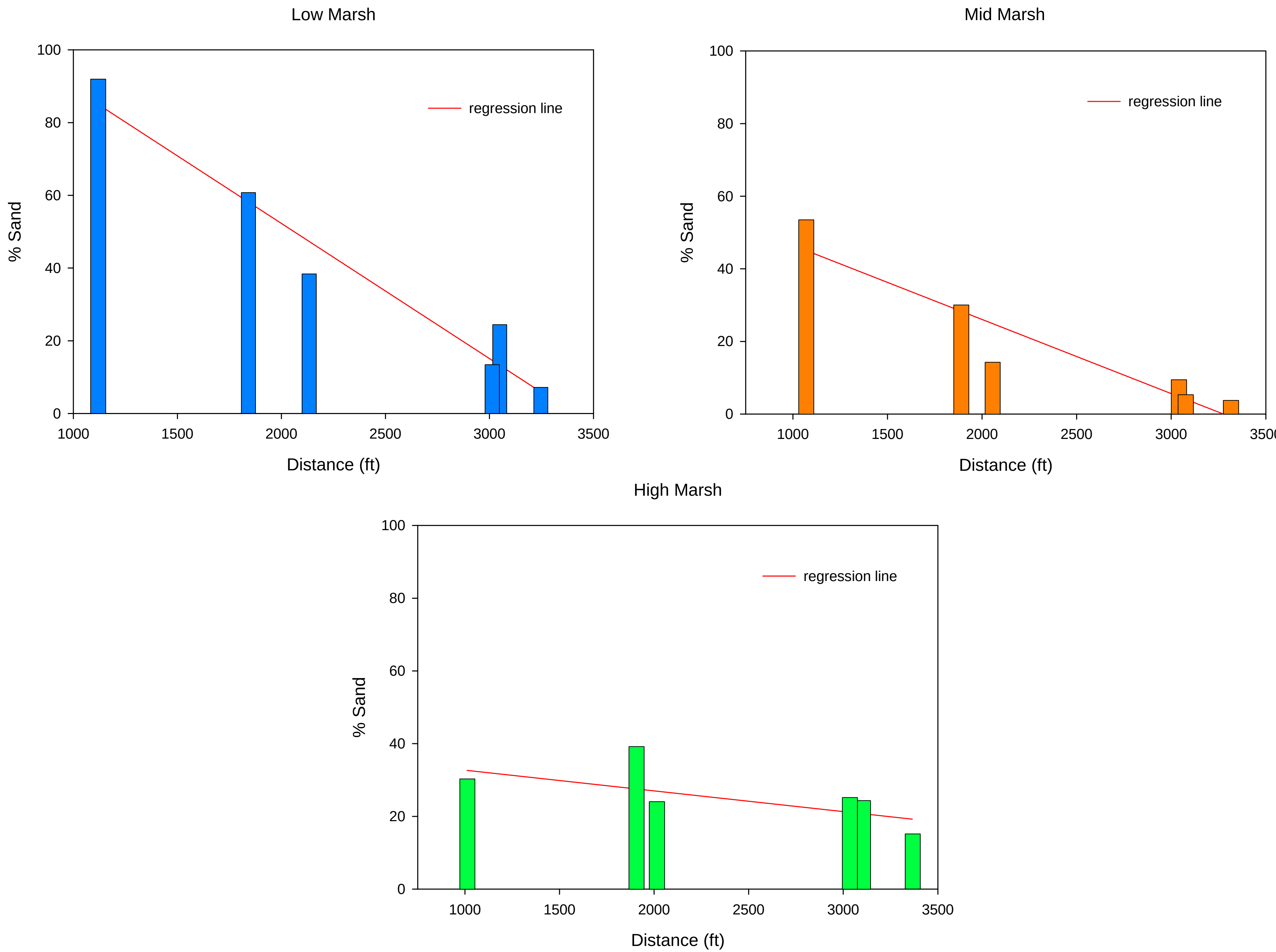


Figure A-11. Substrate texture plotted against distance from inlet for high, mid, and low marsh habitats.



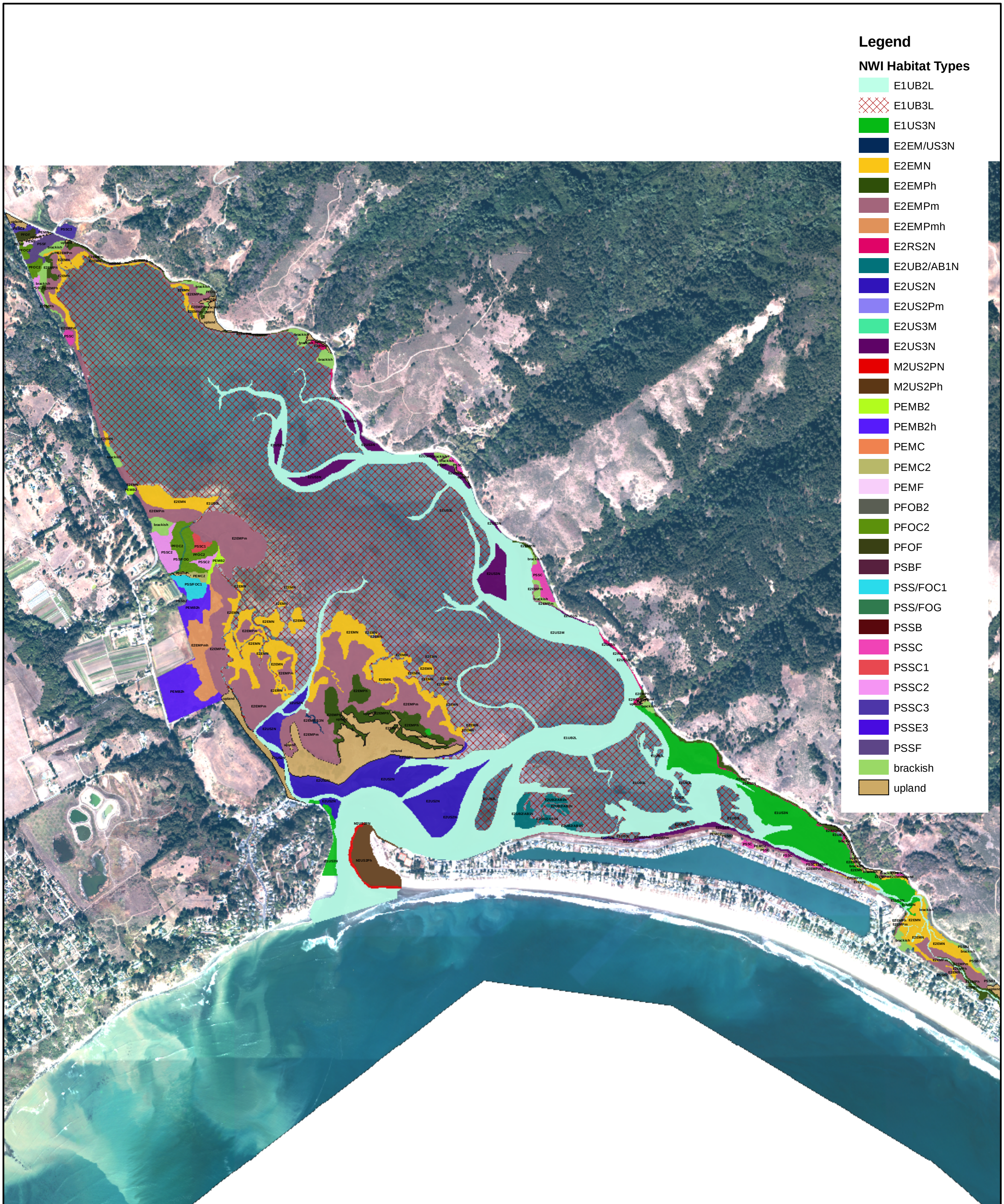


Figure A -12.
Year 0 Map of NWI
Wetland Habitat Types

Bolinas Lagoon, California

SCALE
2,000 1,000 0 2,000
Feet
1 inch equals 2,000 feet

N

ENVIRONMENTAL CONSULTANTS
Map By: Gabe Olson

Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transects\TRG Memo\Fig5_NWIMap.mxd

Figure A-13.
Map of Point Reyes bird's beak occurrences on Kent Island

Bolinas Lagoon, California

SCALE
500 250 0 500
Feet
1 inch equals 500 feet

N

wra
ENVIRONMENTAL CONSULTANTS
Map By: Gabe Olson

Filepath: I:\Acad2000 files\13029\gis\Arcmap\Transects\TRG Memo\Fig8_BirdsBeak.mxd

APPENDIX B
TIDAL DATUMS, BENCHMARKS AND ESTIMATES OF HISTORIC TIDAL PRISM

Appendix B – Section 1

Tidal Datums and Benchmarks

NOS tidal datums are available for Bolinas Lagoon for the 1983-2001 epoch (Table B-1). We applied the difference between MHHW and MLLW (4.3 ft) as the effective diurnal tidal range in our calculations of tidal prism and tidal power. We should note that these datums were established from relatively short tide gage deployment (Nov-Dec 1979) by the National Ocean Service (NOS), and vary slightly from the diurnal range reported by Johnson (1969). Although Johnson reported a similar diurnal tide range (4.4 ft), the geodetic elevation of MSL (NGVD29) differed by 0.3 ft. We should note however, that his values were not for the 1983-2001 tidal epoch.

Table B-1. Tidal Datums for Bolinas Lagoon

	ft (MLLW)
MHHW	4.30
MHW	3.97
MTL	2.19
MSL (NGVD29)	2.19
MLW	0.70
MLLW	0.00

Source: NOS station 9414958

Due to questions regarding the accuracy of benchmarks used to establish the tidal datums and reference the photogrammetric/hydrographic surveys of 1968 & 1998, Marin County established a network of geodetic benchmarks around the lagoon as necessary to control elevation and planimetric surveys as recommended by the Project's Technical Review Group (TRG). Although differential leveling was not adequate for inclusion in the Height Modernization survey, analysis confirmed that the leveling observations were within 2 cm (Geodetic Solutions, 2005).

In order to increase our confidence that NOS benchmark 4958-C has not significantly subsided, we compared its re-surveyed elevation to the published elevation from 1979. This required the use of a NGVD29-NAVD88 conversion, which we generated from VERTCON. A second benchmark, established by Caltrans in 1992, along Highway 1 (TF-HW-1) was examined in a similar manner. For this benchmark, PWA performed a level loop between the re-surveyed 4958-C and TF-HW-1 to establish NAVD88 control. In both cases, the difference between their original and revised elevations were less than 0.08 ft (see Table A-1).

Estimate of Historic Tidal Prism

Approximate values of historic tidal prism may be computed from inspection of T-sheets. For the present study, PWA calculated the tidal prism of Bolinas Lagoon by:

- measuring the extent of subtidal and intertidal habitats in the 1854 and 1929 T-sheets,
- assuming that historic tidal ranges were similar to contemporary values (see Table A-1),

- applying an algebraic equation for the volume between two conic sections

In addition to the volume of water between subtidal and marsh elevations, we have accounted for a contribution from subtidal channels within the marshplain using hydraulic geometry relationships derived from San Francisco Bay (Williams and others, 2002).

Details of these computations are shown in Table B-3. A summary of tidal prism estimates is provided in Table B-4.

Table B-2. Comparison of Original and Revised Benchmark Elevations

Previous Survey Elevation				**Agency**	**NGVD/NAVD Conversion**
Description	Feet (MLLW)	Feet (NGVD29)	Feet (NAVD88)		(ft)
4958-C	14.41	12.94	15.6	NOS	2.66
TF-HW-1		9.66	12.35	Caltrans	2.69

2005 Survey Elevation		
Description	feet (NAVD88)	
4958-C	15.67	(from Geodetic Solutions report, 2005)
TF-HW-1	12.27	(from PWA level-loop)

Elevation Change		
4958-C	0.07	8/7/81 to 2/23/05
TF-HW-1	-0.08	7/22/92 to 2/23/05

NOTE: NGVD/NAVD conversion based on VERTCON

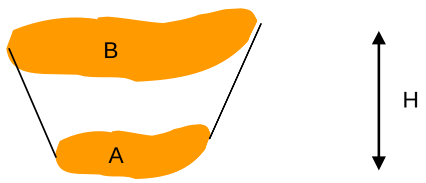
Table B-3. Calculating Tidal Prism from Historic T-Sheets

1. Areas based on T-sheets

	1854 (acres)	*1929 (acres)*
marsh	170	77
intertitdal	910	682
subtidal	130	487
	1,210	1,246

2. Using equation for conic sections, calculate volume between intertidal flats and marsh.

V=H/3 * (SQRT(AB)+A+B)



H = mean diurnal range 4.3 ft (based on NOS benchmark 9414958)
A = subtidal area
B = subtidal + intertidal area

	a (ac)	b (ac)	volumes (ac-ft)	volumes (MCY)
1854	130	1040	2,204	3.6
1929	487	1169	3,455	5.6

3. Use SF Bay hydraulic geometry equations to calculate tidal prism contribution from salt marsh

	volumes (MCY)
1854	0.172
1929	0.068

4. TOTAL TIDAL PRISM

add conic volumes and contribution from salt marshes

	tidal prism (MCY)
1854	**3.7**
1929	**5.6**

Possible error-bar, assuming +/- 0.5 ft difference in historic tidal range (3.8 to 4.8 ft):

date	*MCY*
1854	*3.3 to 4.1*
1929	*5.0 to 6.3*

Table B-4. Summary of Tidal Prism Calculations

Data from UCB cores:

1850-1906	6.2 mm/yr
1906-2005	6.8 mm/yr

Sea level rise

1850-1906	2 mm/yr
1906-2000	2.1 mm/yr
2000-2050	2.35 mm/yr

Tidal 'footprint' of Bolinas Lagoon

pre-development	1,250 acres
post-development	1,160 acres

Size of area of affected by 19th C. logging
400 acres

Tidal prism estimated from T-sheets

1854	3.7 MCY
1929	5.6 MCY

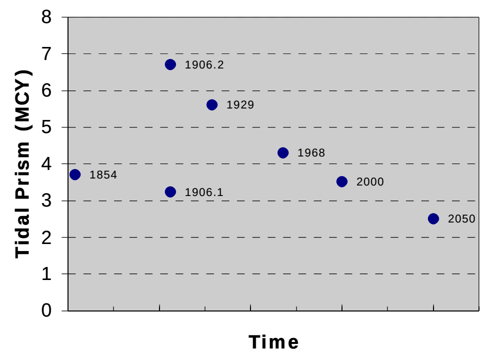
Conversion factors
304.8 mm/ft
1613 CY/ac-ft
4,047 m2/acre

Tidal prism estimated from Corps TINs

1998	3.5 MCY
1968-1998 change	0.8 MCY

Tidal Prism

Date	MCY	m3 (million)
1854	3.7	2.8
1906.1	3.2	2.5
1906.2	*6.7*	5.1
1929	5.6	4.3
1968	4.3	3.3
2000	3.5	2.7
2050	2.5	1.9



apply Byrne post-1906 rate over 1200-ac lagoon	43,183	(CY/yr)
rate of sed accuml based on Corps' TINs (1968-98)	45,000	(CY/yr)
rate of TP loss: 1906 to 1998 (based on TP time series)	34,115	(CY/yr)
rate of TP loss: 1929 to 1998	29,577	(CY/yr)

NOTES: 1906.2 estimate of tidal prism inferred by extrapolating 20th century rate. YR 50 projection established from PLANIMETRIC changes - NOT by applying historic sedimentation rates.

References

Geodetic Solutions. 2005. Bolinas Lagoon Height Modernization Project. GPS Accession Number 2030 Final Report. January 23, 2005 (revised February 10, 2005).

Johnson, J. 1969. Tide Data: Bolinas Bay and Bolinas Lagoon. Unpublished memorandum. July 1969.

Williams, P.B., M. Orr, and N. Garrity. 2002. Hydraulic Geometry : A Geomorphic Design Tool for Tidal Marsh Channel Evolution in Wetland Restoration Projects, *Restoration Ecology*, September 2002.

Appendix B – Section 2

T I D A L   B E N C H   M A R K S

BENCH MARK STAMPING: 4958 C 1979
DESIGNATION: 941 4958 C

MONUMENTATION: Tidal Station disk VM#: 11858
AGENCY: National Ocean Survey (NOS) PID:
SETTING CLASSIFICATION: Concrete sea wall

The bench mark is a disk set in top of a concrete seawall, 33 m (108 ft) SSE of
the SW corner of the last house on Wharf Road, 12 m (39 ft) NNW of the south end of the seawall (south end of Wharf Road), and 4.57 m (15.0 ft) ENE of the centerline of Wharf Road.

T I D A L   D A T U M S

Tidal datums at BOLINAS, BOLINAS LAGOON based on:

LENGTH OF SERIES:	2 MONTHS
TIME PERIOD:	November 1979 - December 1979
TIDAL EPOCH:	1983-2001
CONTROL TIDE STATION:	9414290 SAN FRANCISCO, SAN FRANCISCO BAY

Elevations of tidal datums referred to Mean Lower Low Water (MLLW), in METERS:

MEAN HIGHER HIGH WATER (MHHW)	=	1.311
MEAN HIGH WATER (MHW)	=	1.120
MEAN TIDE LEVEL (MTL)	=	0.667
MEAN SEA LEVEL (MSL)	=	0.667
MEAN LOW WATER (MLW)	=	0.214
MEAN LOWER LOW WATER (MLLW)	=	0.000

Bench Mark Elevation Information — In METERS above:

Stamping or Designation	MLLW	MHW
4958 C 1979	4.314	3.194

TIDE DATA

Bolinas Bay and Bolinas Lagoon

J.W. Johnson
July 1969

Tidal Relationships

The reference tide station for central California is the USC&GS gage located at The Presidio, San Francisco. Lower-low-water datum at this station is based on miscellaneous observations prior to 1907, and adopted as standard in March, 1907. Elevations of other tide planes referred to this datum are based on 19 years of records, 1941-1959. The USC&GS operated a tide gage for a short period at Bolinas (probably at the Lagoon entrance) and apparently used these data in calculating the difference in the time and height of tides at Bolinas Bay and Bolinas Lagoon with respect to The Presidio in San Francisco. The 1969 USC&GS Tide Tables for the West Coast, North and South America, gives the tidal differences shown in Table 1.

Table 1
Tidal Differences
Bolinas Bay and Bolinas Lagoon

Place	Differences				Ranges	
	Time		Height		Mean	Diurnal
	High water	Low water	ft.	ft.	ft.	ft.
Bolinas Bay	h.m. -0 29	h. min. -0 17	0.0	0.0	4.0	5.7
Bolinas Lagoon	-0 20*	+0 31	0.74**	0.73**	3.0	4.4

* A plus (+) sign indicates that the tide at the subordinate station is later than at the reference station (i.e. The Presidio) and the difference should be added, a minus (-) sign, that it is earlier and should be subtracted.

** Ratio of height at subordinate station to the height at The Presidio.

Additional statistical data on tidal planes at The Presidio, Bolinas Bay, and Bolinas Lagoon have been obtained in recent correspondence from the USC&GS and are presented in Table 2.

Table 2
Tidal Data

Tide Plane	Presidio (ft.)	Bolinas Bay (ft.)	Bolinas Lagoon (ft.)
Highest Tide, Dec. 24, 1940	8.0	-	-
Higher High Water	5.7	5.7	4.4
High Water Spring	5.5	5.5	4.1
Mean High Water	5.1	5.1	3.8
High Water, Neap	4.7	4.7	3.5
Mean Tide Level	3.1	3.1	2.3
Sea Level Datum (1929)*	-	-	1.86
Low Water, Neap	1.5	1.5	1.1
Mean Low Water	1.1	1.1	0.8
Low Water, Spring	0.7	0.7	0.5
Mean Lower Low Water	0.0	0.0	0.0
Lower Low Water	-0.2	-	-
Lowest Tide, Dec. 26, 1932 and Dec. 17, 1933	-2.70	-	-

Table 2 contd. Tidal Data

Tidal Range			
Diurnal	5.7	5.7	4.4
Mean	4.0	4.0	3.0
Spring	4.8	4.8	3.6
Neap	3.2	3.2	2.4

* The USGS Mean Sea Level is identical with the 1929 USC&GS sea-level datum.

During 1968 and 1969 the USGS operated on occasions several tide gages within Bolinas Lagoon. The control gage is located at the boat dock inside of the lagoon entrance with three other gages located as shown in Figure 1. The tidal difference between the boat dock gage and the other gages are shown in Table 3.

Table 3
Tidal differences in Bolinas Lagoon
Between Boat Dock and other Gages

Gage	Heights		Time Lag for lower low water min.
	MHH to MLL ft.	Ratio	
Boat Dock	5.01	-	-
Southeast	4.94	0.98	49
East Central	4.76	0.95	32
Upper-Basin	5.35	1.07	93
Bolinas channel	4.88	0.97	31

Other information on tidal conditions in Bolinas Bay was obtained from a gage installed offshore of the Bolinas Lagoon in about 16 ft. of water (Fig. 2)* and operated from May 15-27, 1968. This gage pressure-type tide gage was installed by the Bolinas Harbor District in cooperation with the USC&GS. Analysis of the tide gage records showed that there was little difference in tidal heights between the gage in Bolinas Lagoon (Boat Dock) and the gage outside in Bolinas Bay. For example, on May 20, 1968 the following values of tidal range between the various high and low tides are as shown in Table 4.

Table 4
Tidal changes in Bolinas Bay and Bolinas Lagoon

	Tidal Range	
	Bolinas Bay (ft.)	Bolinas Lagoon (ft.)
Low to High	1.7	1.7
High to Low	3.7	3.6
Low to High	4.5	4.4
High to Low	2.8	3.0
Low to High	2.1	2.0

Tidal Datum

To determine the hydrography in both Bolinas Bay and Bolinas Lagoon, as well as to evaluate seasonal changes of the shoreline in this area, several beach and bottom surveys have been conducted

*- not included

over the last few years by various agencies. These surveys and the datum* to which elevations and depths are related are as follows:

1. Corps of Engineers. Five ranges along the Stinson Beach Spit were surveyed in March and August 1961. Depths and elevations are referred to local MLLW. At the time of these surveys, MLLW was listed by the USC&GS as being 2.07 ft. below the 1929 sea-level datum (SLD). On May 6, 1965, the USC&GS revised these values such that now MLLW at Bolinas is listed as being 1.86 ft. below the 1929 SLD. The five Corps of Engineer ranges were resurveyed (on the beach face only) by the State Lands Commission on April 3, 1969 and on March 3-4, 1969. The Corps' beach marks as previously established in their 1961 surveys were used for the vertical control; that is, mean-lower-low-water was assumed as 2.07 ft. below the 1929 USC&GS sea-level datum.

2. Bolinas Harbor District. In 1968 and 1969 the Harbor District contracted with R.M. Towill Corp. of San Francisco to conduct five bottom surveys offshore in Bolinas Bay. The dates of these surveys were:

   May 17, 1968
   Aug. 21, 1968
   Dec. 19, 1968
   April 15, 1969
   May 16, 1969

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* A description of tidal beach marks in the vicinity of Bolinas appears in The Appendix.

Bottom surveys of Bolinas Lagoon were also made by R.M. Towill Corp. from aerial photographs taken at low tide on May 16, 1968. All of the above surveys give soundings below the 1929 USC&GS sea-level datum.

3. U.S. Geological Survey. In August and September 1967 profiles of the bottom of Bolinas Lagoon were surveyed along 26 referenced ranges to document the location and configuration of channels. Erosion and deposition in the lagoon can be determined by future surveys on these ranges. Elevations and depths were referred to the 1929 USC&GS sea-level datum.

4. State Lands Commission. In the period from 1948 to 1968 the State Lands Commission has determined the alinement of Mean High Tide for a distance of about 500 ft. along the beach face near the southern end of the Seadrift development on Stinson Spit. Mean High Tide in this instance was assumed to be 3.8 ft. above the mean-lower-low-water for Bolinas Lagoon (see Table 2) or 1.9 ft. above the 1929 sea-level datum.

BENCH MARKS

Bolinas, Bolinas Lagoon
Lat 37°54'.6; long 122°40'.9

Marin County, California

BENCH MARK TIDAL 1 (1947) is a standard disk, stamped "BOLINAS TIDAL 1", set flush in top of concrete wing wall at entrance to Bolinas Lagoon. It is 103 feet south of south end of heavy riprap at end of street leading from village of Bolinas, 0.3 mile east along street from post office 52 yards south of end of street, 5½ feet higher than beach, and ½ foot west of east end of concrete wall. Elevation: 8.517 feet above mean sea level.*

Coordinates: x = 520,079.45
y = 1,370,746.79

BENCH MARK TIDAL 2 (1947) is a standard disk, stamped "BOLINAS TIDAL 2", set flush in top of east concrete curb at entrance to U.S. Coast Guard Station. It is 11 feet from inner line of walk along village street and 18½ feet east of station flagpole, 4½ feet east of center line of concrete sidewalk, 1½ feet north of east end of bottom concrete step, and 1 foot above sidewalk. Elevation: 8.363 feet above mean sea level.

BENCH MARK WILKINS (1947) is a 2½-inch brass cap, stamped "WILKINS 1947", set in top of concrete post flush with ground, at north end of Bolinas Lagoon, in a marsh at east edge of a large group of small trees. It is 113 feet southeast of center line of California State Highway No. 1, 166 feet south of junction of California State Highway No. 1 and gravel road leading northeast and 470 feet northeast of the junction of California State Highway No. 1 and road leading south to Bolinas. Elevation: 4.403 feet above mean sea level.

Coordinates: x = 529,684.75
y = 1,366,536.67

BENCH MARK GALLOWAY (1947) is a 2½-inch brass cap, stamped "GALLOWAY 1947", set in top of concrete post, near southwest edge of wide highway shoulder on California State Highway No. 1, 30½ feet southwest of center line of highway, 14½ feet northwest of telegraph pole No. 307 and at minor point of land projecting into Bolinas Lagoon in vicinity of three dilapidated small piers. It is 75½ feet northwest of southwest end of 12-inch corrugated metal pipe culvert No. B-3.37, 4½ feet northeast of southwest edge of riprap, and about 2 feet higher than center of highway. Elevation: 7.936 feet above mean sea level.

Coordinates: x = 526,532.29
y = 1,371,420.31

*"mean sea level" is the 1929 USC&GS sea-level datum. MLLW is 1.86 below this datum.

[illegible] MARK PARADISE VALLEY (19[illegible]) is a 2½-inch brass cap, stamped "PARADISE VALLEY 1947", set in top of [illegible] flush with ground, on grassy delta at mouth of Paradise Valley on west side of Bolinas Lagoon and 15 feet northeast of ruins of old [illegible]. It is about ¼ mile north of Bolinas Union School, 170 yards northeast of road, 52 yards northwest of northwest bank of Pine Gulch Creek, and 4[illegible] feet northeast of telegraph pole No. 39[illegible]. Elevation: 4.682 feet above mean sea level.

Coordinates: x = 52[illegible],868.00
y = 1,3[illegible]3,602.78

BENCH MARK XX 480 (1951) is a 2½-inch brass cap, stamped "XX 480 1951" about 0.2 mile northwest along State Highway 1 from the Post Office at Stinson Beach, at the junction of the State Highway and Calle Del Sierra, in the top and near the east end of a very large and long outcrop, 93 feet southeast of the center line of Calle Del Sierra, 32½ feet southwest of the center line of the highway, 2.7 feet northwest of the southeast edge of the highest projection of the outcrop, and set about 5 feet higher than the highway. Elevation: 18.031 feet above mean sea level.

BENCH MARK M 480 (1951) is a 2½-inch brass cap, stamped "M 480 1951" about 0.9 mile north along an asphalt road from the Post Office at Bolinas, about 130 yards north of the Bolinas Union School, at a bridge over Pine Gulch Creek, in the top of the southwest wingwall, 16½ feet west of the center line of the road, 11.4 feet southwest of the southwest corner of the bridge, and set about level with the road. Elevation: 15.026 feet above mean sea level.

BENCH MARK YY 480 (1951) is a 2½-inch brass cap, stamped "YY 480 1951", about 1.2 miles northwest along State Highway 1 from the Post Office at Stinson Beach, at the Stinson Beach School, set vertically in the south face of the concrete foundation, 0.5 foot west of the southeast corner of the building, and set 1.4 feet above the sidewalk. Elevation: 23.602 feet above mean sea level.

BENCH MARK ZZ 480 (1951) is a 2½-inch brass cap, stamped "ZZ 480 1951", 2.2 miles northwest along State Highway 1 from the Post Office at Stinson Beach, between two cuts, 25½ feet west of an 18-inch tree which is the westernmost of three, 19½ feet north of the center line of the highway, 7.1 feet northwest of the west end of the concrete headwall of a 14-inch concrete pipe culvert No. B2.23, 2.5 feet east of a witness post, 1.2 feet south of a fence, level with the highway, and set in the top of a concrete post projecting 0.2 foot. Elevation: 10.945 feet above mean sea level.

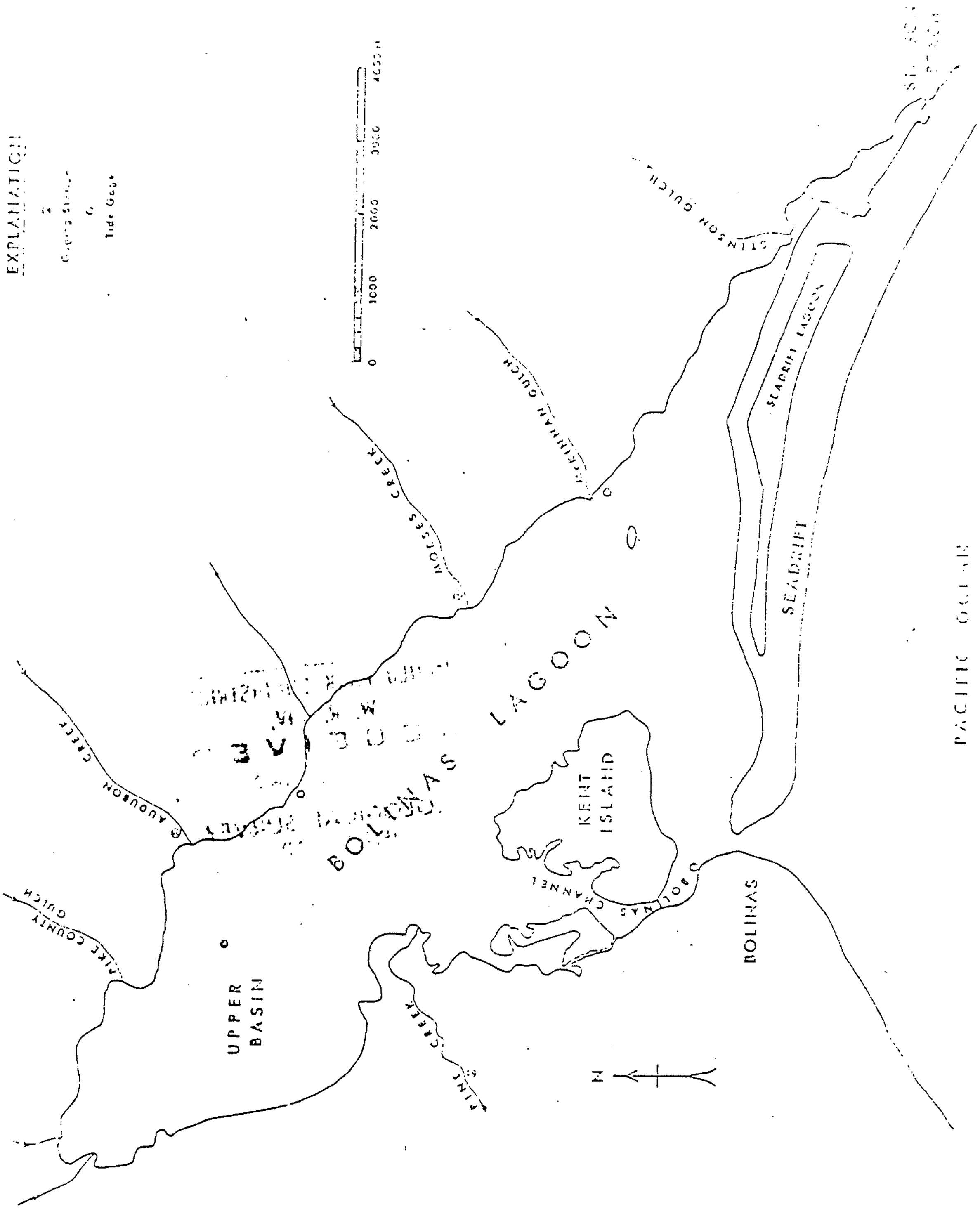
EXPLANATION
Tide Gage
0
1000
2000
STINSON GULCH
MORSES CREEK
AUDUBON CREEK
PIKE COUNTY GULCH
PINE CREEK
BOLINAS LAGOON
KENT ISLAND
BOLINAS CHANNEL
BOLINAS
UPPER BASIN
SEADRIFT LAGOON
SEADRIFT
N

Fig. 1

APPENDIX C
ESTIMATING WATERSHED DELIVERY

Pre-Euroamerican Sediment Production and Delivery

Researchers have recently demonstrated that the concentrations of cosmogenic radionuclides in stream sediments can be used to measure basin erosion rates averaged over 1000s of years (Granger et al., 1996; Bierman and Steig, 1996; Kirchner et al., 2001; Perg et al., 2003). Cosmogenic nuclides are produced in minerals by the bombardment of cosmic rays. Since cosmic ray penetration decreases exponentially with depth below the surface, the concentration of cosmogenic nuclides provides a record of the speed of exhumation. Stream sediments are a mix of sediments from different source areas that are delivered to the stream channel by a variety of transport processes. As a result, cosmogenic nuclide concentrations in stream sediments provide a spatially averaged measure of long-term basin erosion rates via all hillslope processes (e.g., soil creep, shallow and deep-seated landslides, gully and rill erosion, overwash, and rainsplash). This methodology provides an estimate of watershed erosion rates over millennial time scales prior to disturbances from human activities.

Heimsath et al. (1997, 1999) estimated a Holocene average basin erosion rate of 0.077 mm/yr for Tennessee Valley in the Marin Headlands from cosmogenic analysis of stream sediments. Tennessee Valley has been subject to the same climate as the Bolinas watershed and is composed of the Franciscan formation, the main component of the Bolinas Ridge watersheds. Given the climatic and lithologic similarities, we have applied Heimsath's rate to the Bolinas watersheds (using an area of 16.7 mi^2) to estimate a pre-Euroamerican rate of sediment production of 4,500 yd^3/yr. In the small, steep coastal watersheds of California, such as those draining to Bolinas Lagoon, sediment production is in balance with sediment export out of the watershed over long time scales (e.g., > 1,000 years). The predominance of steep hillslopes, narrow river canyons, and small floodplain areas are the morphological expressions of this long-term balance between sediment production and export. Since over these long-time scales we assume that sediment production equals sediment delivery to the lagoon, this rate of 4,500 yd^3/yr also represents the average annual volume of sediment delivered to the lagoon.

Present-Day Sediment Production and Delivery

In Tetra-Tech's (2001) sediment input study for Bolinas Lagoon, they estimated watershed production and assumed that over the period of their sediment budget (1950 – 2001) all sediment produced (10,000 yd^3/yr) was exported to the lagoon without changes in sediment storage. We have plotted the estimates of sediment yield for Bolinas Lagoon and Redwood Creek (Stillwater, 2003) against estimates from other Californian coastal watersheds (Figure C-1). The good comparison in the data increase our confidence that the TetraTech value is reasonable.

In this report, we estimate both the suspended and bedload components of sediment delivery from Pine Gulch Creek to Bolinas Lagoon. These individual estimates assist us in assessing if watershed delivery along this important tributary is supply- or transport-limited. In the supply-limited condition less sediment is produced by hillslope processes, and the rate of sediment delivery to the lagoon is approximately equal to the rate of sediment production, or 'yield'. In the transport-limited condition, more sediment is delivered to the creek than it has the capacity to transport. Thus, the rate of sediment delivery should be approximately the same as the sediment transport capacity of the creek, with the excess sediment being stored in the channel or on the floodplain. In the long term (10,000s of years) sediment supply and sediment transport capacity will tend to equilibrate, as supply-limited rivers erode into their valleys while transport-limited rivers aggrade, disconnecting the valley sides from the channel and reducing sediment supply. Determining which condition exists is crucial to estimating sediment delivery to the lagoon.

Geomorphic Reconnaissance of Pine Gulch Creek

PWA staff performed a geomorphic reconnaissance of Pine Gulch Creek to assess whether the creek was supply or transport-limited. It is important to recognize that this was not a full watershed assessment, and that identifying long-term channel trends from individual site visits is prone to uncertainty. However, the reconnaissance revealed strong evidence of recent channel aggradation in the downstream reaches. This evidence includes the presence of an in-stream gravel pit on the Pine Gulch delta and the presence of sediment accumulation around the base of trees on gravel bars further upstream. Unlike many streams in the Bay Area, Pine Gulch Creek is not incised. This provides further evidence of channel stability or aggradation.

Aggradation in the channel suggests that the system is transport-limited in the lower reaches. Thus we can estimate sediment delivery based on the sediment transport capacity of the channel rather than the sediment production rate of the watershed. We should note however that over the long term sediment production and sediment transport capacity will equilibrate, so the sediment production data published by TetraTech (2001) provide a useful cross reference to validate long term sediment delivery rates.

Delivery of Suspended Sediments along Pine Gulch Creek

Existing suspended sediment and bedload transport data on Pine Gulch were used to develop sediment-rating curves to estimate the variability in watershed sediment delivery to the lagoon in wet, dry, and average years. Tetra-Tech (2001) developed a suspended-rating curve based on a third-order polynomial relationship between streamflow and sediment transport, overestimating the sediment transport potential for episodic high flow events. We used the same gage data to derive a more appropriate power law suspended-rating curve (Glysson, 1987). This revised rating curve (Figure C-2) was then used to estimate the inter-annual variability of sediment discharge. Flow data from Corte Madera Creek was adjusted and applied to supplement gaps in flow data from Pine Gulch Creek. Results from this analysis are summarized in Table C-1.

Table C-1. Average Suspended Sediment Delivery Along Pine Gulch Creek

Time Period	Average Annual Qs (yd^3/yr)	Total Qs (yd^3)
1952-1993	4,935	207,282
1968-1988	6,100	128,109
1952-93, 1999-2003	5,048	29,951
Watershed Area	8 mi^2	
Suspended Yield	617 (yd^3/mi^2yr)	

Since Pine Gulch Creek drains approximately half of the watershed, these data suggest that the average annual suspended sediment discharge from 1952-1993 is approximately 10,000 yd^3/yr. This estimate agrees well with the sediment yield established by TetraTech (2001) for the same period, suggesting that over this 50-year period there have not been *net* significant changes in sediment storage.

Bedload Transport Modeling along Pine Gulch Creek

A bedload transport analysis was performed for the lower reaches of Pine Gulch Creek in order to assess the approximate volume of coarse alluvium delivered to the lagoon. The average annual bedload transport capacity at the downstream cross-sections was estimated by magnitude-frequency analysis based on the long-term flow record. The analysis is based on the unpublished guidelines produced by Thorne and others (1998).

The magnitude-frequency analysis involves integrating a flow-frequency histogram with a sediment-rating curve to produce a histogram of sediment load as a function of discharge. The peak of this histogram represents the "effective discharge", which is the discharge class responsible for transporting the largest fraction of the bed material load in a stable channel over a period of years (Andrews, 1980). The effective discharge is approximately equivalent to bankfull or dominant discharge for natural alluvial channels that are "in regime". A self-formed alluvial channel is in regime if there are no net changes in discharge capacity or morphology over a period of years.

The basic approach to estimate average long-term bedload transport capacity entails dividing the range of stream flows recorded at a station and calculating the total amount of sediment transported by each class by multiplying the frequency of occurrence of each flow class by the median sediment load for that flow class. The input requirements for the analysis are:

- *Flow data*. We used the mean daily flow as recorded at the USGS gauging station (Station no. 11460170), as well as the flows recorded by the Audubon Society gauge at the Olema Road Bridge and the long-term flow record at the nearby Corte Madera Creek station. Pine Gulch Creek was monitored for flow and sediment during the period from 1967 to 1970. The Audubon society has been recording the flows at the site since 1999. We used Corte Madera Creek station record to extend Pine Gulch Creek's record of daily mean flow. The augmented record that we used for our analysis covers the period between 1952 and 1993, and between 1999 and 2003.

In addition to uncertainties inherent to the flow and sediment measurement, the limited amount of flow data limits the certainty in this analysis. Ideally, the period of record should be sufficiently long to include a wide range of flows to include wet and dry periods, but not so long that changes in the climate, land-use or runoff characteristics of the watershed produce significant changes with time in the data. A reasonable minimum period of record for an effective discharge calculation is approximately 10 years (Thorne et al, 1998). Using a nearby station with a longer period of record to extend the data requires that the stations have similar physical, hydrologic and geomorphic characteristics so that discharge-basin area relationships are comparable. These sources of uncertainties are inherent to all sediment transport estimates, which should not be considered as absolute numbers of transport but rather as mean values of a wide range of transport conditions.

- *Sediment transport rating curve*. We used the sediment transport equation of Bagnold (1980) to relate transport capacity to hydraulic conditions. Specific input data (e.g., energy gradient and hydraulic radius) were generated by constructing and running a HEC-RAS hydraulic model of the lower reach of the creek.

- *Cross-section geometry*. A field survey was conducted to obtain channel cross-sectional geometry and longitudinal profile of the thalweg along the lower Pine Gulch Creek (downstream of the bridge). Sediment transport estimates are very sensitive to channel slopes. Therefore, average slopes between upstream and downstream cross-sections were used with each cross-section within the analysis.

- *Grain size information.* The sediment size data used in the magnitude-frequency sediment transport analysis were derived from bulk samples taken through the bed, therefore incorporating both surface sediment and substrate. Samples were taken at one location at each cross-section, at approximately trapezoidal cross-sections between riffles and pools and were sieved at Cooper Testing Laboratory.

Results of the bedload transport modeling were interpreted considering the geomorphic features observed during the reconnaissance. Key findings from the modeling are:

- Bedload transport capacity at the downstream reach of PGC suggests that approximately 750 CY/yr gravel/sand/cobble is deposited on the supra-tidal riparian reach of Pine Gulch Cheek downstream of the Bolinas-Olema Road.
- Modeling of suspended transport capacity at the downstream reach of PGC suggests that 300 CY/yr of coarse alluvium is deposited atop lower (intertidal) elevations of the Pine Gulch Creek delta.

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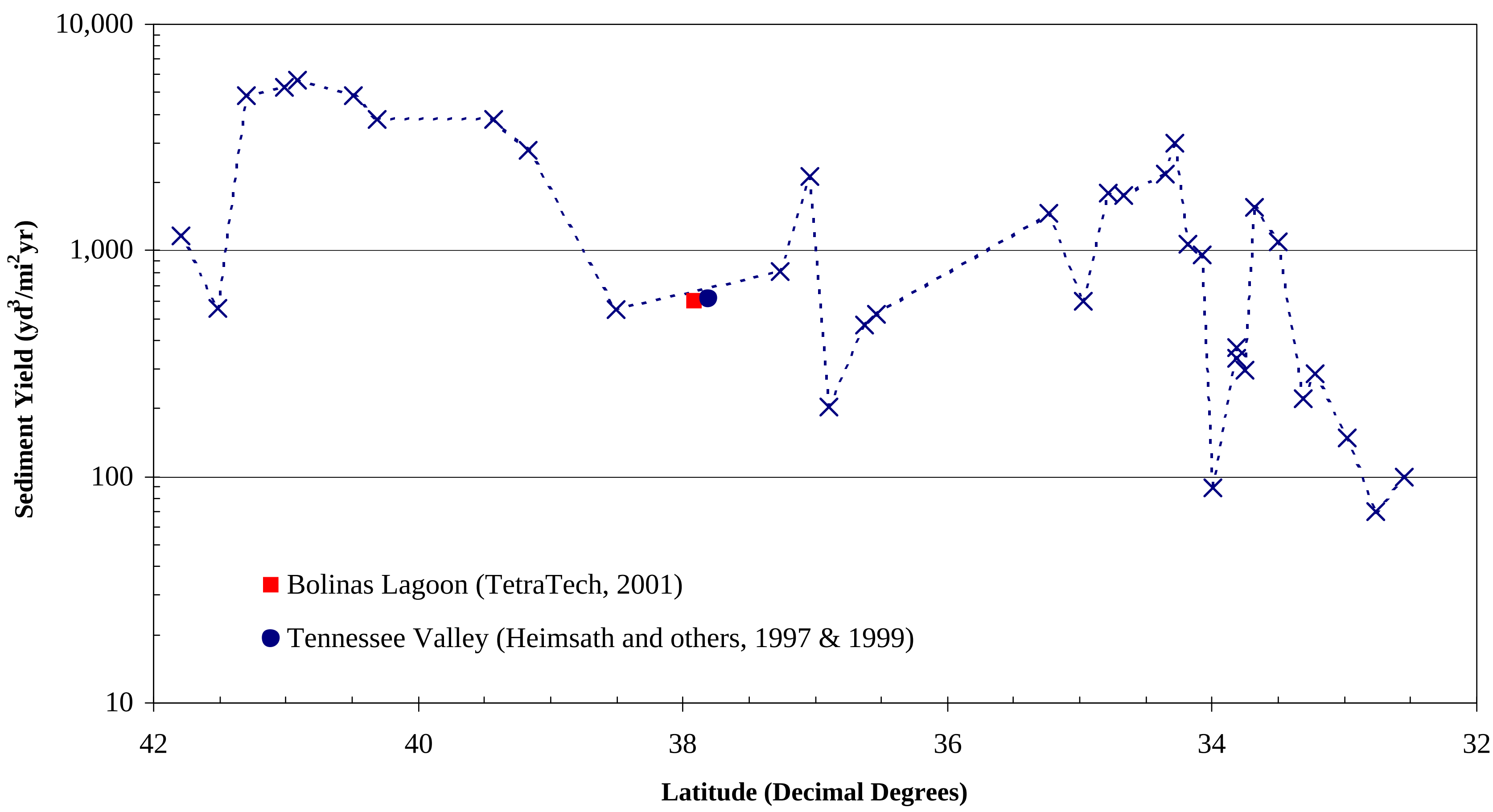

Notes
Source: Data on coastal streams from Willis & Griggs (2002)

figure *C-1*

Projecting the Future Evolution of Bolinas Lagoon
Sediment Yield in Pacific Coastal Streams

PWA Ref # 1686.02

PWA

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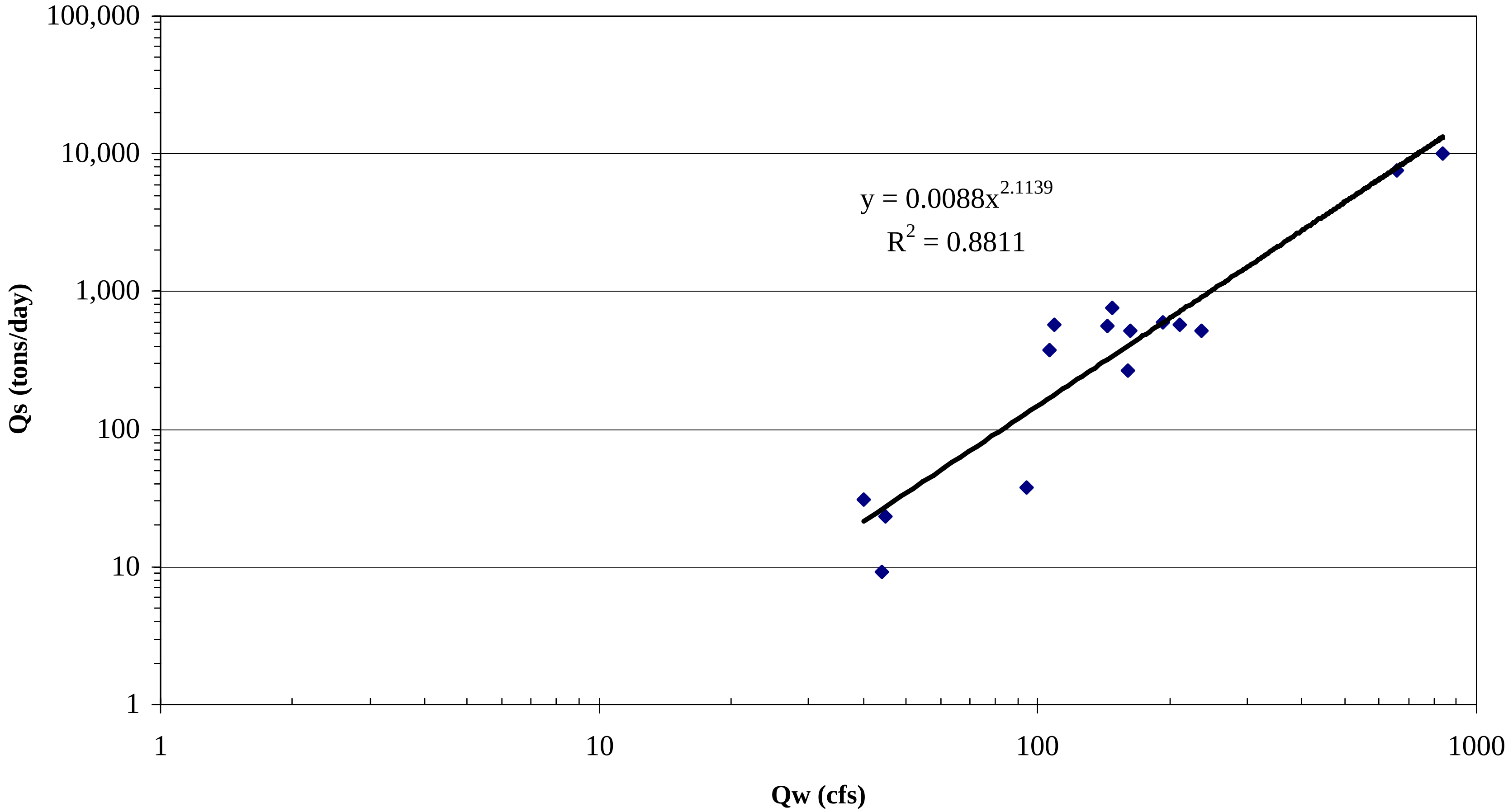

Notes
Source: Rating curve based on stream USGS stream data (Ritter, 1973)

figure C-2

Projecting the Future Evolution of Bolinas Lagoon

Rating Curve for Pine Gulch Creek

PWA Ref # 1686.02

PWA