Bothin Marsh Geomorphology, Ecology, And Conservation Options

Introduction

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Introduction

Report Overview

This report was produced on behalf of the Marin County Parks based on review of the science related to restoration and protection of tidal marshes in upper Richardson Bay, Marin County, California.

The authors are thankful for the opportunity to produce this report. We were able to apply our collective century of experience as investigative wetland and watershed scientists to a familiar locale, and in the processes learn from each other's expert perspectives. Adequately covering the breadth of subject matter would not have been possible without such a diverse and experienced team. We especially Veronica Pearson, Marin County Parks, for her support and guidance.

We produced this report as six standalone Chapters with two Appendices. This approach separates an otherwise massive report into a set of six technical references that we hope will be useful to current and future environmental planners, scientists, and engineers working in Richardson Bay and beyond. This report covers the following major subjects.

Chapter 1:	Tidal marsh formative processes
Chapter 2:	Sea level rise and adaptation management strategies
Chapter 3:	History and causes of physical environmental change
Chapter 4:	Ecological response to environmental change
Chapter 5:	Conservation options
Chapter 6:	Synthesis of key findings
Appendix 1:	Review of regional tidal marsh plant and wildlife technical literature
Appendix 2:	Guide to common vascular plants in the Bothin Marsh Complex

Although the Chapters are designed as standalone references, there is a flow of information from one Chapter to the next, and the content of one Chapter can be better understood if the preceding Chapters have been read. Chapters 1-3 are especially helpful to understand Chapters 4-5. The concluding Chapter is a succinct summary and synthesis of the previous five Chapters. The two Appendices can be especially useful to amateur and professional wetlands botanists.

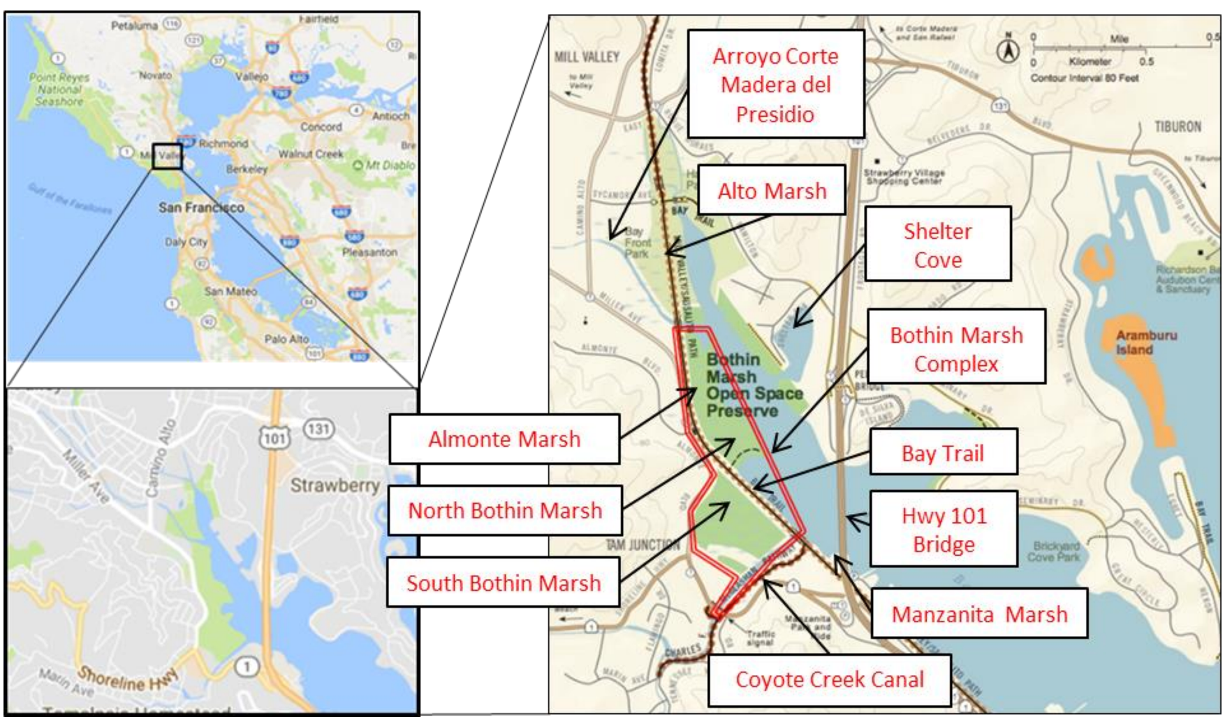
This is one of many scientific reports focused on the tidal marshes of upper Richardson Bay, herein called the Bothin Marsh Complex (see the Section on Setting below). The other reports on Bothin Marsh and Richardson Bay are narrower in scope. This report reviewed those reports and a wealth of additional relevant technical information, representing more than three hundred documents and more than two hundred maps and other images, spanning the period from 1795 to the present.

This report focuses on restoring and conserving the natural functions and values of the Bothin Marsh Complex. It does not comprehensively address the critically important social-economic aspects of adaptation to sea level rise. Chapter 2 identifies some of the common adaptation strategies and methods to facilitate societal adaptions in the Bay Area and other coastal regions of the U.S. However, this report mainly addresses the threats of sea level rise to tidal marsh ecosystems in upper Richardson Bay, north of the Highway 101 Bridge. For the purposes of this report, this area is referred to as the Bay. Other areas of the San Francisco Estuary are identified by their full names.

Setting

Prior to the end of the last ice age, the V-shaped valley that is now occupied by the Bay drained southeast to what was then the most southern extent of the Sacramento River. Waters draining from valley would have met the antecedent Sacramento River as it headed out the Golden Gate and across the Gulf of the Farallones to the Continental Shelf. With the melting of the polar icecaps, sea level rose through the Golden Gate and began creating San Francisco Estuary about 10,000 years ago (Atwater *et al.* 1977). By about 6000 years ago, as the rate of sea level rise declined from about 0.75 inches per year (about 6 feet per century) to 0.075 inches per year (about 0.6 feet per century), tidal water began entering Richardson Bay. A profile of the Pleistocene stream that drained into the nascent Bay, indicates that it sloped between 100 and 130 feet per mile. Over time, the submerged valley was filled with up to 150 feet of tidal sediment (Connor 1983). The Bay bottom changes to a virtual cliff face where it meets the greater San Francisco Bay near the Golden Gate. In its natural state, the Bay bottom was remarkably uniform in depth and sediment type. A modern profile of the Bay bottom varies only between 5 and 50 feet per mile (Means, 1965). Over geologic and historical time, the gradient of the Bay has continued to flatten.

Richardson Bay trends southeast-northwest, and is separated by Strawberry Peninsula into two roughly parallel sub-bays or arms. The northern arm is shorter but broader and extends between Belvedere Island and Strawberry Point. The southern arm is longer and narrower, and extends between Strawberry Point and Sausalito. The southern arm is commonly referred to as Richardson Bay, given that it is crossed by the Richardson Bay Bridge. The Bay was formally named Pickleweed Inlet by the U.S. Board of Geographic Names in 1979. This report does not use the name Pickleweed Inlet.



Map of the Bothin Marsh Complex and its component marshes in upper Richardson Bay in relation to the Arroyo Corte Madera del Presidio and Coyote Creek as the focus of this report.

Eastward aerial view of upper Richardson Bay and the Bothin Marsh Complex. Wikimedia Commons (By Bento00 (Own work) [Public domain], via Wikimedia Commons).

Two streams, Arroyo Corte Madera del Presidio and Coyote Creek, are by far the largest watersheds draining to Richardson Bay. Their areas are 5.7 square miles and 3.3 square miles, respectively. They account for 78% of the total catchment for the Bay. Both streams drain into the upper Bay. They receive about 90% of their rain between October and April, with an average of 36 inches per year. Seasonal max/min temperatures are 41.5 ^{0}F/59.6 ^{0}F for the wet season and 50.5^{0}F/86.5 ^{0}F for the dry season U.S. National Weather Service (https://www.weather.gov/phi/localclimate).

Local data for vegetation, land use, and human demographics are reported below.

Demographic and land cover statistics for the lands draining to upper Richardson Bay (EcoAtlas, December 2017. https://www.ecoatlas.org/).

Human Demographics	
Population Size	59,582
Population Density	5,207 per mi^2
Housing Units	27,036
Housing Unit Density	2,363 per mi^2

Land Cover	
Land Cover Class	**Percent of Profile Data**
Developed Open Space	46%
Low Intensity Development	32%
Medium Intensity Development	20%
High Intensity Development	2%

Upland habitat Abundance		
Habitat Type	**Area (acres)**	**Area (%)**
Urban	2,363	32.4%
Coastal Oak Woodland	1,175	16.1%
Montane Hardwood	954	13.1%
Mixed Chaparral	584	8.0%
Annual Grass	520	7.1%
Coastal Scrub	487	6.7%
Eucalyptus	421	5.8%
Montane Hardwood-Conifer	313	4.3%
Montane Riparian	48	0.7%

This technical report includes technical terms that may be unfamiliar to some readers. Common terms are defined when first used in each Chapter. This glossary is provided for terms used in this Report.

Term	Basic Meaning in This Report
Accretion	Process of maintaining or gaining height of tidal marsh or flat due to sedimentation
Alluvial fan	Fan-shaped deposit of sediment by a creek at its mouth
Autochthonous Sediment	Organic material produced by marsh plants adding to accretion
Backshore	Boundary between tidal marsh and upland
Beach	Unvegetated sloping foreshore of highly mobile sediment
Berm	Elevated ribbon of land, raised bank, or terrace bordering a channel or foreshore
Delta	An alluvial fan subject to tidal submergence
Drainage Network	System of channels conveying water from one to another
Eco-Geomorphic Unit	Land features formed and maintained by interactions between physical and biological processes.
Erosion	Loss of tidal lands or uplands due to actions of wind and water
Fetch	Length of water surface over which wind blows
Foreshore	Boundary between tidal marsh and tidal flat or shallow subtidal area
Lag Surface	Layer of coarse sediments preventing erosion of underlying finer sediments
Levee	Elevated strip of land or raised bank along a channel or foreshore; higher than a berm.
Managed Retreat	Planned relocation of people and built environment out of sea level rise migration space.
Mean High Water	Average of all high tides for a designated number of tide cycles
Mean Higher High Water	Average of higher of two daily high tides for a designated number of tide cycles
Mean Low Water	Average of all low tides for a designated number of tide cycles
Mean Lower Low Water	Average of lower of two daily low tides for a designated number of tide cycles
Mean Sea Level	Average of hourly heights of the tide during the National Tidal Datum Epoch.
Migration Space	Area of uplands the tides will submerge at a designated future time
Panne	Shallow high marsh pond subject to seasonal desiccation
Run-up	The action of waves reaching lands above the height of the high tide.
Scarp	Very steep channel or foreshore bank caused by erosion
Sedimentation	Process of sediment deposition or creation at a tidal, subtidal, or upland surface
Sediment Transport	Process of water carrying or moving sediment
Shell Hash	Sediment consisting of broken shellfish shells
Splay	Fan-shaped sediment deposit smaller and less maintained than an alluvial fan
Subtidal	Below Mean Lower Low Water
Supratidal	Above the maximum height of the tide
Suspended sediment	Sediment contained within a volume of water
Terrigenous sediment	Sediment transported by upland runoff and not by tide
Tidal	Sedimentation or anything else depending upon tides or within the tidal zone
Tidal Flat (mud or sand)	Unvegetated tidal lands between Mean Lower Low water and the foreshore
Tidal Marsh	Vegetated tidal lands between the foreshore and backshore
Tidal Prism	A tidal prism is the volume of water in an estuary or inlet between mean high tide and mean low tide, or the volume of water leaving an estuary at ebb tide
Tidal Zone	Area between Mean Lower Low Water and maximum high tide
Watershed	Area of upland or tidal land draining to a point or place
Wind-wave	Waves of water created by wind blowing along a fetch

Citations

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Bothin Marsh Geomorphology, Ecology, and Conservation Options

Chapter 1:
Physical and Biological Processes Influencing Evolution, Maintenance and Degeneration of Tidal Salt Marshes

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Chapter 1:
Physical and Biological Processes Influencing Evolution, Maintenance and Degeneration of Tidal Salt Marshes

1.0 Introduction

This Chapter presents an overview of the natural geomorphic processes that govern the evolution, natural maintenance, and degeneration of tidal marshes, and the general effects of people intervening in these processes, with special regard for the Bothin Marsh Complex. Because of the importance of sea level rise and the tides, they are covered in a separate Chapter (see Chapter 2).

1.1 Tidal Marsh Evolution

In a general sense, tidal marshes evolve from non-vegetated tidal flats, such as sand-flats or mudflats, when the flats become high enough to be colonized by marsh vegetation (Byrne *et al*. 2004, Fagherazzi *et al*. 2004, Wallace *et al*. 2005, Palaima 2012, Gunnell *et al*. 2013). An understanding marsh evolution therefore requires some understanding of how flats evolve. It should be noted that marshes can also evolve on terrestrial lands, rather than on tidal flats, as the lands are transgressed due to sea level rise. Accelerated sea level rise is a major concern for tidal marsh protection and restoration, and is addressed separately in Chapter 2.

Tidal flats represent a balance between the deposition and erosion of sediments in shallow areas near low tide (Black 2002, Fagherazzi *et al*. 2007, Bearman *et al*. 2010, van der Wegen *et al*. 2017). Flats are formed when and where the tidal currents and wind-generated waves are not strong enough to prevent suspended sediment from being deposited, or to lift and resuspend deposited sediment. The power of wind-generated waves to resuspend and carry sediment depends on their height, which in turn depends on water depth and the strength of the winds. Higher and more powerful waves occur at the downwind end of longer fetches over deeper water (Karimpour *et al*. 2017). Resuspended sediment can be moved by waves and tidal currents from one tidal area to another. When the winds and waves subside, some of the sediment can be redeposited on the flats (Friedrichs and Aubrey 1996).

Given the right conditions of these factors, there can be enough sedimentation on a tidal flat for it to achieve heights suitable for colonization by marsh vegetation. Different regulatory and management programs use different thresholds for the amount or percent cover of marsh vegetation to indicate when a flat becomes a marsh. The tidal elevation at which the colonization occurs depends on many factors, especially salinity. Plants grow lower in the intertidal zone under fresher conditions (Atwater and Hedel 1976). The species composition of this vegetation also varies with salinity.

Since sea level is rising, the flats and marshes must also rise. The supply of sediments must be adequate for the flats and marshes to rise in pace with sea level, or the flats and marshes will drown, and their surfaces will erode. The amount of sediment that is added to the flats and marshes must be replaced with additional sediment, or there will be a net deficit in the sediment supply, and the flats and marshes will not keep up with the rising sea level.

Marshes do not have to drown to erode. Wind-generated waves and tidal currents can erode the bayward margins of the marshes, here called the foreshore (see Figure 1.1 below), such that the marshes will become narrower. The marsh foreshore tends to be unstable, eroding when the waves are strong and the

Figure 1.1. Aerial view of portion of Bothin Marsh showing relative positions of mudflat bayward of the marsh, foreshore between the marsh and mudflat, and backshore between the marsh and uplands, formed her by the Bay Trail.

supplies of suspended sediment are low, and growing outward when the waves are weak and sediment supply is high (Silvestri and Marco 2004). A narrow fringe of tidal marsh can evolve and persist along the boundary between the Bay or marsh and the land, here called the backshore (Figure 1.1), under various conditions of waves, sediment supply, and sea level rise. In this case, the height of the land determines the height of the marsh. As sea level rises, the fringing marsh migrates upslope and inland (Chapter 2). Under favorable conditions, marshes can grow in size by expanding outward from the backshore fringe, and by the establishment of pioneering plant colonies on the tidal flat away from the backshore (Watson and Byrne 2013).

Not all tidal flats evolve into marshes. Tidal flats tend to persist where the balance between sedimentation happens at a height too low for colonization by marsh vegetation (Friedrichs and Aubrey 1996, Black *et al et al*. 2002, Weerman *et al*. 2010, Gunnell *et al*. 2013).

There are three basic sources of sediment to establish and maintain tidal marshes in Richardson Bay.

- Upland or *terrigenous sediment* includes sands, silts, clays, and large floating debris that are delivered more or less directly to a marsh from their upland sources by rivers, streams, canals, storm drains, and unchannelized flow (i.e., surface runoff outside of a natural or artificial drainage channel). Gravels and cobbles that might be transported along the stream beds are too heavy to be carried onto the marsh surface. The sediment that reaches the Bay is stored there, or is transported out by the ebbing tides. The larger, heavier materials are restricted to the deeper areas and the small, finer materials are stored in deeper areas and on the flats and marshes. Any actions on land that increase erosion or flooding can also increase the delivery of terrigenous sediment.
- Sediments that are circulated within the Bay, or conveyed seaward or landward by the tides, are regarded as *tidal sediment.* Fine sediment stored in the flats that is resuspended by wind-generated waves is considered tidal. The resuspended materials can be delivered to the marshes by the waves and flood tides. Extreme events, such as storm surges, tsunamis, and major river floods can deposit both tidal and terrigenous sediments on marsh surfaces. Dredging that increases the amount of sediment suspended in tidal waters can increase the rate of delivery of tidal sediment to a marsh. Changes in land use can strongly affect local terrigenous and tidal sediment supplies.
- *Autochthonous sediment* includes any materials produced within a marsh that contribute to its height. Most autochthonous sediment of a tidal marsh consists of roots, rhizomes, and other organic materials produced by marsh vegetation (Drexler 2011, USDA 2015, Morris *et al*. 2016). In general, a local watershed contributes more of its sediment to its nearest marshes. Marshes more distant from a local watershed receive more of a mixture of sediment from many watersheds (Byrne *et al* 2001).

Tidal marshes are commonly classified as low or high depending on their surface heights relative to the high tides (Figure 1.2). These height classes can represent stages in marsh development from young to old marshes (Redfield 1972, Kneib *et al*. 2008). As explained above, marshes subject to rapid increases in the frequency or duration of tidal flooding can drown, which can reverse their developmental process, such that high marshes are converted to low marshes or tidal flats. Drowning can result from sea level rise (e.g., Stralberg *et al*. 2011), marsh subsidence (Darienzo and Peterson 1990, Gillespie *et al* 2011), or decomposition of autochthonous sediment (Hartig *et al*. 2002, Deegan *et al*. 2012).

The drainage system of a tidal marsh consists of one or more networks of channels large and small that deliver tidal waters to and from the marsh surface. Each network primarily serves one area of marsh and has its own opening to the Bay, through the foreshore. The largest channels of the more extensive networks in older, larger marshes originate on the predecessor mudflats. The smaller channels of these networks evolve as the marsh gains elevation. The smallest channels evolve on the marsh plain (Collins *et al*. 1987).

1.2 Natural Tidal Marsh Maintenance

Tidal marshes evolved along the shores of Richardson Bay beginning sometime within the last 2,000 years. The ages of the oldest areas of tidal marsh are not known. However, marshes older than 2,000 years are uncommon elsewhere in San Francisco Bay (Atwater *et al*. 1977, Gorman *et al*. 2008, Malamud-Roam *et al*. 2006, Watson and Byrne 2013). The fact that tidal marshes have naturally persisted in San Francisco Bay for thousands of years indicates that they have ways to maintain themselves despite short- and long-term variations in the rate of sea level rise. The ability of tidal marshes to survive any amount of sea level rise depends on the rate of rise relative to the rate of sedimentation. Under moderate rates of sea-level rise, the increased frequency and duration of tidal flooding increases the rate of tidal deposition of silts and clays on marsh surfaces, as well as the development of organic marsh sediments, such as plant roots, resulting in marsh accretion in response to sea level rise (Reed 1995, Morris *et al*. 2002, Kirwan *et al*. 2010, Fagherazzi *et al*. 2012).

The rate of tidal sediment deposition on tidal marsh surfaces decrease with increasing marsh height (e.g., Krone 1987, French 1993, Allen 1994). As the rate of tidal sediment deposition decreases, the role of allochthonous sediments increases. However, the rate of allochthonous sedimentation depends on the rate of plant growth, which tends to be maximum within a narrow range of tidal heights (e.g., Redfield 1972, Orson *et al*. 1985, Morris *et al*. 2005). If the marsh is lower than the optimum range in elevation for plant growth, an increase in the depth of tidal flooding leads to a decrease in plant growth. This can lower the rate of allochthonous sedimentation, which in turn lowers the height of the marsh surface, relative to sea level, which can lead to an increase in the rate of tidal sediment deposition.

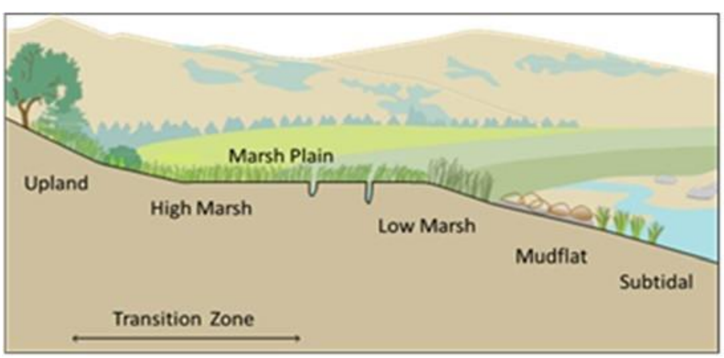

Figure 1.2 Diagram of tidal marsh zones in context pf a complete tidal marsh ecosystem including subtidal areas, mudflat, and upland. Goals Project 2015.

The overall accumulated sediment of a tidal marsh is therefore a mixture of terrigenous, tidal, and autochthonous materials (Church *et al*. 2006, Mudd *et al*.

2010, Morris *et al*. 2016), and the relative importance of tidal and allochthonous sediments to the rise of tidal marshes therefore varies over time. Young marshes tend to be dominated by inorganic tidal sediments. As a marsh matures, the contribution of allochthonous material to the rise of the marsh plain increases. This is evidenced by vertical cores of sediment taken from the interior areas of marshes that show layers of autochthonous and tidal sediments relating to marsh age, different rates of sea level rise, and changes in tidal sediment supply (e.g., De Groot *et al*. 2003, Gorman *et al*. 2008, Watson and Byrne 2013).

Within mature high marshes, these three different kinds of sediment tend to be predictably distributed (Collins *et al*., 1987, Reed *et al*. 1999, Christiansena *et al.* 2000, Sanderson *et al*. 2000, Culberson *et al*. 2004, Collins and Grossinger 2004, Temmerman *et al.* 2005). The relative amount of tidal sediment tends to decrease with distance away from the foreshore, and away from the tidal marsh channels across the marsh plain. Channel beds, banks, and natural levees tend to be almost entirely composed of inorganic tidal sediments, although channels and levees that convey upland runoff can also contain terrigenous sediment. Since terrigenous sediments are relatively heavy, they tend to be deposited in areas nearest their points of input. For example, splays of terrigenous sediment are commonly observed where creeks discharge into marshes. Sediments in the interior areas of a mature marsh tend to be mostly autochthonous. This is because the marsh vegetation effectively filters the inorganic sediment out of the tidal water as it floods from the channels across the marsh plain (Stumpf 1983, Leonard and Croft 2006, Mudd *et al*. 2010). Wave-deposited marsh berms along the foreshore tend be heterogeneous mixtures of coarse mineral sediment (sand to silt) and organic debris deposited by waves. Mature high marshes are therefore maintained by a combination of tidal sedimentation within and along channels and at the foreshore, and autochthonous sedimentation in areas away from channels.

The wave-cut erosional marsh cliffs (scarps) of tidal marshes are inherently unstable (Mariotti and Fagherazzi, 2010). Bayward expansion of flats and marshes can be rapid, up to several meters per year, when the necessary supplies of sediment are available (Winfield 1988, Gunnell *et al.* 2013). Erosion of the foreshore can also be rapid, especially if the energy of waves attacking the shore is increased by gains in sea level, since wave energy increases with water depth. The lack of feedback between the processes of foreshore erosion and those of marsh expansion suggests that the foreshore is always either expanding or contracting (Fagherazzi *et al.*, 2013). Sediment cores taken from marsh foreshores in San Francisco Bay reveal layers of flats and marshes, indicating their repeated conversion back and forth from one to the other, as the foreshore waxes and wanes over time (Winfield 1988).

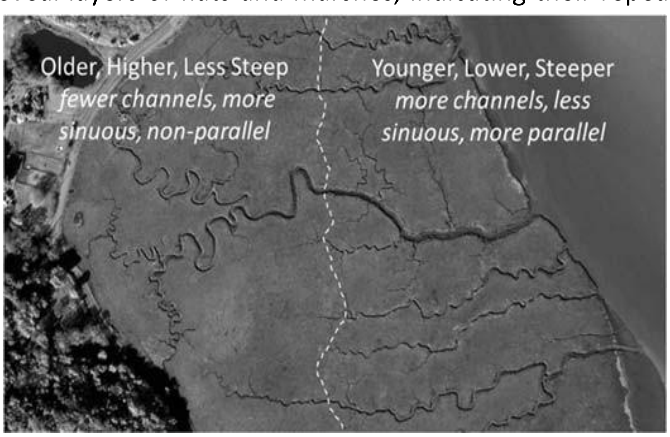

Figure 1.3. Aerial image of San Francisco Bay tidal marsh showing differences in channel networks between marsh plains that differ in age, height, and slope.

The channel networks of mature tidal marshes are remarkably stable over time. Each network tends to be just large enough in terms of its total length and volumetric capacity to deliver and drain the flood tides to and from the marsh surface that it serves (Collins and Grossinger 2004). There is a close relationship between the surface area of tidal marsh and the total capacity of its drainage network (Novakowski *et al*. 2004, Hood 2007). This relationship varies however, with marsh age or height, topographic slope, and salinity regime (Collins and Grossinger 2004).

Higher marshes tend to have smaller networks because they convey less water to and from the marsh surface. Steeper marshes tend to have more linear and parallel channel networks (Figure 1.3). Less saline tidal marshes tend to have smaller networks because the marsh vegetation grows at elevations that would otherwise be mudflat or channel beds (Atwater and Hedel 1976, Atwater *et al*. 1977).

Recent studies of past and present conditions in tidal marshes around SF Bay have revealed some local aspects of sediment movement and deposition applicable to Bothin Marsh. The studies have not matured to peer review publication but are generating considerable interest. The Flood 2.0 initiative and some Total Maximum Daily Load (TMDL) studies have been working with expert teams and local interests to explore future landscape solutions to water quality, flood management, and habitat conservation in the context of climate change. A number of these explorations have identified multiple benefits of restoring natural connections between tidal wetlands and streams. The benefits of utilizing the terrigenous sediment of local streams to nurture tidal marshes are well recognized. A related need is to move bedload through the tidal portion of the stream to prevent the channel from trapping sediment and thus losing capacity to convey floodwaters. It has been recognized that the natural levees that form along the tidal reaches of streams confines their flood flows and thus increases their power to move bedload though the intertidal zone (Marvin-DiPasquale and Cox 2007), especially when the tidal ebb flows entering the channel downstream of the levees contribute to stream power (Collins and Leising 2004, SWRCB 2008). In the cases of streams lacking perennial flow, the concept of allowing wet season deposition of sediment loads to form backshore deltas and fans is commonly considered (SFEI-ASC 2015).

1.3 Spatial Gradients in Tidal Flooding and Soil Salinity between and within Marshes

Local variations in tidal salinity among the tidal marshes of Richardson Bay are due to discharges of freshwater from local streams and storm drains. In general, the salinity of tidal waters will increase with distance away from these sources of freshwater. The differences will decrease during the warm-dry season, as stream discharge decreases, such that the salinity of tidal waters along the foreshore of the Bay becomes more uniform.

Salinity gradients also exist with tidal marshes. Tidal marshes are not flat. Slight variations in height across a marsh surface can result in significant variations in tidal flooding, drainage, leaching, and evapotranspiration, all of which affect soil salinity. As height increases, the sensitivity of these factors to changes in height also increases. Ecologically significant changes in these factors correspond to slight variations in height across a high marsh. For example, a 0.4-inch (1 centimeter) increase in height of a very high, mature marsh surface can result in a 35% decrease in its flood frequency (Collins unpublished). This phenomenon is due in part to the effect of the marsh vegetation on the time it takes waters to cross the marsh plain during flood tide, before the tide begins to ebb. The friction of the vegetation slows the water, such that it does not reach the height in the interior areas of the plain as it would without vegetation (e.g., Leonard and Croft 2006). This effectively raises the height of these areas, relative to the tides.

Floodwater that infiltrates the marsh surface away from channels and the foreshore does not drain away, even at low tide. After infiltration, the height of the groundwater in these areas is very near the marsh surface. Evapotranspiration of this water increases the concentration of salt in the marsh soils. In areas very near the channel bank or foreshore, the surface and subsurface soils drain better. Soil salinity therefore tends to increase with distance from channels and the foreshore (Balling and Resh 1982,

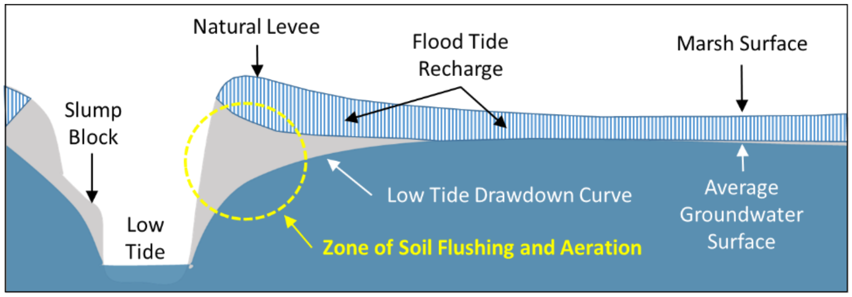

Figure 1.4. Diagram of the channel zone of a mature tidal marsh channel, showing characteristics processes and features (after Balling and Resh 1982).

Fagherazzi *et al*. 2004). However, areas of the marsh surface that are seldom flooded by the tides, such as natural high marsh levees, can be leached of salt by rain. Natural tidal marsh levees and the backshore tend to have zones of decreasing soil salinity with height above the average marsh plain (NOS 1978, Traut 2005, Fagherazzi *et al*. 2013).

There are many processes and features along the margins of a tidal marsh channel that distinguish this area from other areas in a tidal marsh. We refer to this area as the channel zone (Figure 1.4). It incorporates the channel bank, plus any slump blocks, the bank top, plus any natural levee. It also includes the area beneath the marsh surface that is affected by drawdown of the near-surface groundwater through the channel bank during ebb tides, and recharge through the bank and the marsh surface during over-bank flood tides. The clayey banks have very slow hydraulic conductivity, such that recharge through them, as the tide rises in the channel, is negligible. However, the tide spends most of its time at or below mid-bank, such that the water table near the channel is subject to long periods of drawdown. As a result, there is an area beneath the bank top and between the recharge and drawdown processes that tends to be unsaturated (i.e., aerated). The drawdown also tends to lessen the salinity of the soils in this area. This provides habitat in the channel zone for plants with deeper rooting depths and less tolerance of saline conditions.

The sedimentation and sub-surface gradients establish subdued but ecologically significant microtopography, including natural, low-relief levees atop the banks of larger channels in mature tidal marshes (Pestrong 1972, French and Stoddard 1992, French and Spencer 1993, Reed *et al*. 1999). These levees are due to sedimentation gradients from tidal creek sources of suspended sediment, across the tidal marsh plain. Turbulent flood tidal flow in large channels maintains large concentrations of suspended sediment in the upper water column. When overbank tidal flooding occurs, tidal flows spread over the marsh plain where suspended sediment is rapidly deposited due to tidal energy loss from friction of marsh vegetation. Concentration of local overbank sediment deposition at the channel bank top gradually builds a small natural levee as tidal marsh topography matures. As the tidal flood flow proceeds upstream, it slows and becomes more laminar, allowing the suspended sediment to settle, and reducing its availability to the bank top and marsh surface. The heights of natural levees therefore tend to decrease upstream within drainage networks, and the smallest, most head channels usually lack levees (Collins *et al*. 1987).

In a mature tidal marsh, the soils tend to become less clayey and their hydraulic conductivity increases with increased soil organic matter accretion, which increases with distance away from the channel zone. Vertical fluctuations of the water table in these areas are mainly due to infiltration by overbank tides and evapotranspiration; there is very little lateral movement of the groundwater. Therefore, the groundwater and soils in the areas away from channels tend to be more saline.

1.4 Generalized Effects of Alteration

For the purposes of this report, alterations are unnatural modifications to the bottom of tidal bays, the foreshore or backshore of tidal marsh, marsh channels or the marsh plains, or modifications of the adjoining uplands that affect the processes of tidal marsh evolution or natural maintenance.

1.4.1 Reclamation

Reclamation is the diking or leveeing of intertidal or subtidal areas to create arable lands for public or private uses. Partial reclamation of a marsh can lessen the tidal prism (i.e., the volume of tidal water conveyed by a tidal channel), and therefore can also reduce the velocities of tidal currents. Enough reclamation can disrupt the balance between sedimentation and erosion to cause net sedimentation, until a new balance is achieved between the reduced tidal prism, wave and current power, and sediment supply. The sedimentation induced by reclamation tends to first occur as shoaling in the nearby tidal or subtidal channels, followed by channel narrowing, but can also involve the expansion of tidal flats and marshes. The effect of reclamation in tidal rivers or embayments on the dimensions of their inlets is well known (Tao *et al*. 2010, Kidd *et al.* 2017, D'Alpaos t al 2010).

1.4.2 Dredging

Dredging within the intertidal zone (i.e., between MLLW and MHHW), which can include the breaching of dikes to increase the tidal area, increases tidal prism and therefore increases tidal current velocities, which in turn increases the power of the tides to erode bottom sediments and foreshores. Deepening the tidal waters can also increase the height and thus the erosive and sediment transport capabilities of wind-generated waves.

Dredging increases the amount of suspended sediment in the affected tidal waters, and can thus cause the unintended redistribution of sediments by the tides. Mobilized sediments that are conveyed to sufficiently low energy tidal areas can settle and increase local sedimentation rates. Dredging can also exhume contaminated sediments and thus increase their interactions with food webs (Rich 2010).

1.4.3 Water Control Structures

Levees, dikes, and berms are water containment structures addressed in the section above on reclamation, and with regard to managing sea level rise in Chapter 2. Here the focus is on weirs or sills, culverts, tide gates, pumps, and siphons used to control the flow of water into or from a diked or reclaimed area. Weirs or sills are areas of containment structures that are intentional notched or lowered to allow an upper layer of the high tidal waters or upland runoff to pass over the structure, and to control the level of water stored in the diked area. Some sills have ways to be raised or lowered to further control tidal flooding or drainage. Culverts are usually installed in containment structures to allow the flood and ebb of the tides to and from the diked area, or to convey upland runoff to a tidal area. Their height, length, and diameter can be designed to restrict the tidal flow, such that the maximum height of the tides is lowered, relative to adjoining fully tidal areas. Tide gates can be fitting on culverts to enable diked areas to drain at low tide, but not fill with tidal water during flood tide. Tide gates are commonly used at stormwater retention basins, where storm runoff from uplands is stored during high tide, to reduce upstream flood risks, and then release the water during low tide, to make room for additional storm runoff. Unless they are properly maintained, tide gates tend to be fouled by floating debris, such that they do not close or open properly. Pumps and siphons are used to drain diked areas without interfering with the design of containment structures.

Unless they are sized to convey unrestricted tides, culverts reduce tidal prism to some degree. Weirs always reduce tidal prism. Any water control structure that conveys water that is either more saline or less saline than the receiving tidal waters will create an aqueous salinity gradient that can affect the distribution and abundance of tidal plants and animals.

1.4.4 Upland land uses

Upland land uses can significantly influence the quality and quantity of freshwater runoff and terrigenous sediment entering tidal areas. In general, any increase in impervious area will increase runoff to the nearest tidal area, unless the runoff is somehow put into the ground. Impervious surfaces include pavement, roofs, and ground compacted by ranching, dairying, and off-road vehicle use. Wildfires can create impervious soils by increasing their content of plant oils and waxes (e.g., Kalendovsky and Cannon 1997, Neary *et al.* 2008). The quality of the runoff tends to vary with land use type and actual land use practice. Agricultural land uses can increase the loads of nutrients, herbicides, pesticides and other chemicals used in ranching and farming. Runoff from industrial lands can include a wide range of chemicals including heavy metals. Conversion of agricultural lands to industrial and other urban land uses, as well as changes in industrial uses can create mixtures of legacy contaminants in runoff. Urban areas typically provide large amounts of chemicals derived from petroleum, due in large part to runoff from paved vehicular roads. The chemistry of agricultural and urban runoff is the subject of abundant applied and basic research (e.g., USEPA 2016, McKee *et al.* 2003, Lye 2009).

Land uses that increase runoff into earthen channels are likely to increase their erosion. Channels will deepen and /or widen to accommodate the increased flow. Flooding out of the channel during major storms will not prevent the erosion due to increased average runoff amounts. Without bedrock or other natural or artificial feature that prevent channel beds from eroding, channels will continue to deepen as average amounts of runoff increase, through a process called degradation or incision. Channels can eventually incise deep enough to abandon their floodplains. As the channels adjust to contain greater flows, they deepen. Incision can be chronic until the amounts of runoff stop increasing. Incision can lead to bank erosion and collapse, causing significant increases in terrigenous sediment supply to tidal areas.

Land uses that increase runoff to steep hillsides can cause surface erosion as well as landslides. Periods of intense rain plus runoff on hillsides from impervious surfaces can trigger multiple landslides, especially if the geology is prone to landsliding, which in turn can cause pulses of sediment to enter tidal areas though streams and storm drains. Various approaches to reducing runoff and related erosion, such as constructing catchment basins, planting dense vegetation, preventing development on steep slopes, converting from impervious to pervious surfaces, etc., can reduce sediment supplies.

1.5. Relevance to Bothin Marshes

1.5.1 Marsh Evolution

Tidal marshes have always been larger in the upper areas of Richardson Bay than in the more downstream areas. There are at least five factors that help explain this condition.

- Firstly, these areas are the lower reaches of gently sloping valleys where tidal and terrigenous sediments can settle and accumulate as broad tidal flats and marshes. Most of the other lands around of Richardson Bay are much steeper and therefore can only support fringing marshes.
- Secondly, a submarine cliff or scarp about 60 ft high exists across the mouth of Richardson Bay (Figure 1.5). This drop-off tends to cause the tidal waters flowing through Raccoon Strait from the

Figure 1.5 showing scarp at the mouth of Richardson Bay and adjoining deep subtidal area directing the flow of tidal waters through Raccoon Strait (see Figure 1.6) (from Means 1965).

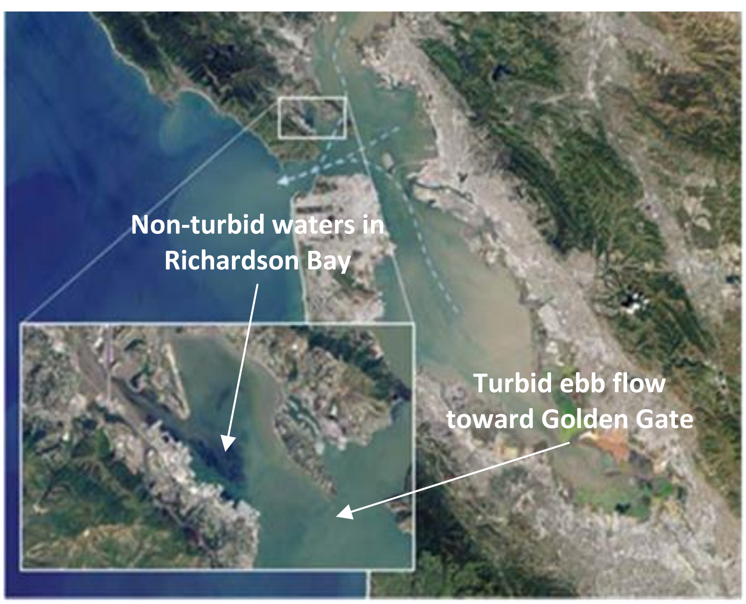

Figure 1.6. Plume of turbid, sediment-laden water (brown in color) of a wintertime ebb tide bypassing the less turbid water (lighter brown and blue) in Richardson Bay.

northern reaches of San Francisco Bay to bypass Richardson Bay (Figure 1.6; Means 1965). Although these ebb flows from the northern areas of San Francisco Bay can carry large amounts of fine suspended sediment, more than 400 parts per million during winter storms (Schoellhamer *et al*. 2013), very little of this sediment enters Richardson Bay.

- Thirdly, since the mouth of the Bay is very near the Golden Gate, the flood tides entering Richardson Bay involve waters from the Gulf of the Farallones. These waters tend to have small amounts of fine suspended sediment, less than about 90 parts per million (Schoellhamer *et al*. 2013). The suspended sediment concentration can be expected to increase during periods of high freshwater runoff from the Sacramento River in the winter and spring, when some of the sediment-laden water that flows out of the Golden Gate during ebb tide will come back in toward the mouth of Richardson Bay during flood tide. For example, perhaps 3 inches of shoaling took place in some areas of the Bay immediately after the historic storms of January 1982, and were subsequently resuspended by waves and redistributed within the Bay by the tides (Williams 1983). Yet, in general, the tidal waters flowing into Richardson Bay lack much tidal sediment.

- Fourthly, although there is no sediment budget for Richardson Bay that quantifies the relative amounts of terrigenous verses tidal sediment that comprise the total sediment supply, a substantial portion of the fine sediment in the Bay clearly originates from adjoining local watersheds (Van Geen et al. 1999). This is indicated by the fact that tidal marshes evolved first in the upper Bay, near the mouths of the local watersheds, beginning with the formation of small deltas or bars of coarse sediment (Connor 1975). Tidal marsh have existing off and on at the mouth of Arroyo Corte Madera del Presidio since about 4,500 years ago, although the historical marshes are less than a few hundred years old (Connor 1975).

- Finally, the net direction of tidal sediment transport is toward the upper areas of Richardson Bay, due to flood tide velocities exceeding ebb velocities, and due to the southeast wave fetch that directs waves into the upper Bay during major storms (Williams 1983) that resuspend sediment from tidal flats and deliver it to the tidal marsh channels, which then directs it onto the marsh surfaces (Krone 1962 as cited in Williams 1983)

1.5.2 Bothin Marsh Eco-geomorphic Units and Tidal Marsh Processes

This discussion applies the general tidal marsh processes reviewed above (sections 1.1 to 1.4) to the eco-geomorphic units defined in Chapter 4 specifically for Bothin Marsh. The eco-geomorphic units comprise a conceptual landscape framework that integrates dynamic geomorphic and ecological features into self-evident components or “working parts” of the marsh system. The eco-geomorphic framework can help place marsh-forming and marsh-maintaining processes in the local context, especially for the translation of physical processes to ecological consequences for focal habitats and populations of plants and wildlife. Habitats, wildlife, and plants have specific interactions with particular aspects of eco-geomorphic processes, landforms and vegetation structure that can be made explicit in the context of general marsh-forming processes. This application of the framework to the Bothin Marsh Complex relies on information provided by local studies as well as complimentary investigations of comparable marshes in San Francisco Bay and other estuaries.

1.5.2.1 Wave Processes at Marsh Foreshore

Despite emphasis on vertical marsh sediment accretion in relation to sea level changes over the Holocene Epoch through the modern era, recent analysis of the Bothin Marsh Complex (Chapter 3) shows that tidal salt marshes are vulnerable to wave erosion and collapse as a result of inherent horizontal instability (Leonardi and Fagherazzi 2014, Fagherazzi 2013). In many locations, tidal marsh resilience in vertical adjustment to sea level rise is greater than horizontal resilience (Kirwan *et al*. 2016). Horizontal marsh erosion is primarily controlled by wave power (Schwimmer 2001), and does not require sea level rise; however, sea level rise can indirectly intensify horizontal salt marsh instability by affecting water depth, which positively affects wave power (see Section 1.1 above).

Horizontal salt marsh erosion in the San Francisco Estuary, and at the Bothin Marsh Complex, can occur at the bay mudflat/salt marsh edge with a variety of morphological variations (Beagle *et al*. 2015). Erosional retreat by erosion of marsh scarps (cliffs in cohesive marsh mud or peaty soil), with slump block rotational failure (Allen 1988), or detachment and toppling of undercut, overhanging marsh sod (root mat/soil masses; Beagle *et al*. 2015, Schwimmer and Pizzuto 2001), is prevalent at bay fringing salt marsh of Bothin Marsh (Chapter 4). As in tidal creek bank slump bloc dynamics (Gabet 1998), slump blocks at the bay margin can either rapidly erode and disintegrate underhigh wave power, or become recolonized by low marsh vegetation (cordgrass), which establishes as seedlings or vegetative fragments in the temporary shelter of eroded slump blocks. Depending on erosion rates, slump blocks can either initiate a phase of fringing marsh recovery and progradation, erode progressively, or cycle between erosion and progradation phases. Intense storms can trigger episodes of marsh scarp retreat, and so can frequent periods of non-storm high wind-wave activity.

The shear strength of sediments and soils in the scarp influence the rate of erosion in response to wave power. Pickleweed marsh soils are relatively strong compared with cordgrass mud or unvegetated bay mud (Pestrong 1965). North Bothin Marsh is currently fringed by salt marsh outside the bay levee, which buffers erosion of the levee. If scarp erosion retreats into the levee, it will expose levee foundations on unvegetated bay mud. Behind the levee is a platform of dredged bay mud fill at the south end of North Bothin Marsh. This substrate may be less erosion resistant than salt marsh soils. At Muzzi Marsh, erosion rates appear to accelerate when the scarp retreats into dredged materials landward of the perimeter levee, after collapse of the levee (P. Baye, personal observation). Scarp retreat processes at North Bothin Marsh may undergo changes in rates and styles of slope failure in relation to the variation in substrates exposed at the foot of the scarp, where wave action undercuts the slope.

Figure 1.7. Caption next page.

Figure

1.7. Wave-cut salt marsh scarps at Bothin Marsh. (A) Active scarp at east end “headland” of south-facing levee, North Bothin Marsh. Note collapsing, undercut salt marsh sod and canopy. (B) Detached rotational slump block (tops still near horizontal) below scarp, submerged at high tide. (C) Cordgrass colonized a narrow zone of slump blocks (submerged at high tide). Pickleweed and other high marsh plants “drown” on blocks rotated to low marsh tidal elevations with excessive duration of daily tidal submergence; cordgrass seedlings colonize the sheltered, stable substrate of blocks and dead/dying high marsh vegetation. (D) Active cliff in compacted, cohesive levee at North Bothin Marsh “headland” at south end. Waves generate visible suspended fine sediment plume from eroding levee scarp. Trampling (public access) compacts soil and waves shear vegetation, producing a prostrate saltgrass turf on levee substrate, in contrast with high pickleweed salt marsh. (E) Abrupt zonation between fringing high salt marsh bayward of North Bothin Marsh east-facing levee north of “headland” (pickleweed, saltgrass, alkali-heath and Jaumea dominants) and uniform narrow cordgrass marsh belt below relict scarp (abrupt change in slope). Vegetation and topographic structure results from post- erosion scarp recovery phase. (F) Progressive active erosion of south-facing bay fringing marsh north of Coyote Creek mouth, with undercut sod and topping failures rapidly disintegrating from erosion by frequent wind-waves (from long fetch towards Golden Gate). Little or no persistent cordgrass colonization occurs in highly exposed scarp segment. (Photo dates: A – June 2012; B – Oct 2015; C-E Oct 2017; F – June 2016)

Figure 1.8. Oblique view of North Bothin Marsh bay-edge salt marsh scarp shows active erosion and retreat indicators. Topping and rotational failures of recent slump blocks at north end are circled. Recent failure is indicted by persistence of high marsh vegetation at top of slump block. April 2017.

Figure 1.9. Areas of low and high wind-wave settings of salt marsh show erosional scarps. (A) Muzzi Marsh bay edge is exposed to chronic ferry wakes at higher tide stages and long wind-wave fetch to south. The old levee has eroded, exposing dredged bay mud fill on which restored tidal salt marsh forms a "crust" over low-strength consolidated mud with no root mats. Slump blocks rapidly deteriorate before cordgrass can establish well-anchored seedlings or clones. August 2017. (B) Manzanita Marsh (south) toppling slump block failure formed during wave erosion phase, followed by mudflat accretion. This cycle establishes sheltered microsites for potential cordgrass recolonization by seedling establishment and spread of clones. April 2013.

1.5.2.2 Wave damping (energy attenuation) by salt marsh vegetation

Waves propagating over the rough surface of a vegetated tidal marsh submerged during high tides rapidly lose energy to bottom friction, which results in rapid wave height decay. Fringing tidal salt marshes cause much more rapid and efficient loss of wave energy (large wave energy loss over short distance/marsh width) than tidal mudflats, and they can effectively cancel significant erosion potential or wave run-up flood potential of bay waves over distances less than 20 m from the bay/marsh edge in shallow, narrow bays (Feagin *et al*. 2011, Möller 2006, Möller and Spencer 2002) like Richardson Bay. Wave damping properties of salt marsh vegetation depend on vegetation height, shoot flexibility, and density of shoots and leafs. Landward high marsh and transition zones are protected from wave erosion by wide salt marsh plains. Protected shorelines include high salt marsh habitat of rare plants and vegetation providing high tide refuge cover for wildlife. Marsh vegetation does not itself protect the erosional bay scarp below it (Feagin *et al*. 2009), but attenuates wave energy landward of the canopy through which waves propagate, significantly protecting landward marsh and shorelines against wave energy impacts on flooding or erosion (Gedan *et al*. 2011). At Bothin Marsh, high salt marsh vegetation that covers the levee crest of North Bothin damps waves during tides that overtop the breached levee. Bay fringing salt marshes from the Coyote Creek mouth to North Bothin Marsh establish local wave-shelter zones with reduced wave erosion intensity along the bike/pedestrian path shoreline.

Figure 1.10. Wave damping at the bay edge of north Muzzi Marsh in low wave energy conditions during high spring tide, January 2011. (A) Waves intercepted by leading edge of pickleweed vegetation. Wave height approximately 10 feet, meeting or exceeding height of pickleweed canopy top. (B) Wave damping zone marked by wave-wetted (darker) pickleweed shoots contrasting with dry (lighter) shoots where waves are damped to height less than pickleweed shoot canopy above still water level. Wave-wetted (wave damping) zones are less than 30 feet-wide.

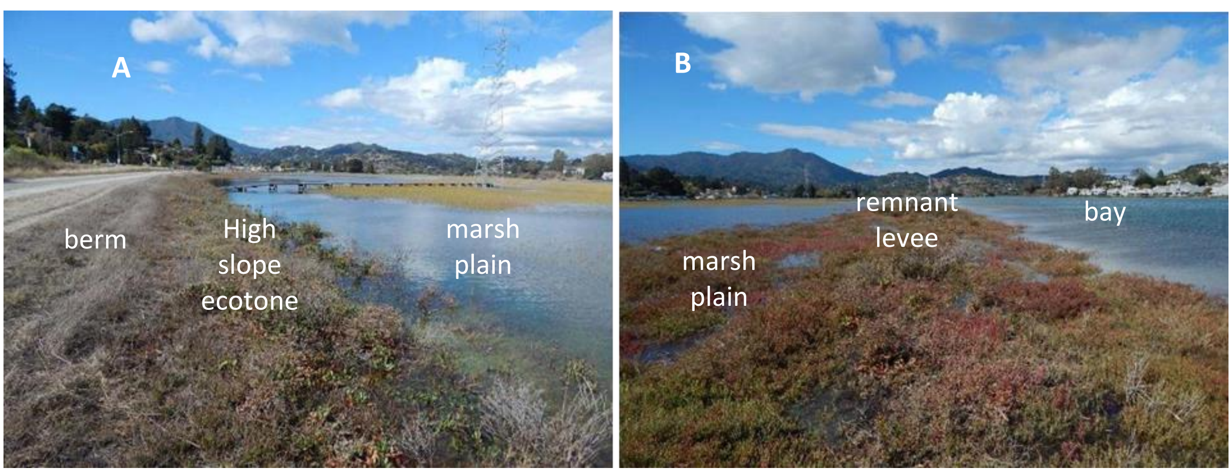

Figure 1.11. Canopy of emergent marsh vegetation is shown during calm-weather spring high tide submergence of (A) the North Bothin Marsh plain and (B) levee crest. Vegetation roughness provides wind-wave attenuation during storm conditions. October 2015.

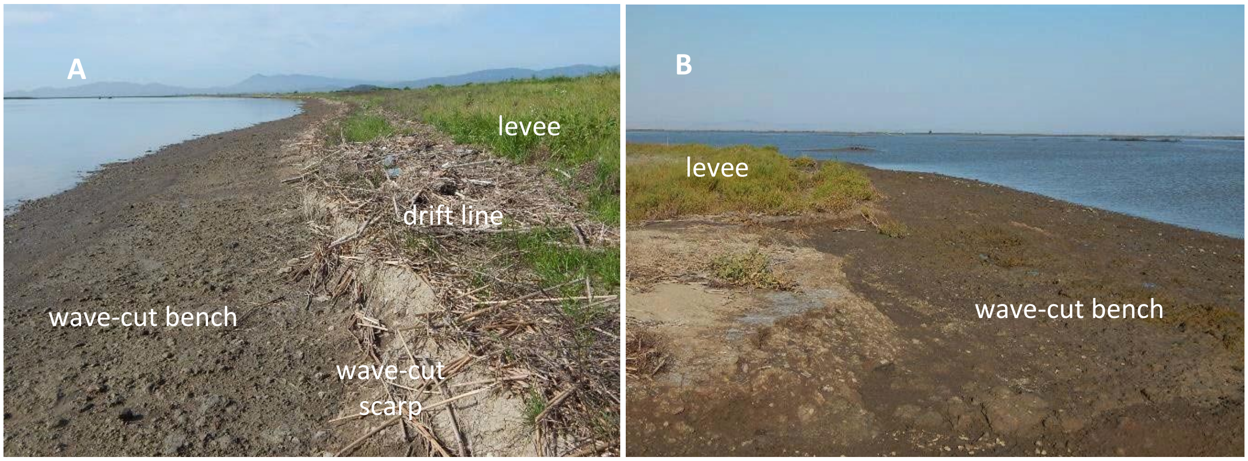

Figure 1.12. An example of wave erosion is shown on salt marsh restoration shorelines that do not have wave-damping intertidal vegetation. Low-gradient "horizontal levee" of new tidal marsh restoration site (Sears Point, Petaluma) in the bare, graded intertidal flats. Rapid, significant erosion of gentle gradient designed for 10:1-20:1 (south-facing levee) in a single year indicates the essential contribution of wave attenuation by marsh vegetation to the stability of low-angle slopes. Steeper slopes (less than 10:1) are most vulnerable to wave erosion unprotected by fringing salt marsh. (A) About 1 to 1.7 feet of high erosion scarp has formed in the levee facing away from dominant westerly winds, and a wide scour zone has removed approximately 1 foot of fill from the south-facing levee (B) one year after tidal breaching. Negative feedback processes (wave-cut bench flattens slope with increased exposure of more cohesive, higher-strength compacted mud with high roughness to trap seeds and shelter seedlings) eventually shifts intertidal profile to frequent seedling colonization phase and marsh shoreline stabilization. August 2017.

1.5.2.3 High Salt Marsh Berm and Beach Accretion (swash bar, beach, marsh-fringe barrier)

Estuarine or bay beaches worldwide can develop along the bay edges of salt marshes, where they form marsh-fringing barrier beaches (Pilkey *et al.* 2009), originally classified as "marsh bars" (marsh berms or barriers) where swash bars (small beach ridges deposited by the swash and backwash of breaking waves) develop along wave-eroded edges of tidal marshes, and develop marsh vegetation (Johnson 1919). Estuarine beaches have morphodynamic processes comparable with, but distinct from, beaches of open sea and ocean coasts (Jackson *et al.* 2002), and provide similar wave-dissipating and wave-break functions. In San Francisco Bay, small marsh-fringing barrier beaches develop from sand, shell hash, and gravel. They shelter salt marshes and levees otherwise exposed to high rates of direct erosion by wind-waves.

During periods of relative stability, the crests of wave-built berms develop well-drained, tall salt marsh vegetation, including gumplant. This is similar to non-maintained artificial bay mud levees. Unlike levees, the crest elevations of marsh berms are maintained or increased in elevation by wave runup, and rapidly adjust to changes in wave height and sea level. At Aramburu Island in Richardson Bay, artificially nourished coarse gravel and sand beaches, spontaneously accreted to elevations approaching extreme high tide levels, in response to storm wave runup. Unlike sand beaches, gravel berms generally accrete during storm wave action and high tides. (Gillenwater and Baye 2016). The unvegetated beachfront is often used by roosting shorebirds at high tide, when mudflat foraging habitat is submerged. Historically, marsh-fringing barrier beaches and barrier spits occurred in Richardson Bay, including the shore opposite from Almonte (North Bothin) Marsh.

Like barrier beaches, coarse beaches can migrate landward rapidly in response to wave overwash ("rollover": bayward erosion, landward deposition; Allen and Pye 2002). Beaches intercept and dissipate breaking wave energy (Jackson *et al*. 2002). If the foreshore of the marsh lacks a beach then it is unprotected and a wave-cut scarp may occur (Feagin *et al*. 2009). The natural vertical and horizontal adjustment of bay beach profiles in response to storms and sea level makes them function like mobile, flexible self-maintaining levees where coarse sediment supply is provided naturally or artificially. Coarser sand, gravel and shell material develop steeper and more storm-resilient beachfronts and berms. Shell hash is more mobile and less stable than gravel as beach sediment in the Bay. Mobile shell hash marsh-fringing barriers, however, buffer wave erosion of highly exposed (wide bay wind-wave fetch) salt marsh scarps in San Francisco Bay, such as outer Bair Island in South Bay. Naturally formed barrier beaches with gravel also shelter pocket salt marshes and protect segments of levees enough to change the bayward slope of levee to minimize erosion. They have also caused some armored concrete riprap slopes to become vegetated.

Figure 1.13. Gravel bay barrier beach formed from erosion of historic landing fill is shown at Newark salt ponds west of Coyote Hills, San Francisco Bay. (A) Unvegetated levee exposed to waves is armored with concrete slabs and rubble. (B) Salt pond levee in lee of barrier beach supports salt marsh and a vegetated levee slope. October 2014

Figure 1.14. Gravel and sand berm accretion by wind-waves in Richardson Bay under the 101 Highway, south of Bothin Marsh. Local shoreline erosion of fill supplies the coarse sediment. Waves deposit a swash bar over the edge of the paved path. September 2017.

Figure 1.15. Fringing barrier beaches. (A) pocket sand and shell berm at Hayward Shoreline salt marsh ; (B) high marsh berm formed from organic debris and sand, Pinole Creek ; (C) gravel and sand beach capped with high tall gumplant and pickleweed; Emeryville Crescent Marsh, (D) highly mobile, mostly unvegetated barrier oyster shell hash exposed to wind-wave and ship wakes, outer Bair Island, San Francisco Bay.

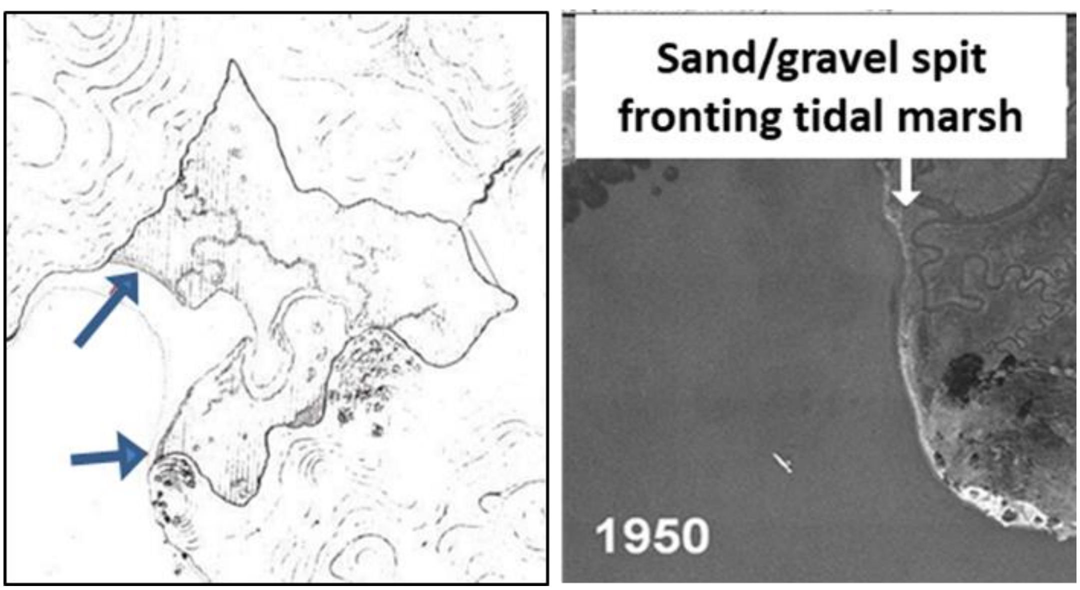

Figure 1.16. (A) Historical barrier beaches fronting tidal marsh and end of Richardson Bay (USCS T- sheet 334N, 1851); and (B) a gravel spit with back-barrier tidal marsh relating to the erosional headland of the Richardson Bay Audubon Center. This gravel spit persisted at least until 1950, when it was developed.

1.5.2.4 Tidal Marsh Creek Sedimentation, Drainage and Vegetation Gradients

Tidal creeks are the arteries of the tidal marsh plain, distributing tidal energy for sediment transport into the salt marsh interior, and tidally "pumping" marsh soil porewater and dissolved oxygen in the root zone of steep salt marsh creek banks (Figure 1.4; Li *et al*. 2005). The distinct marsh vegetation zones, and important wildlife habitat structure of salt marsh creek banks are formed and maintained by strong, steep, tidal sedimentation gradients between the tidal creek edge and a narrow zone of tidal marsh plain bordering it (Section 1.3, this chapter; Culberson *et al.* 2004). The sedimentation gradients establish subdued but ecologically significant microtopography: natural low-relief levees occupy tidal creek banks in geomorphically mature tidal marshes (Reed *et al*. 1999, French and Spencer 1993, French and Stoddart 1992, Pestrong 1972). A local example in an ancient salt marsh (China Camp Marsh) is shown in Figure 1.17.

The combination of the topographic highs (levee patterning) and tidal drainage along tidal creek banks supports a distinct zone of salt marsh vegetation structure and habitat in San Francisco Bay: tall-form pickleweed, and tall nearly evergreen gumplant vegetation delineates relatively well-drained high salt marsh of tidal creek banks, a characteristic signature of mature San Francisco Bay tidal salt marshes (Culberson *et al*. 2004, Pestrong 1972, Hinde 1954). The elevated vegetation canopy of this eco-geomorphic zone (taller vegetation on topographic highs of subtle natural levees) provides critically important sub-habitats that remain emergent above most extreme high tides and wind-wave crests. This eco-geomorphic interaction generates habitat structure essential for marsh wildlife species that maintain territories or home ranges within the interior marsh. Secretive salt marsh birds like California Ridgeway's rails feed and travel primarily under or close to cover of cordgrass/mud edges below tidal creeks banks, sheltered by vegetation canopies and overhanging bank-top sods at low tide.

At high tide, and especially at extreme high tides that submerge the interior marsh plain entirely, rails must find local cover to avoid avian predators (harriers, egrets) and terrestrial predators. Rails are forced to make long-distance cross-marsh movements to find cover when salt marsh plains are submerged, exposing them to higher predation risks, or greater exposure to terrestrial predators along the landward edge of the salt marsh. If high tide cover is distributed in banks above tidal creeks, wildlife access to high tide refuge cover is optimized, and cross-marsh movements from foraging habitat to high tide refuge within the rail's home range is minimized. In addition, high marsh creek banks mantled with tall pickleweed and gumplant also provide the primary nesting habitat for California rails (USFWS 2013, Albertson and Evens 2000). Other salt marsh birds that occur in Richardson Bay, including San Pablo song sparrows and California black rails (Spautz and Nur 2002), depend on the high marsh zone along tidal creek banks for foraging and nesting as well (Trulio and Evens 2000, Cogswell 2000). Small mammals similarly utilize creek bank high marsh vegetation canopies as high tide refuge (USFWS 2013).

In geomorphically immature salt marshes with limited internal tidal creek development or restricted interior marsh sediment supply, high marsh development at creek banks may be slow or fail to develop adequately for important habitat functions even after decades, such as at interior Cogswell Marsh (Hayward) and interior Muzzi Marsh (San Rafael; Figure 1.18)). In contrast, bayward reaches of tidal creeks with mouths connected to sediment-rich mudflats are relatively well supplied with sediment to form tidal creek banks, and develop high salt marsh vegetation zones (Figure 1.19). In restored salt marshes, if high marsh zones are decoupled from tidal creeks, critical tidal creek habitat in high tide refuge, nesting, and foraging habitat functions for wildlife will not developed. This is apparent in most of Bothin Marsh. South Bothin marsh lacks any high marsh near tidal channels: all salt marsh bordering tidal creeks is pickleweed-cordgrass ecotone or pure cordgrass vegetation. North Bothin salt marsh vegetation adjacent to tidal creek banks is dominated by middle marsh vegetation (pickleweed-cordgrass) or nearly prostrate high marsh vegetation (saltgrass mixtures). Gumplant is restricted primarily to artificial levee crests, slopes, and high salt marsh mounds near the outer edges of the salt marsh plain.

Figure 1.17. Tidal creek bank patterning of high marsh showing (A) sinuous zones of dense gumplant, interior prehistoric salt marsh plain, China Camp Marsh, San Rafael; (B) continuous high tide refuge cover from front to back of same marsh; and (D) well-developed creek banks (natural levees in ancient tidal marsh plain) support steep tidal drainage gradients with tall gumplant and pickleweed as refuge; December 2012, and December 2008).

Figure 1.18. Interior Muzzi Marsh tidal channel, after over 40 years of tidal restoration, still lacks sufficient topographic and tidal creek drainage gradients along creek banks to support tall-form pickleweed or gumplant. Olive-green diatom films on channel muds indicate their immobility. The interior marsh plain formed on dredged sediment fill and was ditched to initiate channels and improve internal tidal drainage. It remains continuous monotypic pickleweed marsh with minimal high tide refuge (compared to interior North Bothin Marsh). August 2017.

Figure 19. Bayward Muzzi Marsh tidal creek with mouth directly connected to San Rafael Bay (wave-exposed mudflat with high suspended sediment supply) has developed natural steep banks with high salt marsh levee topography and tidal drainage, supporting dense gumplant and tall-form pickleweed, with local high tide refuge cover. Gumplant delineates banks. (A) August 2017; (B) October 2011.

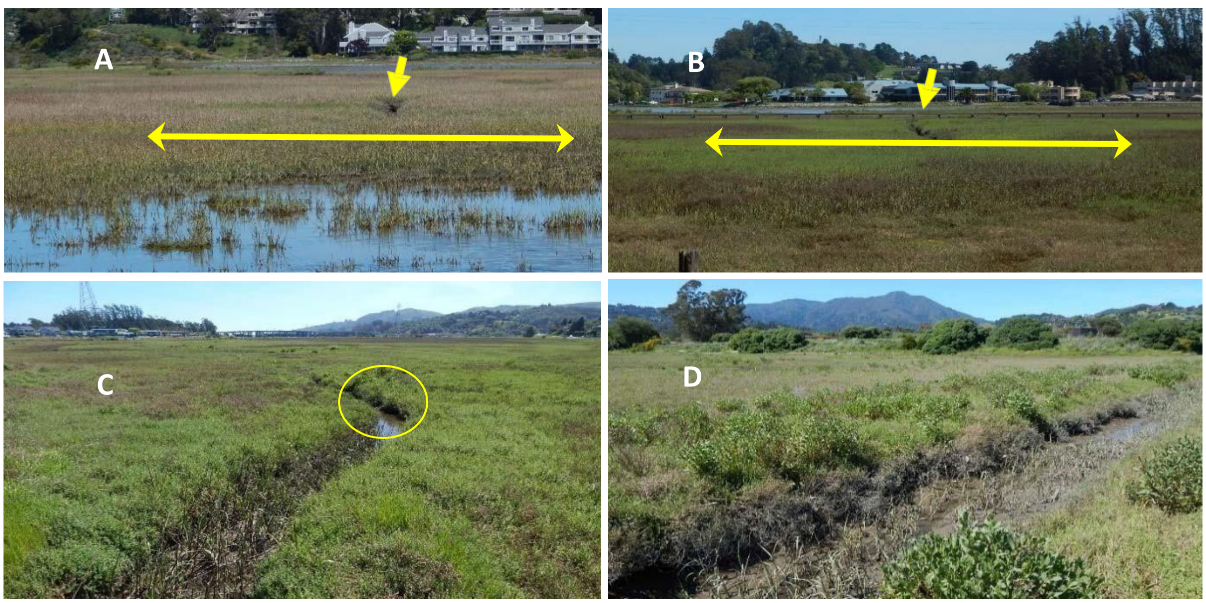

Figure 1.20. (A) Tidal channels in South Bothin Marsh and North Bothin Marsh exhibit some zonation typical of high marsh on banks, despite a lack of natural levees. (B) South Bothin Marsh channels are bordered by cordgrass and short pickleweed (yellow horizontal arrow), and (C) North Bothin Marsh channels are bordered by mid-marsh vegetation (yellow double arrow), with only isolated gumplant (yellow circle). In contrast, (D) Alto Marsh (north of Bothin Marsh) has tall gumplant along natural levees at ancient marsh remnants. Although South Bothin Marsh has been evolving for more than a century, it's tidal sediment supply has been restricted. This is also true for North Bothin Marsh, which has been evolving on natural mudflat and dredged sediment for as long as Muzzi Marsh.

Figure 1.21. Main trunk channels branched near the levee breach, close to tidal sediment sources in Richardson Bay, also lack natural levee. Most of the marsh plain is dominated by intermediate low and middle marsh vegetation. A saltgrass meadow occurs locally along banks closest to the tidal breach, with only scattered individual gumplant. The creek banks are steep, cohesive, and support overhanging root mats – all indicators of normal bank processes, although slump blocks rare. Development of natural levees is still lagging after several decades of tidal action.

Figure 1.22. Small mammals, including voles capable of diving and swimming, are forced to cross open water to reach the nearest emergent cover along the terrestrial edge of North Bothin Marsh, where internal tidal creek banks have not developed high salt marsh vegetation that would provide flood refuge at short distance from, or within, the home ranges of salt marsh wildlife. Like California rails, small mammals are vulnerable to avian predators (egrets, herons, harriers) during daytime marsh submergence. January 2017.

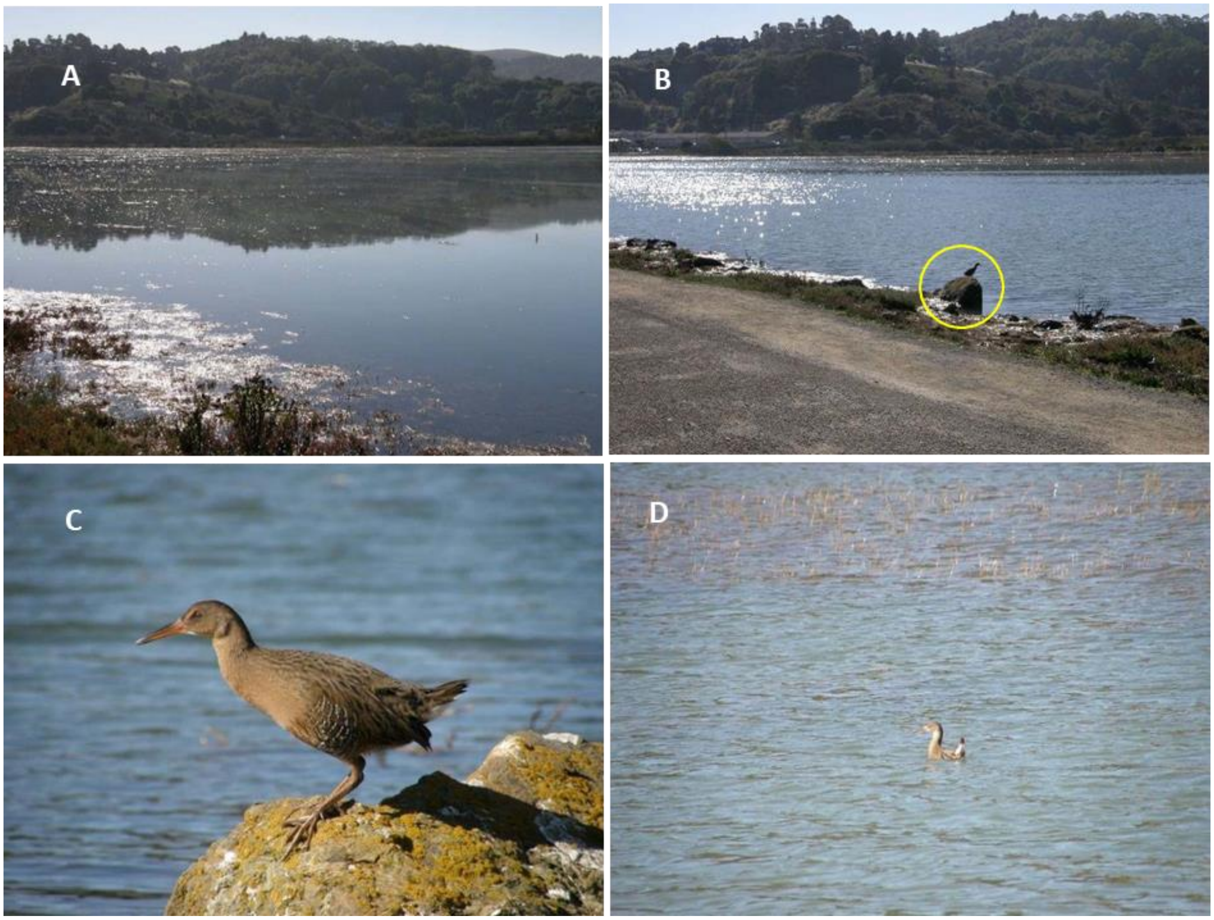

Figure 1.23. Ecological consequences of undeveloped internal high marsh creek banks: The failure to develop internal high marsh along creek banks as the first line of high tide refuge cover in South Bothin Marsh, combined with scarcity or absence of high tide refuge cover along the shoreline, strands vulnerable marsh wildlife during extreme high tides that submerge the marsh. Without internal high tide refuge cover along tidal creeks, extreme high tide marsh submergence has forced California rails to shorelines lacking cover for protection. This deficiency in salt marsh internal and edge structure exposes rails to detection by avian predators during marsh-submerging daytime high spring tides. The following example is indicative of a recurrent ecogeomorphic constraint. (A) All marsh vegetation is completely submerged in South Bothin Marsh in fall of a non-El Niño year (November 2008). (B) California rail displaced from flooded marsh reaches nearest emergent surface: interior berm slope (compacted fill and rock) with prostrate high salt marsh vegetation providing negligible terrestrial ecotone cover. Terrestrial ecotone cover is an alternative to creek bank high marsh refuge. (B-C) California rail remains exposed and highly vigilant, with no available escape routes leading to cover. (D) Rail swims to the first cordgrass cover visibly emergent above the water surface as the tide levels in the basin slowly fall, lagging behind open bay marshes. Duration of rail high tide exposure: over 45 minutes. November 13, 2008.

1.5.3 Large-scale Climate Drivers of Salt Marsh Processes

1.5.3.1 Estuarine Transgression; landward tidal marsh migration with Holocene sea level rise

Landward transgression of the tidal marsh lowland valleys and plains in response to variable rates of sea level rise has occurred throughout the Holocene Epoch in San Francisco Bay, and globally (Atwater *et al*. 1979). Estuarine transgression is an inherent feature of salt marshes, and is not a new or anthropogenic process; it is the process by which the Estuary's tidal marshes initiated in the mid-late Holocene when sea level rise rates were as high or higher than predicted for the Twenty-first Century), followed by marsh plain vertical accretion under low, variable rates of sea level rise and fluctuating climates during the last 2000 to 4000 years (Atwater *et al*. 1979, Malamud-Roam *et al*. 2006, 2007). Climate change-induced global sea level rise has added a new awareness and urgency about the artificial rapid acceleration of this process, but landward transgression has always been an inherent, natural process for tidal marsh evolution as wave and tidal sedimentation/erosion processes drive "normal" tidal marsh evolution.

Kirwan *et al.* (2016) developed coupled numerical models of erosional salt marsh retreat, sea level rise, and landward transgression (without barriers), and concluded that marsh loss is nearly inevitable where topographic and anthropogenic barriers limit migration. Models show that where tidal marshes are unconstrained by barriers however, rates of marsh migration are much more sensitive to accelerated sea level rise than rates of edge erosion: landward transgression over pre-existing lowland plains or valleys can occur without the need for sediment accretion to form new tidal marsh.

Paradoxically, sea level rise can cause tidal marsh expansion during sea level rise, despite marsh edge erosion, where barriers to transgression do not constrain salt marsh encroachment of terrestrial lowlands (Kirwan *et al*. 2016). The geomorphic accommodation space for high tidal marsh transgression in the Bay Area, however, is limited to land uses such as open space and low-intensity agriculture, which are primarily found in the North Bay and Suisun Marsh (Callaway *et al*. 2011). According to the most comprehensive tidal marsh models of ecogeomorphic evolution calibrated for the San Francisco Estuary, (Marsh Equilibrium Model, MEM; Schile *et al*. 2014), the ability of tidal marshes to compensate for marsh loss and submergence under the high rates and stands of sea level rise depends on landward transgression of the tidal marsh gradient over available lowland valleys and plains, especially critical high tidal marsh habitats under moderate to low estuarine sediment supply.

In Marin Baylands, including Richardson Bay, estuarine accommodation space is scarce in steep canyon and hillslope terrain with urbanized valleys that impose a "coastal squeeze" constraint: economic and engineering priority for "holding the line" (stabilization and flood control to protect high-value land uses) at modern shorelines, while bay edges of tidal marshes retreat from increased erosion. "Coastal squeeze" results in relative narrowing and compression of coastal marsh gradients with sea level rise instead of compensatory landward transgression, and measurable impairment of estuarine and adjacent watershed ecosystem functions adjustment to rising sea level (Torio and Chmura 2013, Turner *et al*. 2007).

At Bothin Marsh, landward transgression in the foreseeable future is highly constrained by steep privately owned fill embankments and platforms at Tam Junction, but some estuarine accommodation space for transgression is potentially recoverable from large, steep weed-dominated artificial upland fills placed in historical Coyote Creek tidal marsh during the Twentieth Century (Part 3). Almonte Boulevard road embankments, and the steep hillslope behind it, limit landward transgression of tidal marsh under current/foreseeable land use. Even road realignment with landward set-back would provide relatively modest (but significant) increase in scarce accommodation space, because hillslope topography naturally restricts tidal marsh adjustment to vertical accretion over horizontal migration processes. This makes long-term loss of high tidal marsh bordering hillslopes effectively inevitable under long-term high rates and stands of sea level under moderate or low sediment supply (Kirwan *et al.* 2016, Schile *et al*. 2014, Kirwan *et al*. 2010).

The lifespan of tidal marshes bordering natural topographic barriers like hillslopes, however, can potentially be expanded significantly (for decades) with marsh sediment nourishment methods (Part 5). Providing a broad ramp profile (gentle suitable sediment fill slope from high intertidal to lowland supratidal zones) straddling existing uplands and upper marsh edges can potentially maintain a complete tidal marsh gradient with all ecologically important habitat zones (Schile *et al*. 2014, Parker *et al.* 2011), including critical high salt marsh habitats. This may require bayward encroachment of an existing tidal marsh plain at the lower landward edge of a constructed sediment ramp profile (Chapter 5), leaving less marsh space for valuable tidal creek networks.

1.5.3.2 Extreme climate events and cycles

The late Holocene stratigraphic history of San Francisco Estuary tidal marshes is punctuated with sediment and soil layers that indicate relatively abrupt extreme climate fluctuations and events consistent with infrequent storms, extreme persistent droughts, and deluges (Watson 2008, 2012; Goman *et al*. 2008, Malamud-Roam *et al*. 2006, 2007) that temporarily re-set marsh vegetation and soil conditions, sometimes for long periods. These past climate fluctuations occurred during the slowest sea level rise rates of the Holocene. Future extreme climate events, such as extreme droughts and heat waves, are predicted to intensify and increase in frequency globally and in California (Allan 2014, Scherer and Diffenbaugh 2013, Cornwall *et al*. 2012, Dieffenbach and Ashfaq 2010). Under scenarios of accelerated sea level rise affecting tidal marsh vertical and horizontal adjustments (submergence and erosion; Kirwan *et al*. 2016) extreme climate events are likely to interact with tidal marsh changes forced by accelerated sea level rise. The cumulative impacts of extreme climate events and accelerated sea level rise are likely to substantially change tidal marsh eco-geomorphic functions, vegetation and habitats, particularly in San Francisco Estuary upper (mid to high) tidal marsh zones where soil porewater can concentrate salts during neap tides (Parker *et al*. 2011, Day *et al*. 2008).

Abrupt, extreme climate events may result in many impacts, and some opportunities for Bothin Marsh adaptive management. Adverse impacts may include mass dieback of mature gumplant (critical high tide refuge) and recruitment failure of gumplant during extreme persistent droughts and heat waves causing high marsh hypersalinity (Parker *et al.* 2011), and loss of marsh soil shear strength (erosion resistance) due to root dieback and soil drying and shrinkage during summer neap tides (Allen 1988). Extreme flood events, if coupled with high sediment yield in the Coyote Creek watershed, could result in pulses of sediment to the tidal marsh and Richardson Bay mudflat. This supports longer periods of elevated tidal marsh sediment supply (mudflat resuspension and transport to tidal marsh creeks, trapping sediment in tidal marsh). This would be most likely if tidal constraints between Coyote Creek, South Bothin Marsh, and Richardson Bay were modified to make the tidal marsh receptive to fluvial-tidal sediment transport.

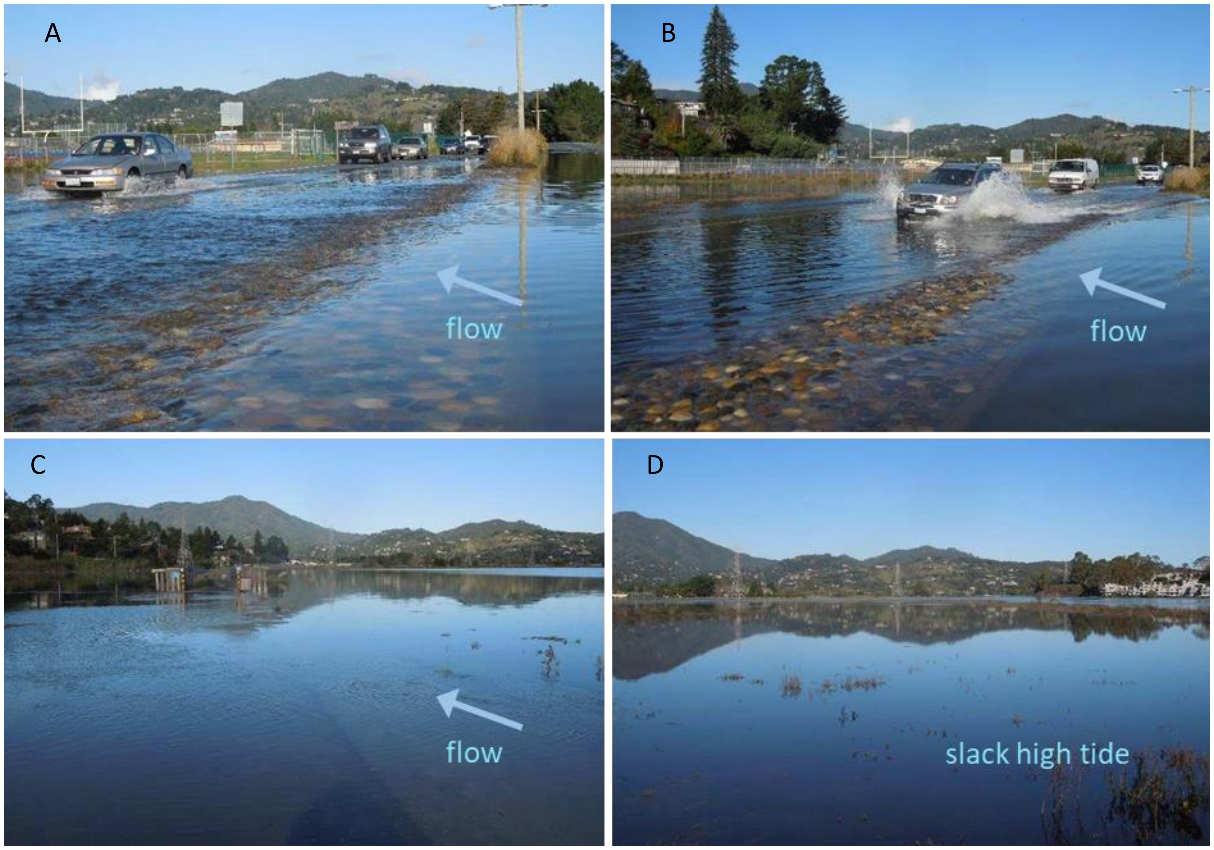

Figure 1.24. Local Bothin Marsh flood tide during anomalously high local sea level event (higher than astronomic predicted tide) during calm weather in a non-El Niño year, before the winter solstice. The median strip of Almonte Boulevard (A, B) became an floodway for the bay, with road is submerged by up to 2 feet of tidal water, and with (C) submerging South Bothin Marsh, (D) North Bothin Marshes and the Bay Trail during slack high tide, December 12, 2012.

1.5.4 Important Local-Scale Drivers of Salt Marsh Processes

1.5.4.1 Alluvial Fan deposition and estuarine submergence

Terrestrial sediment transport processes can significantly influence the landward margins of tidal salt marshes. Ancient stream deltas and alluvial fans or plains form the foundations for tidal marshes that override them during Holocene sea level rise and estuarine transgression (Watson 2012, Atwater *et al*. 1979). Active deltas and alluvial fans can also deposit sediment over tidal marsh surfaces, creating foundations for new tidal-terrestrial ecotones that support important plant and wildlife habitats (Collins *et al*. 2015, Baye *et al*. 2000). Diking, flood control, and shoreline stabilization has minimized terrestrial and fluvial process interactions with San Francisco Estuary tidal marshes, but they are still locally evident in a few intact San Pablo Bay shorelines, such as China Camp and Point Pinole.

At China Camp, a hillslope gulch erosion event deposited a new alluvial fan over tidal salt marsh during winter storms in 2006, shallowly burying high salt marsh vegetation dominated by pickleweed and saltgrass. By 2008, most of the alluvial fan surface, composed of terrestrial sediments (sand, silt, and clay eroded from weathered shale and sandstone subsoil) was recolonized by buried clonal vegetation and lateral spread from contiguous salt marsh. The alluvial fan regenerated high salt marsh gradients, with wider, gently sloping zones in the spring high tide elevation range. By 2012, the fan supported a new salt marsh-terrestrial ecotone including gumplant (Baye, personal observation, 2006- 2012; see Figures 1.25 and 1.26 below). This alluvial fan-tidal marsh depositional process, though extinct at Bothin Marsh, remains relevant because artificial surrogate processes simulate functionally equivalent landforms at restored tidal marsh edges.

At Sonoma Baylands, Petaluma (U.S. Army Corps of Engineers and California Coastal Conservancy tidal marsh restoration project), dredge sediment including sand and shell was deposited hydraulically in diked baylands to raise subsided elevations (Figures 1.27-1.28). The dredge discharge points along the landward levee were moved intermittently, forming a series of sediment splays (dredge sediment fans or mounds, analogous with alluvial fans) around the discharge point in 1995. The fans were stratified with layers of coarser and finer sediment, distributed in variable sediment lobes that established variable soil textures for tidal marsh plant growth. This "constructed" feature (partially removed by subsequent grading) subsequently formed the only high salt marsh vegetation gradients with high tide refuge cover (abundant tall gumplant) in the project's restored tidal marsh plain by 2000. They remain the only wide, gently sloped high salt marsh gradients at Sonoma Bayland.

At Montezuma Wetlands Project (Suisun Marsh), similar hydraulic dredge sediment fans analogous with alluvial fans nearly identical with those of Sonoma Baylands (20 years earlier) were deposited during dredge sediment filling operations. These artificial sediment fans became vegetated with non-tidal salt marsh in various stages of succession (see Figure 1.29). At North Bothin Marsh, shell fragment-rich, sandy to silty old dredge sediment mounds or fans (Chapter 4) persist along its landward edge, bordering the historic railroad berm (Figure 1.30). These historic relict features now support large colonies of the rare salt marsh bird's-beak and most of the tall gumplant colonies that provide high tide refuge cover internal to the marsh (not located on levee and berm slopes).

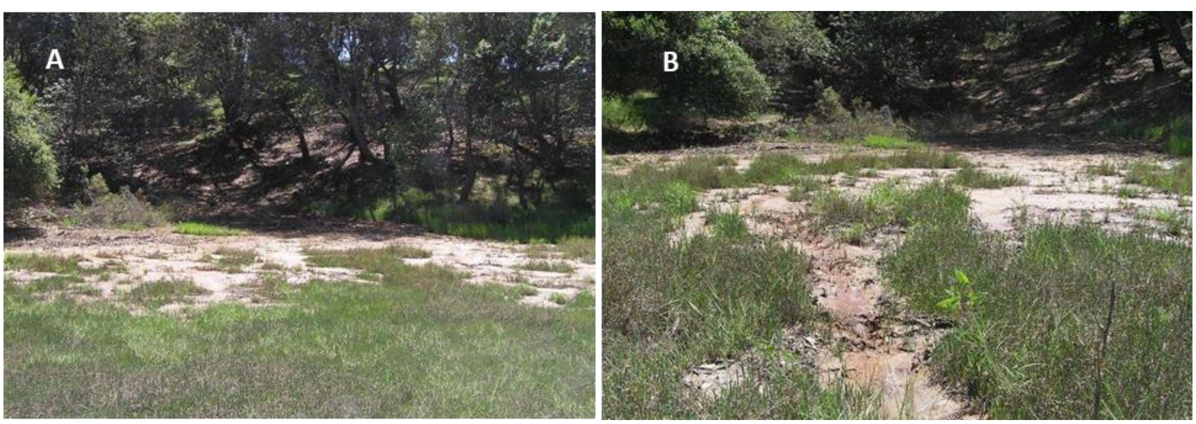

Figure 1.25 China Camp Marsh, new alluvial fan deposited during winter storms at the mouth of a gulch spread over adjacent high tidal salt marsh, shallowly burying saltgrass and pickleweed (less than 1 foot burial depth, mostly less than 0.5 foot accretion). Pickleweed and saltgrass directly regenerated on the raised alluvial fan surface, emerging through shallow terrestrial sediment deposits. May 2006.

Figure 1.26 China Camp Marsh (A, B) alluvial fan over tidal marsh almost completely recolonized by high salt marsh vegetation after two years, leaving only small bare patches of coarse sediment. April 2008, and (B) the head of the fan dominated by tall gumplant vegetation below upland coyote-brush, providing terrestrial-edge high tide refuge.

Figure 1.27. Sonoma Baylands tidal marsh restoration project (Petaluma) unintentionally created dredged sediment fans, analogous with alluvial fans, during hydraulic sediment discharge operations for raising subsided diked bayland elevation. Fans became vegetated with salt marsh vegetation prior to tidal restoration. Winter and summer 1996.

Figure 1.28 Sonoma Baylands dredge sediment fans deposited in 1996 established extensive high salt marsh vegetation gradients across the fan slopes by 2000. The artificial alluvial fans stabilized high salt marsh vegetation dominated by gumplant and tall pickleweed, similar to natural alluvial fan-high salt marsh succession event at China Camp, 2006-2012. (A) Winter 1996; (B) summer 2006.

Figure 1.29. Montezuma Wetlands tidal marsh restoration project (Suisun Marsh) unintentionally created dredged sediment fans during filling of subsided diked baylands. Fans became vegetated with salt marsh vegetation prior to tidal restoration. April 2013 (Google Earth imagery).

1.5.4.2 Anthropogenic Fill and Tidal Breach Legacy Effects

Natural antecedent topography can exert a persistent influence on the development of tidal marsh features, such as tidal creek drainage patterns (partly inherited from mudflats on which tidal marshes develop), and topographic and substrate gradients at salt marsh edges (such as stream deltas, alluvial fans, splays, beach ridges, natural channel levees and overwash wave-formed berms). These inherited estuarine, coastal or fluvial landforms can initiate and sustain tidal marsh processes long after their original formation, and long after the cessation of the processes that formed them (Allen and Pye 2002). Similar residual influences of antecedent morphology and substrate can be inherited from artificial fills and substrates, which also exert ongoing, persistent effects on the evolution of restored tidal marshes. For example, the residual elevation and consolidation (dewatering, cohesion) of dredged materials, or former compacted soils in diked baylands, can inhibit tidal creek evolution (Williams and Orr 2002).

Figure 1.30. Remnant shell-rich dredged sediment left at the backshore of North Bothin Marsh, (A) during low tide in winter, and (B) during a very high tide in early spring, illustrating the value of the sediment pile as a vegetated topographic high area serving as refuge for resident wildlife.

Bothin Marsh is outstanding in the degree of influence that artificial antecedent topography, drainage, and substrate imprinted the template of the marsh, and exerts ongoing influence on tidal marsh processes, on par with natural processes. Nearly all of the tidal marsh-terrestrial ecotone and high salt marsh at landward edges are formed on artificially constructed or deposited bay mud, hydraulic dredge sediment fans, mechanically placed dredged sediment mounds, levees, and berms. Nearly all rare plant habitat and critical high tide cover and nesting habitat for California rails depends on artificial old fills and their remnants, especially in the absence of naturally formed high marsh on channel banks. Levees and dredge sediment fans or mounds composed of pure bay mud or sand-shell-mud mixtures generally support high salt marsh vegetation.

Many relict artificially dredged and filled Bothin Marsh features, however, contain substrates that appear to inhibit erosion, sediment transport, and morphological adjustment to waves and tidal currents, and alter salt marsh vegetation structure. Resistant, dense sandy to clayey or stony fill forms a foundation on

Coyote Creek banks that apparently inhibit tidal channel incision (forming resistant lag deposits of angular rock in ditch beds), restricting incipient channels to vegetated runnels (shallow, vegetated channels) or rocky lag-armored incised shallow channels. Exposed old pipes at the marsh surface similarly act as weirs or tidal channel grade control structures in South Bothin Marsh.

Dewatered bay mud fill platforms left over from non-tidal bayland filling in the 1970s also appear to have channel-inhibiting residual effects on modern tidal marsh processes. Tidal creek development and extension (headward growth) in North Bothin marsh appears to be inhibited where it intercepts mechanically and hydraulically placed dredged sediments from the 1970s formation. Like the relatively high dredged sediment platforms of Muzzi Marsh that were filled above Mean High Water, portions of North Bothin Marsh that exhibit dredge sediment placement at the south end also appear to resist ecologically important tidal channel development.

At the extreme end of the spectrum of channel erosion resistance, the quarry rock-stabilized tidal inlet of South Bothin Marsh appears to significantly choke tidal flows between the bay and tidal basin enclosed by the historical berm and the Coyote Creek high marsh (fill) bank. Significant tidal choking (undersized tidal inlet cross-section relative to tidal prism) is indicated by the lag in tide levels between the tidal basin and the bay, made visible by steep, turbulent water slopes across the inlet throat, and an ebb tide jet (plume of turbulent water, sometimes with standing waves and foam) discharging to the Bay. The tidal asymmetry between the basin and the bay, and the slow, prolonged residual ebb tide in the basin, is a chronic tidal restriction. Restriction of tidal flows through bridges and culverts is a widespread hydrological and ecological impairment of tidal salt marshes of the Atlantic Coast (Tiner 2013), where it has been the primary focus of many tidal restoration projects (Roman and Burdick 2012). The ecological consequences of significant tidal choking at South Bothin Marsh probably include the very slow succession of low cordgrass marsh and cordgrass-pickleweed marsh ecotones, and failure to develop any significant internal high marsh banks along creeks. The choked tidal asymmetry between the South Bothin Marsh basin and fully tidal Coyote Creek may be responsible for the recent scouring of the former high marsh on the northern artificial levee bank of Coyote Creek: during the ebb phase after extreme high tides, the basin drains by turbulent over-marsh flow across the bank to the lower tide level of Coyote Creek. This process scours runnels that have not yet incised to intertidal depths because concentrated rocky lag from artificial fill impedes erosion. This may change as sea level rise continues.

Effects of erosional resistance of artificial surfaces are evident in some other shorelines of Bothin Marsh, and in adjacent tidal flats. In tidal flat areas subject to dredging in the 1960s and 1970s (Chapter 3), concentration of lag armored surfaces have formed. These appear to develop from wind-wave erosion of gravel-contaminated flats: where gravels are mechanically mixed with bay mud by past dredging, wind-wave and current erosion has winnowed out more mobile fine sediment, concentrating heavier gravel at the surface, where it locks down fine sediment beneath it. Tidal flats composed of naturally well-sorted silt-clay (typical bay mud) are subject to wind-wave erosion and resuspension of fine sediment, which can supply adjacent tidal marshes with suspended tidal sediments supporting marsh accretion (Allen and Pye 2002, Pethick 2002). Lag surfaces stabilize the mudflat surface, locally inhibiting mudflat-marsh sediment exchange. The bay shoreline at the historical railroad berm is a steep, impermeable surface composed of boulder-sized riprap and compacted stony fill that inhibits rooting and anchoring of salt marsh vegetation. It appears to act as a wave-reflective seawall, scouring fine sediment and inhibiting marsh initiation and accretion where rock outcrops are prevalent and a soil or mud veneer (root zone) has been lost to erosion.

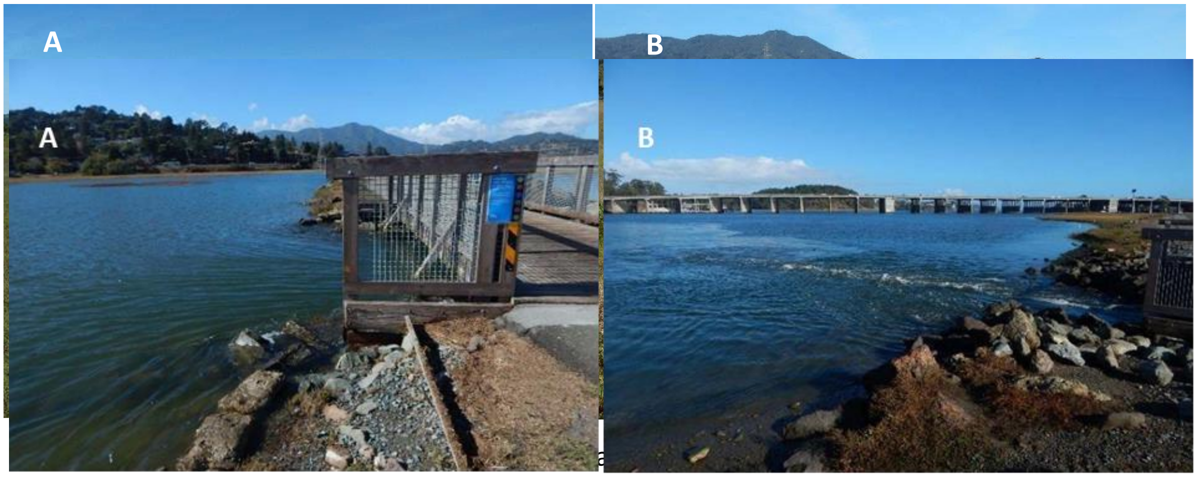

Figure 1.33. Historic infrastructure influences modern tidal hydrology of South Bothin Marsh. The under-sized tidal inlet (see Chapter 3) is a rock-armored breach in the historic railroad berm under the Bay Trail Bridge 2. The tides ebb faster from Richardson Bay than the marsh can drain. As a result, the water level of the Bay drops faster than the water level in the marsh. The difference in water levels can result in very high velocities of ebb flow from the marsh, causing a scour pool on the bay side of the inlet. (A) water streams from the marsh at high velocity, creating (B) turbulent flow through the inlet, creating standing waves in the Bay. Slow drainage of the marsh increases its duration of submergence, relative to fully tidal bay salt marshes.

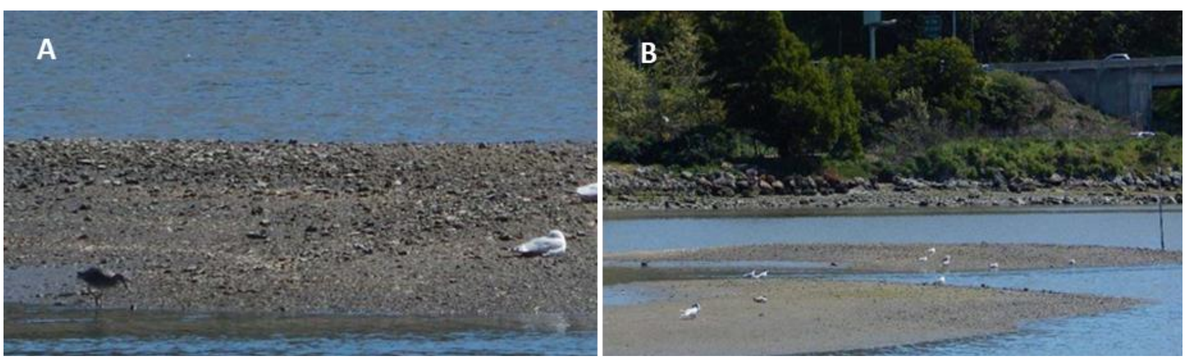

Figure 1.32. Coarse, gravelly sediments form a convex, armored surface on relict old dredge sediments that comprise Richardson Bay tidal flats. The coarse material is concentrated at the surface after wind-wave erosion and tidal currents remove the finer sediment from around the larger particles. The armoring limits resuspension of fines and thus limits their availability to the marshes. April 2017.

Figure 1.35. Old artificial fill and buried structures restrict eco-geomorphic development at South Bothin Marsh. (A) A buried pipeline exposed at the bed of a ditch acts as a grade control structure, preventing the ditch from achieving its equilibrium depth with its upstream tidal prism. (B) Resistant angular gravel in artificial fill along the north bank of Coyote Creek inhibits rapid channel incision and tidal creek evolution through the salt marsh surface (also see Figure 1.34 above). April 2017.

Figure 1.36. Quarried boulders are exposed along the bay mudflat shoreline of the historical railroad berm used for the Bay Trail at South Bothin Marsh, north of the mouth of the Coyote Creek Canal. The resistant, compacted, rocky fill inhibits salt marsh vegetation, which is restricted to shallow, temporary soil pockets or veneers between the rocks. Wind-wave reflection concentrates wave energy and promotes erosion of the soils. The vegetation is unable to gain enough stature and cover to attenuate wave energy. April 2017

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The ditch has cut down through the thin veneer of soft tidal sediment and into the compacted, rocky fill of the old levee. The ditch is slowly widening and deepening as it conveys more tidal prism, yet its rate of erosion is slowed by resistant gravel in the levee. It is, however, evidence of a tidal marsh channel evolution. April 2017.

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Bothin Marsh Geomorphology, Ecology, and Conservation Options

Chapter 2:
Overview of Sea Level Rise and Land Management Response

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Chapter 2:
Overview of Sea Level Rise and Land Management Response

2.0 Introduction

This Chapter is a critical review and synthesis of the readily available scientific and technical information about recent and likely future rates of sea level rise, plus general land management responses to sea level rise, pertaining to the protection and restoration of the Bothin Marsh Complex.

2.1 Tides

San Francisco Bay experiences a mixed diurnal tide, meaning there are two high tides and two low tides each lunar day, with the two low tides usually having different heights, and the two high tides also having different heights (Figure 2.1).

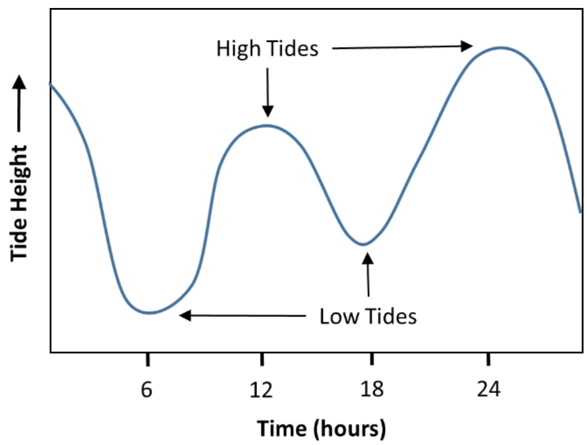

Figure 2.1. Diagram of the mixed semi-diurnal tide showing two high tides of different height and two low tides of different height each lunar day.

2.2 Mean Sea Level

Mean Sea Level (MSL) is the arithmetic mean of hourly tide heights observed over the National Tidal Datum Epoch (NTDE; NOAA 2000). MSL, as well as other average tidal heights, including the average of the high and low tides, are called vertical tidal datums, and are discussed further in section 2.4.1 below. NTDE is the specific 19-year period adopted by the National Ocean Service as the official time segment over which sea level observations are taken and reduced to obtain mean values for datum definition. The present NTDE is 1983 through 2001. It is reviewed annually for revision and must be actively considered for revision every 25 years.

The semi-diurnal range is the difference in height between consecutive high and low waters. It varies in approximately a two-week cycle. About twice a month, around the new moon and full moon, when the Sun, Moon, and Earth are aligned, the solar and lunar forces that cause the tide reinforce each other, and the semi-diurnal range achieves its monthly maximum. This is called spring tide, as if the high tide springs or jumps in height. When the Moon is at first or third quarter, the Sun and Moon are separated by 90° when viewed from the Earth, and the solar tidal force partially cancels the lunar tidal force. At these times, the semi-diurnal range is at its monthly minimum. This is called neap tide. In Middle English, neap means “without power” (https://www.etymonline.com/word/neap). Spring tides result in high waters that are higher than average, low waters that are lower than average, and stronger tidal currents than average. Neaps result in less-extreme tidal conditions. There is about a seven-day interval between springs and neaps.

2.3 Sea Level Rise

Absolute or eustatic sea level is the average height of the sea surface (Cazenave and Llovel 2010, Merrifield *et al*. 2014). Eustatic sea level rise is mainly due to thermal expansion of the sea and the addition of freshwater from melting of ice on land. Relative sea level is the average height of the sea relative to the land. It is affected by land rising or falling, as well as eustatic sea level. Understanding relative sea level is essential for coastal management (Morton 2003).

2.3.1 Long Terms Trends

Sea level has been rising globally since the end of the last ice age about 18,000 years ago. Global mean sea level rose about 400-450 feet during this period. Much of this rise took place between 18,000 and 8,000 years ago at average rates of about 45 inches per century, and then began to slow (Griggs *et al*. 2017). The global trend in sea level rise over past millennia is reflected in the record for San Francisco Bay (Atwater *et al*. 1977, IPPC 2014, Meyer 2014) (Figure 2.2).

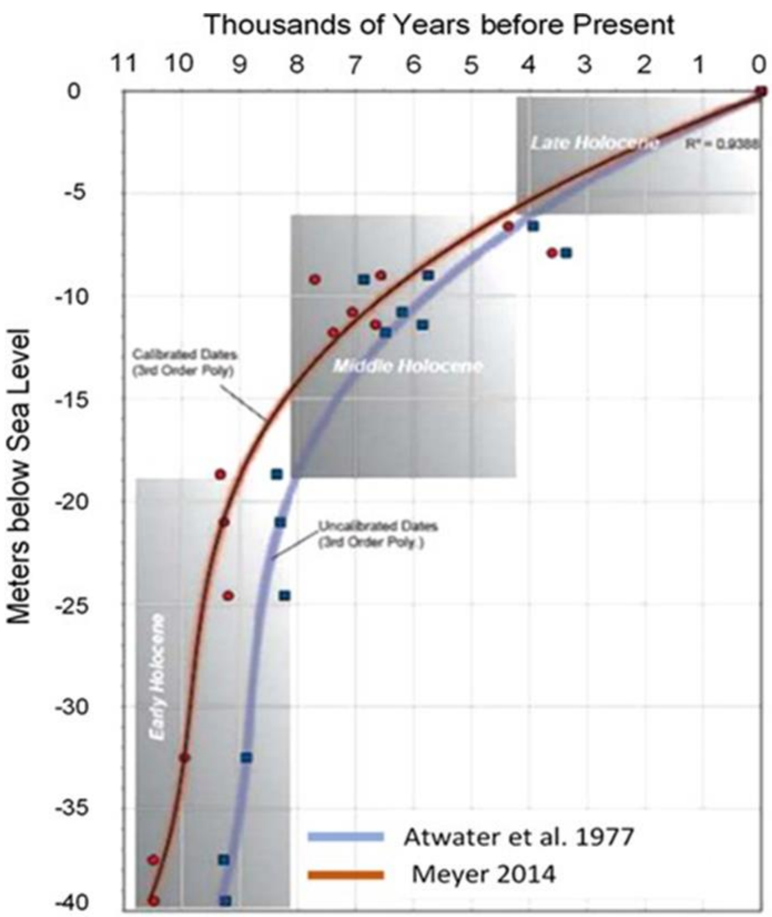

Figure 2.2. Two versions of the long-term trend in sea level for San Francisco Bay, from Meyer 2014.

Of particular interest is the fact that the oldest known tidal marshes in San Francisco Bay are less than 3,000 years old (Byrne et a.2001, Goman *et al*. 2008, Drexler *et al*. 2009, Watson and Byrne 2013), suggesting that they could not form until after the rate of sea level rise slowed to nearly its current rate about 6,000 years ago (Malamud-Roam *et al*. 2006). The implication is that long-term persistence of tidal marshes depends on a slow average rate of sea level rise, although this can be mediated by increases in the supply of inorganic sediment delivered to the marshes by the tides and from land, plus production of organic sediments within marshes (see Chapter 1).

2.3.2 Historical Trends

Rates of global sea level rise have ranged from about 0.05 inches per year to 0.06 inches per year (about 0.5 to 0.7 inches per decade) for the 20th century. However, since 1990, the rate has more than doubled, and the rise continues to accelerate (Church and White 2011, Ray and Douglas 2011, Hay *et al*. 2015). Since 1993, the measurement of eustatic sea level has been greatly improved with the use of satellites, especially since the advent of the U.S.-German Gravity Recovery and Climate Experiment (GRACE) beginning in 2002. These measurements reveal an average global rate of sea level rise of 1.3 inches per decade, which is more than twice the average rate over the 20th century (Leuliette and Nerem 2016).

The historical trend in sea level for San Francisco Bay is well documented, owing to the continuous record of tide height observations beginning in 1854 for the NOAA Tide Station at Fort Point (Figure 2.3). These data reveal an average rate of sea level rise just inside the Golden Gate of about 0.08 inches per year (about 8 inches per century). Short-term processes, including Pacific Basin climate fluctuations (e.g., El Niño Southern Oscillation), perigean high tides (i.e.; "King Tides"), and winter storms can produce significantly higher water levels than sea level rise alone (USGS 1999), and can cause actual sea levels to be significantly higher than predicted (Figure 2.4).

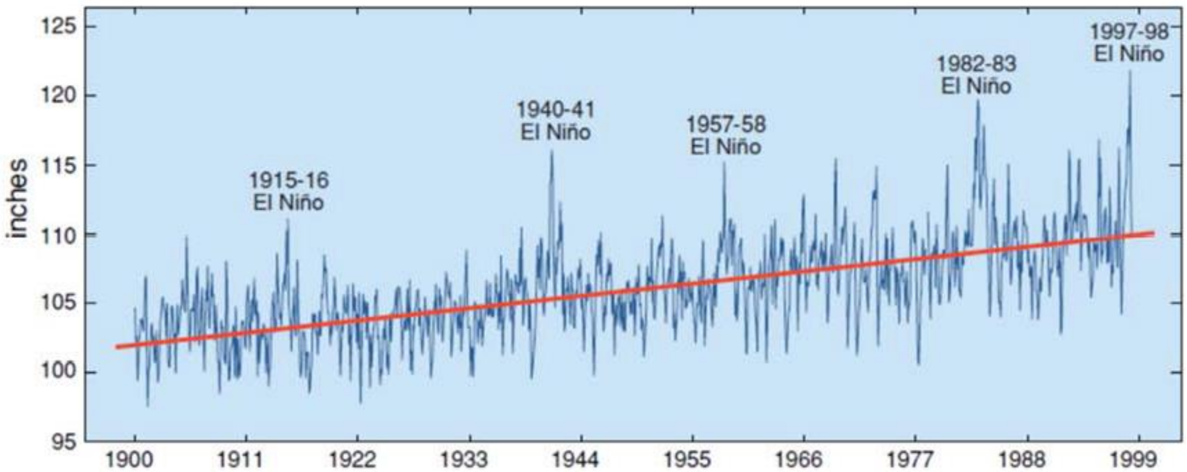

Figure 2.3. Sea level data from the Fort Point Tide Station 9414290 accounting for the historical shift in the local datum. Note the correspondence between extreme high tides and El Nino events (USGS 1999).

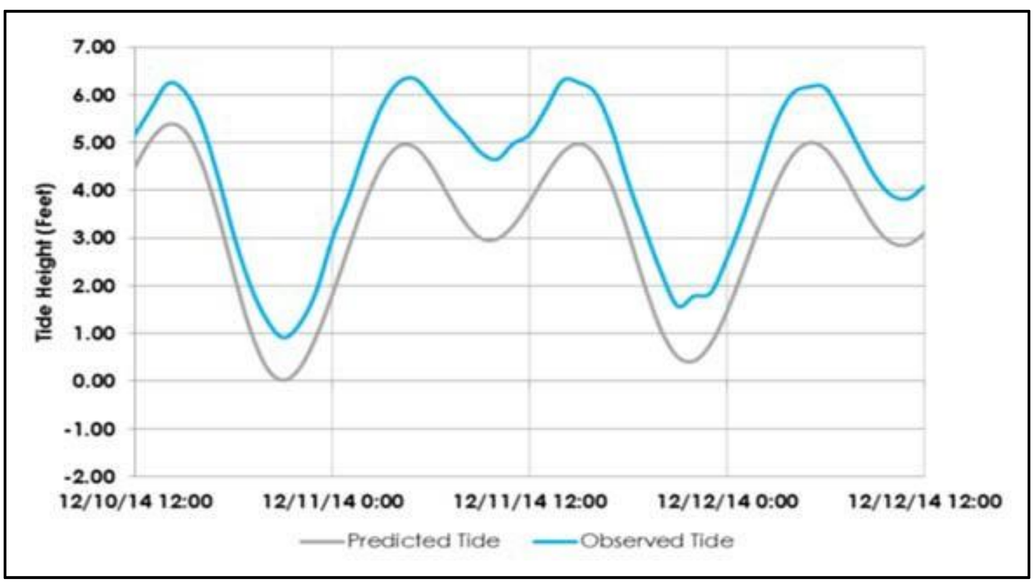

Figure 2.4. Predicted versus observed tide heights showing effect of storm surge on December 11, 2014 (BCDC 2016).

2.3.3. Extreme Events and Short-Term Variations

The sea level record provided by the Presidio Tide Station shows that extreme tides have become more frequent in recent decades. The annual maximum tide level has been rising at a rate of about 0.1 inches per year in recent decades, which is faster than the average rate of sea level rise (BCDC 2016). This has obvious implications for tidal flooding on lands adjacent to the Bay. Extreme high tides tend to have the greatest negative impacts (Goals Project 2015). If the maximum height of the tides is rising faster than the average tide height, then it represents a greater threat to life and property.

Sea level rise on the California coast is expressed as a trend of strongly fluctuating annual variations in sea level (Figure 2.5), rather than a smooth, idealized curve generated by numerical models. Short-term Pacific oceanographic events can result in ecologically significant, persistent pulses of sea level rise and falls that are similar in magnitude to average sea level rise over the eighteenth century. ENSO events (El Niño Southern Oscillation, alternating between warm Pacific with elevated sea level, and cool Pacific with lower sea level), Pacific Decadal Oscillations, the metonic tidal cycle (18.6 year, estimated as the NTDE, see Section 2.4.1), and Pacific sea surface temperature anomalies independent of El Niño events can cause both long-term and short-term responses by tidal marsh ecosystems (Kolker *et al*. 2009, Orson *et al*. 1998).

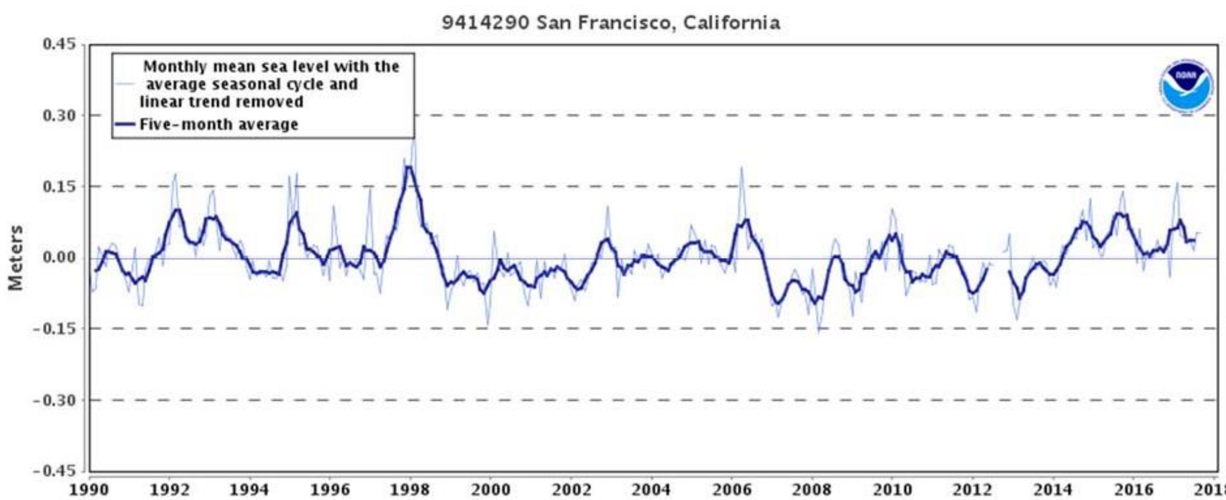

Figure 2.5. NOAA Sea Level Anomalies since 1990 – Central SF Bay and Golden Gate. Source:https://tidesandcurrents.noaa.gov/sltrends/anomalymapmonth.htm
https://tidesandcurrents.noaa.gov/sltrends/residual1980.htm?stnid=9414750

2.3.4 Forecasts

Scientific understanding of sea level rise is quickly advancing. Predictive models are incorporating new data for greenhouse gas emittance and ice sheet melting, and efforts to apply the models at the regional scale are increasing (Griggs *et al*. 2017). The models will continue to improve with gains in scientific understanding. The observed impacts of sea level rise at local, state, national, and global scales will be used to help calibrate the models. Monitoring of regional and local sea level rise will be essential to manage its social and ecological impacts.

The Intergovernmental Panel on Climate Change (IPCC) has adopted a set of four emissions scenarios (i.e., Representative Concentration Pathways, or RCPs), based on the predicted global average capacity of the atmosphere to trap heat in 2100, relative to pre-industrial values. The trapped heat is largely responsible for thermal expansion of the oceans, which has been a major cause of sea level rise (Merrifield *et al*. 2013). The current statewide guidance provided by the Ocean Protection Council (OPC) notes that different RCPs generate minor differences in sea level before 2050, but thereafter the forecasts increasingly depend on greenhouse gas emissions (Griggs *et al*. 2017). Thermal expansion has been the main driver of global sea level rise since the start of the Industrial Revolution, but ice sheets may soon become the primary contributor to global sea level rise (Nichols and Cazenave 2010, Church and White 2011). This is a particular concern for the Bay Area. The global effect of ice loss from West Antarctica is expected to be less than the local effect in San Francisco Bay; for every 1.0 foot of global sea level rise there is expected to be 1.25 feet of rise along the California coast (Griggs *et al*. 2017).

The most recent OPC guidance (Griggs et al. 2017) is based on the current state of science for sea level rise along the California Coast. It employs a probabilistic approach to assign likelihoods to sea level rise forecast (Kopp *et al*. 2014) based on data from three representative Tide Stations: Crescent City in northern California, San Francisco Bay (NOAA Presidion Station 9414290), and La Jolla in southern California. The comprehensive probabilistic approach was determined to be most appropriate for informing public policy and coastal zone planning. To be more specific, the approach enables planners and decision-makers to select an RCP and the related sea level rise forecast that best balances the uncertainty of the forecast with the need and cost to protect society and ecosystems. For example, the public may decide to invest in expensive measures to protect essential resources from a very high sea level, although the probability of that level is low.

The probabilistic approach (Kopp *et al*. 2014) may underestimate the likelihood of extreme sea level rise, particularly under high-emissions RCPs. Therefore the current OPC guidance includes the extreme sea level rise RCP (termed the H++ scenario). Under this scenario, rapid ice sheet loss from Antarctica drives rates of sea level rise in California above 2 inches/year by 2100, resulting in sea levels above 10 feet, relative to the current level. This rate of sea level rise would be about 30-40 times faster than the sea level rise experienced over the last century. It is scientifically premature, however, to estimate the probability of the H++ scenario (Griggs *et al*. 2017). Although the probability of this scenario is currently unknown, its consideration may be important, especially for high-stakes, long-term decisions.

The time horizon for most published forecasts is 2100, although the current OPC guidance extends the forecast for the H++ scenario to 2150. However, it is important to consider that sea level rise is not expected to stop by 2100. The contribution of ocean thermal expansion is unlikely to wane until after 2150, and may continue past that time to increase slightly for at least a thousand years, due to melting land ice, assuming that atmospheric CO_2 concentrations and air temperature stabilize within 300 years (IPPC 2007, Bamber *et al*. 2009, BCDC 2011).

2.3.4.1 Adopted Forecasts

The state of California began issuing guidance about sea level rise for coastal planning and management purposes through OPC in 2010 (OPC 2010), with an update in 2013 (OPC 2013). In 2010, the Governors of Oregon and Washington plus a consortium of federal agencies requested the National Research Council (NRC) to provide estimates and projections of future sea level rise based on the state-of-the-science. The NRC completed its report in 2012 (NRC 2012), based on the most recent Intergovernmental Panel on Climate Change (IPCC) report at that time (IPCC 2007). That NRC report has informed a number of important guidance documents and other materials specific to San Francisco Bay (OPC 2013, Goals Project 2015, BCDC 2016), including the BayWAVE report produced for the Marin County Planning

Department (Marin County 2017b). Since then, a new IPCC report was published containing updated sea level rise projections based on new scenarios, model simulations, and scientific advances (IPCC 2014), including new findings about the melting ice sheets of Antarctica (Kopp *et al*. 2014). Therefore, the California guidance provided by OPC has also been updated (Griggs *et al*. 2017), and is expected to be adopted by the OPC in 2018.

Source	Timeframe	Sea Level Rise Relative to Present Level (in)					
OPC 2010		Average of Models			Range of Models		
	2030	7			5-8		
	2050	14			10-17		
		Low	Med	High	Low	Med	High
	2070	23	24	27	17-27	18-29	20-32
	2100	40	47	55	31-50	37-60	40-69
NRC 2012		Most Likely			Upper Range		
	2030	6 ± 2			12		
	2050	11 ± 4			24		
	2100	36 ± 10			66		
OPC 2013		Range			Mid-Range		
	2030	1.6 – 11.8			6.6		
	2050	4.7 – 24.0			14.4		
	2100	16.6 – 65.8			41.0		
Goals Project 2015		Low Value			High Value		
	2100	20.4			64.8		
Leventhal 2015	2030	12					
	2070	36					
	2100	60					
Marin Co. 2017a (Bothin Marsh Bridge)		50-year Storm + Max. King Tide + Max. Sea Level					
	2030	12					
	2050	24					
	2100	66					
Griggs et al. 2017		50% chance SLR is ≥	67% chance SLR is between	5% chance SLR meets or exceeds	0.5% chance SLR meets or exceeds		
	2030	12	4 - 6	8	11		
	2050	11	7 - 13	17	24		
	2100	20	12 - 29	40	70		
		24	14 - 32	43	72		
		31	19 - 41	55	85		
		120					
	2150	30	18 – 47	68	133		
		37	23 – 58	78	142		
		52	36 - 73	95	160		
		264					

Table 2.1. Forecasts of sea level rise from government guidance for shoreline planning in San Francisco Bay. Red circles mark the higher values reported for the year 2100.

The various forecasts of sea level rise that have been incorporated into public guidance documents relevant to Richardson Bay and Bothin Marsh are compiled in Table 2.1. It may be important that two of the seven adopted forecasts reported here for 2100 are 55 inches, and the five others range from 60 – to about 66 inches, excluding the relatively unlikely forecast of 85 inches provided by the current OPC guidance for its H++ (extreme) scenario (Griggs 2017). The similarity of these adopted forecasts reflects a common dependency on the NRC guidance. The adoption of 55 inches by the 2010 OPC document pre-dates the NRC report. The Goals Project adopted the 55-inch forecast by modifying the NRC forecast based on regional considerations, whereas the current OPC guidance adopted the 66-inch forecast without direct reference to the NRC report. At this stage in the development of sea level rise science, a forecast of 55 to 66 inches for 2100 seems justified. Less likely forecasts, including the 2100 value of 85 inches provided by the current OPC guidance, should not be ignored, however. Revised forecasts of sea level rise will be warranted through improved scientific understanding and the needs of coastal managers, and forecasts of sea level rise are likely to be adjusted upward (DeConto and Pollard 2016, Thompson *et al*. 2016, AMAP 2017).

2.4 Marsh Migration or Transgression

Marine or estuarine migration is the process by which sea level rises relative to the land, such that the extreme and average excursions of flood tide move upstream and inland. As used here, migration is synonymous with estuarine transgression. Migration can be caused by land sinking or the ocean surface rising, since either process can lead to increased inland tidal flooding. Estimates of migration heights and distances depend on knowing the elevation of the lands relative to the tides, and this requires knowing local vertical datums, as explained below.

2.4.1 Vertical Datums

A vertical datum is a fixed surface designated to have a certain numerical value of elevation to which the heights of other surfaces can be referred, such that their elevations can be compared. There are two primary kinds of vertical datums. Those based on a form of Mean Sea Level (MSL), are called orthometric datums, and those based on local measures of high or low tides are called tidal datums. In other words, a tidal datum is an average level of the tides for a selected tide phase, such as high tide or low tide. Tidal datums are used to determine the heights of the tides, and the heights of land surfaces, vegetation, and built structures relative to the tides.

Any effort to forecast the future extent of inland tidal flooding due to sea level rise at any location requires knowing the tidal elevation of the local lands currently above the tides, and this requires knowing the local relationship between orthometric and tidal datums. Federal standards and methods for determining tidal datums and tidal elevations are the responsibility of the Center for Operational Oceanographic Products and Services (CO-OPS) of the NOAA. Federal standards and methods for determining orthometric datums and elevations are the responsibility of the U.S. National Geodetic Survey (NGS). The NGS develops and maintains the current national orthometric vertical datum, called the North American Vertical Datum of 1988 (NAVD 88).

The tidal datums of greatest importance to tidal marsh restoration and protection are Mean Low Water (MLW), the average of all low tides during the National Tidal Datum Epoch (NTDE; see Section 2.1 above); Mean Lower Low Water (MLLW), the average of the lower of the two daily low tides during the NTDE; Mean High Water (MHW), the average of all high tides during the NTDE; and Mean Higher High Water (MHHW), the average of the higher of the two daily high tides during the NTDE. The tidal datums of San Francisco Bay, or Richardson Bay, are not flat, but vary between locations. For example, MHHW observed in San Francisco is lower than MHHW observed across the Bay in Alameda. The CO-OPS of NOAA publishes the relationship between NAVD88 and various tidal datums, such as MLLW and MHHW, as well as other tidal statistics, for each of its currently operating Control Tide Stations, where tide height measurement are ongoing, and some of its historical subordinate stations, where tidal datums have been determined in the past but are not necessarily updated for the current NTDE.

Subordinate Tide Stations located two historical CO-OPS within Richardson Bay. Both are in Sausalito. Station 9414819 is located at the dock used by the U.S. Army Corps of Engineers (COE), and Station 9414806 is located at Alexander Avenue. These were subordinate stations operated in the late 1970s to reference local tidal benchmarks to the 1960-1978 tidal epoch, based on corresponding tide height observations at the primary Tide Station 9414290, located inside the Golden Gate, near Fort Point at the Presidio in San Francisco. Tide Station 9414290 has a period of continuous record beginning in 1854. Of the two subordinate station in Sausalito, Station 9414819, the COE Dock Station, is nearer Bothin Marsh. Its tidal statistics have been updated by CO-OPS for the current tidal epoch (1983- 2001). The tidal datum sheet for COE Dock Station states that NAVD88 is 0.17 feet (2.04 inches) lower than local MLLW, the conventional zero tide datum for the U.S. West Coast (Figure 2.6). MHHW is 5.74 feet above MLLW, and 5.91 feet above NAVD88. For general purposes, tidal elevations at the COE Dock Station relative to NAVD88 are roughly the same elevation relative to MLLW. It is assumed that the correspondence between NAVD88 and MLLW observed for the COE Dock Station in Sausalito also exists for the foreshore (bayward margin) of Bothin Marsh. There are no long-term tide height data for Bothin Marsh or any other location near the upstream terminus of Richardson Bay.

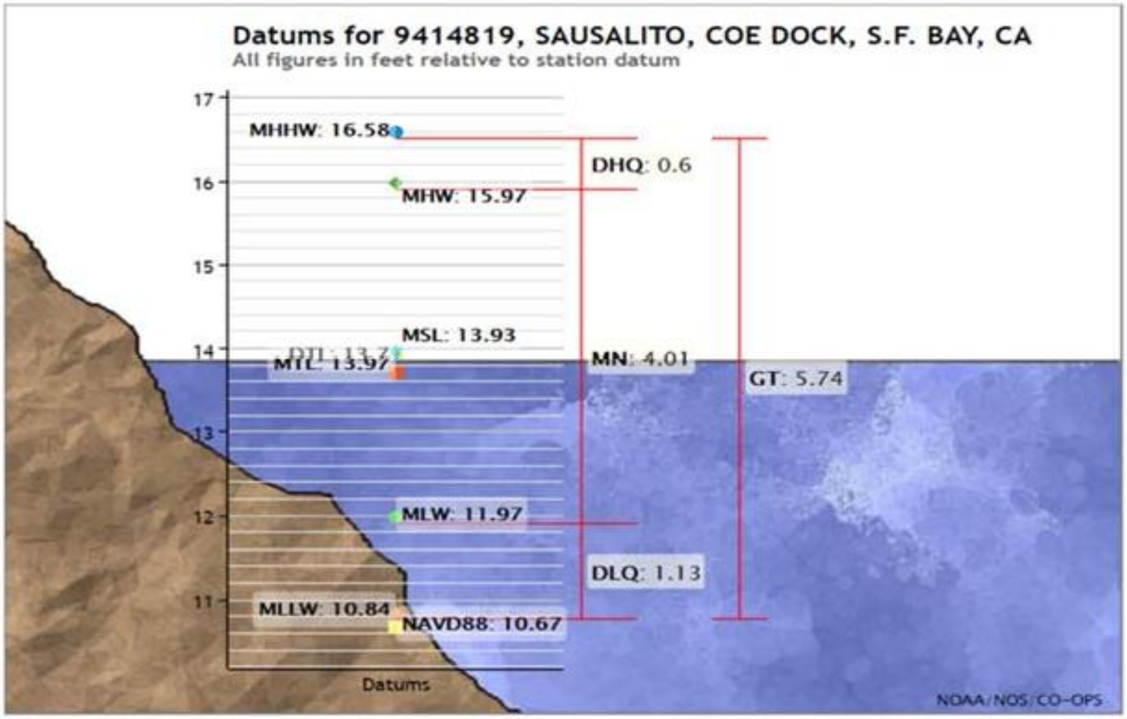

Figure 2.6. Tidal datums and other tidal statistics for the NOAA tidal station closest to the Bothin Marsh Complex, Station 9414819.

Short-term records of tide heights produced near Bothin Marsh for various engineering or other studies were not long enough to reckon tidal datums (e.g., Wetland Research Associates and Hydroikos Associates 2004, ESA PWA and Wetlands Research Associates 2006). However, the distance of tidal excursion between the COE Dock Station and Bothin Marsh is less than 2.0 miles, without obstructions. Furthermore, because of its location close to the Golden Gate, and with very little attenuation of the tidal range through Richardson Bay (Philip Williams & Associates 1983), the tidal statistics for the upstream terminus of Richardson Bay are likely to be very similar to those determined for the Presidio (see Table 2.2 below). Based on this assumption, local MHHW at the foreshore of Bothin Marsh is 5.91 feet NGVD [i.e., 16.58 (MHHW) – 10.84 (MLLW) + 0.17 = 5.91].

A recent regional modeling effort has generated estimates of tidal datums relative to NAVD88 for 900 study locations along the San Francisco bayshore, including locations within Richardson Bay (BCDC 2016). One study location is within 0.25 miles of South Bothin Marsh. While the model estimates agree well with datums determined empirically at NOAA control Tide Stations, their accuracy for subordinate stations and remote locations lacking empirical observations of tide heights remains uncertain. For the study station nearest South Bothin Marsh, the estimate of MHHW is 6.03 ft NGVD88, which is 0.12 feet higher than the estimate derived from the data for the COE Dock Station (6.03 – 5.91 = 0.12). Without knowing which value is truly better, their average might be used. Based on this approach, Local MHHW corresponds to elevations of about 6.0 feet (5.97 ft) NGVD88 on the Lidar DEM of Bothin Marsh provided by Marin County.

For the Bothin Marsh Complex and its immediate environs, the vertical datum used by Google Earth closely approximates NAVD88, such that tidal elevations can be reasonably estimated to the nearest foot using Google Earth. This was determined by overlaying the LiDAR DEM (digital elevation map) on Google Earth and comparing elevations from the two maps for a variety of common locations.

Datum	Sausalito Station: 9414806	Sausalito NAVD88	Presidio Station: 9414290	Presidio NAVD88	Presidio minus Sausalito
MHHW	8.82	5.86	11.82	5.9	0.04
MHW	8.23	5.27	11.21	5.29	0.02
MTL	6.25	3.29	9.16	3.24	-0.05
MSL	6.2	3.24	9.1	3.18	-0.06
DTL	5.98	3.02	8.9	2.98	-0.04
MLW	4.28	1.32	7.11	1.19	-0.13
MLLW	3.13	0.17	5.98	0.06	-0.11
NAVD88	2.96	0	5.92	0	0

Table 2.2. Correspondence between tidal datums for the NOAA Control Tide Station 9414290 at the Presidio in San Francisco and for the NOAA subordinate station 9414806 in Sausalito (NOAA 2017).

2.4.2 Migration Models

The simplest migration models fill Richardson Bay to a designated orthometric or tidal elevation, as if sea level rise were uniform throughout the Bay. For that reason, these models are sometimes referred to as “bathtub models.” They assume that the existing topography will persist, and all structures, such as roadways and levees that might prevent migration are ignored. They do not account for any natural landscape change due to migration, such as the landward migration of dunes, beaches, or overwash berms.

Migration models are gaining sophistication, not only because of their ability to incorporate multiple local phenomena affecting migration distance and rates, but because they are being developed for specific audiences and applications. The status of migration models and visualization tools has recently been summarized for California by Climate Central (The Nature Conservancy et *et al*., 2017). In San Francisco Bay, migration models are beginning to incorporate the concept of a terrestrial-estuarine transition zone (Goals Project 2015), which encompasses the bayward extent of terrestrial and fluvial effects, and the landward extent of tidal effects on ecosystem form, composition, and function.

The most sophisticated modeling product generally applicable to Richardson Bay is the Coastal Storm Modeling System (CoSMoS). It is a dynamic 2-D wave modeling approach developed by USGS for predicting coastal flooding due to both future sea level rise and storms integrated with long-term coastal evolution (i.e., beach changes and cliff or bluff retreat). CoSMoS models all the relevant physics of a coastal storm (e.g., tides, waves, and storm surge), which are then scaled down to local tidal flood projections for use in community-based coastal planning and decision-making. Rather than relying on historical storm records, CoSMoS uses wind and pressure from global climate models to project coastal storms under changing climatic conditions. Projections of multiple storm scenarios (daily conditions, annual storm, 20-year- and 100-year-return intervals) are provided under a suite of sea level rise scenarios ranging from 0 to 2 meters (0 to 6.6 feet), along with an extreme 5-meter (16-foot) scenario. This is intended to enable users to manage future risks within their chosen planning horizons. The current version of CoSMoS for San Francisco Bay incorporates the effect of ocean swell penetration through the Golden Gate, vertical land motion (lifeet or subsidence), marsh accretion or erosion, vegetation-related LiDAR error, DEM uncertainty, and flood model uncertainty. Future integration of the modeled local tidal datums into CoSMoS can be anticipated. All migration models will need to be adjusted for revised estimates of sea level rise rates.

Wave run-up can be a significant factor in local tidal flooding. Waves dissipate upslope to higher elevations than predicted by sea level rise. Run-up can cause levees to be overtopped and significantly increase the risk of shoreline erosion. Wave heights increase with water depth, and the erosive power of waves might increase as sea level rises. Run-up heights and associated risks are greater along shorelines downwind of long fetches. CoSMoS 2.1 incorporates wave run-up inundation estimates in 0.8 feet increments for a variety of storm and tides scenarios.

In upper Richardson Bay, the usual fetch is northwesterly and attacks the levee of the Bay Trail along the northwestern side of South Bothin Marsh. The strongest winds tend to occur during the onset of major storms, however, when winds are southeasterly, and waves attack the foreshore of North Bothin Marsh. This helps explain the overwash berm and associated pannes that characterized the historical southeastern foreshore of historical Almonte Marsh (see Chapter 3)

Public access to output from CoSMoS is provided by Our Coast Our Future (OCOF). OCOF is a collaborative, user-driven web-based information delivery system that provide coastal resource managers in California locally relevant, online maps and tools to help understand, visualize, and anticipate vulnerabilities to sea level rise (http://data.pointblue.org/apps/ocof/cms/uploads/documents/OCOF_two%20pager_Jul2016.pdf). Some important features of OCOF include:

- Seamless Digital Elevation Model (DEM) at 2 meter horizontal resolution;
- Combination of 40 different sea level rise and storm scenarios, plus a King Tide scenario for San Francisco Bay, using the USGS CoSMoS;
- Interactive flood map including tidal flood extent, depth, duration, wave heights, current velocity, minimum and maximum flood potential, as well as the option to compare scenarios;
- Online and downloadable data access tailored to users information needs;
- Information on how and where products have been used, as well as links to end-users to promote sharing of lessons learned;
- New features and products will be available as they become needed and funding is available.

2.4.3 Regional Variability

The likely variability in sea level rise throughout San Francisco Bay is starting to be investigated. This includes modeling sea level rise with respect to spatial differences in tidal datums (Knowles 2010, BCDC 2016), and the effect of the Bay's bathymetry and planform on sea level, including relationships between shoreline modification at one location and sea level in other locations. Hardening the shoreline with levees and sea walls in one area of the bay transfers the risk of flooding to other areas (Holleman and Stacey 2014). Understanding the relationships among shoreline management, sea level rise, and tidal flooding will improve local shoreline planning (see Figure 2.7 below).

Studies to date indicate that future migration can mitigate sea level rise by decreasing tidal amplification, although this is likely to vary among the major basins of the Bay. It is important to emphasize the fact that reinforcing and hardening impacted shorelines can increase flood risks elsewhere. The distance over which these effects can be transmitted depends on the amount of total length of hardened shoreline, and basin bathymetry, as well as where in the bay the hardening occurs. Restoration of tidal marshland and construction of new low-lying tidal areas offer significant protection from rising tides by dissipating tidal energy, and these benefits may extend well beyond the areas directly sheltered by marshland (Holleman and Stacey 2014).

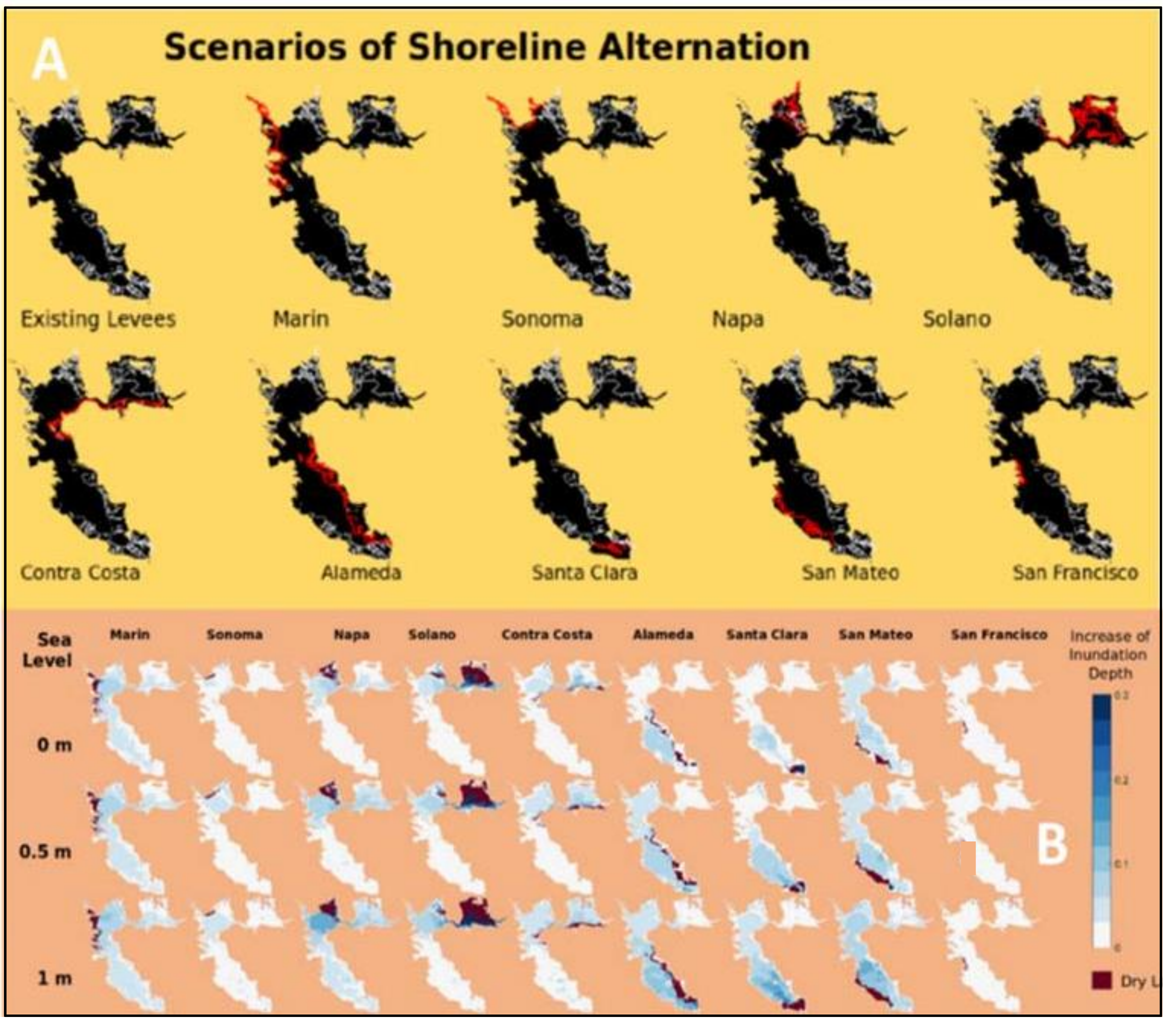

Figure 2.7. (A) Summary of hypothetical, future, county-based shoreline hardening scenarios (colored red) and (B) their regional effects on sea level, with darker areas indicating increased depth. Figure courtesy of Mark Stacey (Stacey 2017)

Studies of the possible effects of sea level rise on local transportation and the economic and overall social well-being of the Bay Area are also underway. The strong indication is that a Bay Area regional approach is needed to coordinate sea level planning and response. The dynamic interactions between shoreline modification in one area and sea level rise and tidal flooding elsewhere (Holleman and Stacey 2014) are matched by the effects on commerce and economy (Stacey 21078) (Figure 2.8).

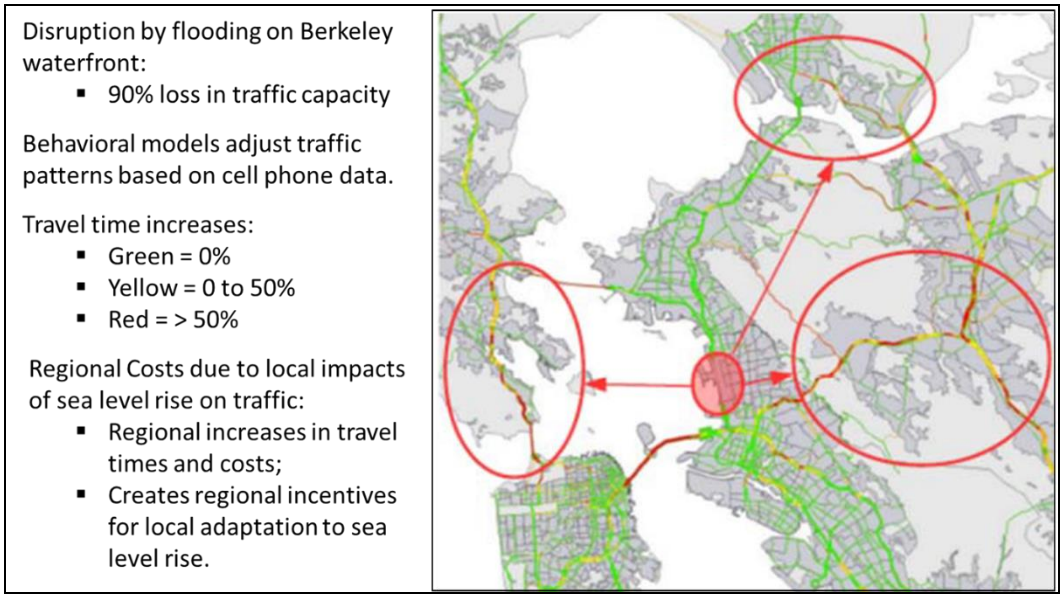

Figure 2.8: The expected effects of tidal flooding in Berkeley on travel times at major highways elsewhere in the region, illustrating the regional scope of inter-relations among local vulnerabilities. Figure courtesy of Mark Stacey (Stacey 2017).

2.4.4 Application of Sea Level Rise Forecasts to Bothin Marsh

Ongoing engineering and planning studies for bridges at Bothin Marsh provide the most current insights into local application of sea level rise forecasts and related tidal statistics. These studies are exploring new hydraulic criterion for the bridges to clear the 50-year storm, plus the highest King Tide on record for the past 20 years, plus the projected maximum sea level rise for 2030 (Figure 2.9 and Table 2.3). While there are uncertainties in the determination of local tidal datums and application of sea level rise forecasts, the studies nevertheless provide an example of incorporating this important information into local coastal engineering analysis and plans.

For the purpose of illustration, OCOF was used to estimate the extent of future tidal flooding at Bothin Marsh (Figure 2.10). OCOF enables the user to choose among a fixed set of sea level rise scenarios, and to choose whether to address King Tides or wave run-up. A sea level rise forecast of 66 inches for 2100 is not available. The 68.4-inch (5.7 feet) scenario was selected instead, plus the maximum expected King Tide. The forecasts for the ongoing Bothin Marsh bridge study and the OCOF illustration therefore differ by a few inches (68.4 inches versus 66 inches). However, the OCOF provides a reasonable approximation of the extent of flooding for the 2100 conditions being considered in the bridge study. It should be noted that the OCOF illustration does not reflect any changes in landform or land use related to migration that might affect the future extent of flooding.

Bothin Marsh Bridge No.	Highest Observed King Tide	50-yr Storm Plus Highest King Tide	50-yr Storm Plus Highest King Tide + Maximum Sea Level		
			2030	2050	2100
1	8.7	8.8	9.7	10.7	14.2
2	8.7	8.7	9.7	10.7	14.2
3	8.7	9.2	10.2	11.2	14.2
4	8.7	8.7	9.7	10.7	14.2

Figure 2.9 and Table 2.3. Locations of four bridges near Bothin Marsh and the associated preliminary forecasts of water surface elevation in feet relative to NAVD88, due to the combined effects of sea level rise, rainstorm discharge, and King Tide. The 50-year storm values were provided by FEMA. King Tide values were evidently taken from the nearest NOAA Tide Station (COE Dock Station 9414819 in Sausalito). The forecasts for seal level rise were provided by NRC (NRC 2012), using the 66-inch value for 2100. Wave run-up was disregarded. All elevations are relative to NAVD88, which equals MLLW minus 0.17 feet.

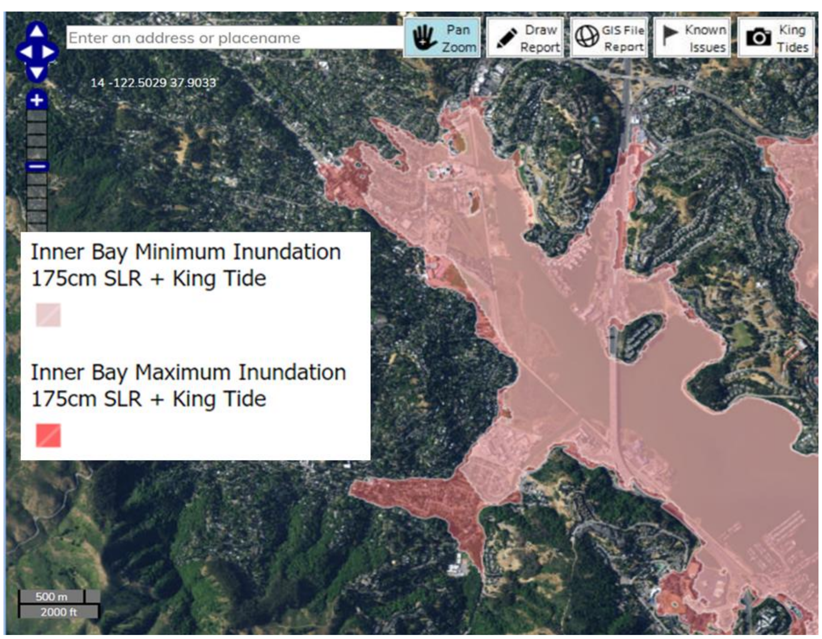

Figure 2.10. Screenshot from the OCOF website showing estimated future inland extend of tidal flooding due to about 69 inches of sea level rise plus maximum predicted King Tide. Stream flow and wave run-up are disregarded. Note that the minimum predicted tidal inundation extends inland and upstream beyond the

2.5 General Adaptation Strategies

Understanding the short and long-term costs and benefits of different adaptation strategies, as well as the costs of not taking action, is critical to choosing a strategy that is optimal. The choice is not based solely on economics. Other factors to consider include community culture, ecological benefits, and administrative and legal aspects. The unique conditions, history, and desired vision of each community will influence decisions about how it should best adapt to sea level rise. The optimal adaption strategy will have multiple benefits across a range of social and environmental considerations.

Sea level rise can negatively impact values of properties and industries within the expected areas of migration (Pew Center 2000, California Climate Change Center 2009). Disadvantaged communities may be especially threatened due to their relative lack of access to financial resources necessary to mitigate the threat through structural or landscape engineering (Martinich *et al*. 2013, Stutz 2017). Furthermore, the depressed equity of properties within disadvantaged communities limits opportunities to retreat to safer areas through real estate transaction. The possibility exists that these communities will be sacrificed as residential or industrial areas to create migration space that mediates the threat of sea level rise for other areas having more highly valued properties and industries. One consideration is that the lands owned by disadvantage communities have value as migration space that can be monetized. Part of this value is the equity of other lands that is protected by the sacrifices of the disadvantaged communities, which can be figured into the purchase of developmental rights (Eastern Research Group, Inc. 2013). These situations raise serious issues about environmental justice that might only be resolved through regional investments in local sea level rise planning (Kerlin 2017, Stacey 2017).

There is a variety of actions that can be incorporated into an adaptation strategy. All strategies involve engineering and economic analyses, as well as public outreach and education. The other actions that distinguish one strategy from another and that might be suitable for Bothin Marsh are outlined below. They generally can be aggregated into two groups: containment and accommodation.

2.5.1 Containment

Containment is the use of engineered structures, such as levees, dikes, and seawalls, to prevent sea level migration. Containment has been the conventional approach to defending lands against gradual rates of sea level rise (Spalding *et al*. 2014), since the advent of long-term, intransient agrarian societies (Needham 1971). The first known coastal dikes or levees are perhaps 5,000 years old (Lander 2014), and their development thus corresponds to the period of marked decrease in the rate of sea level rise (see section 2.1 above). Given the accelerated rates of sea level rise predicted for the future, structures built to prevent migration may have to be raised repeatedly. There are structural limits, of course, to their maximum heights. Large costs are associated with pumping or siphoning floodwaters from behind containments.

2.5.2 Seawalls

Seawalls are vertical or near-vertical structures built along the coast and designed to prevent erosion and coastal flooding of the areas behind them. Seawalls form a protective wall in front of coastal structures and may be constructed from a variety of materials, including concrete, steel, wood, and boulders.

2.5.3 Levees and dikes

Levees and dikes are constructed embankments designed to reduce the risk of flooding to the areas behind them. Levees typically are built parallel to the course of a river or coastline in order to contain, control, or divert the flow of water. Levees are constructed from compacted soil or artificial materials such as concrete or steel. To protect against erosion and scouring, earthen levees can be covered with grass, or a hard surface such as rock rip-rap or concrete.

2.5.4 Horizontal Levees

The horizontal levee is a recent addition to the array of levee types that have been constructed in the Bay Area (ESA PWA 2013, Myers 2017). The version most commonly discussed around San Francisco Bay consists of a levee with adjoining supra-tidal lands (i.e., lands above MHHW) on the outboard or bayward side that are gently graded to provide habitat and perhaps passive outdoor recreation compatible with sea level migration (see Figures 2.11 and 2.12 below). Similar concepts are referred to as “laid back Levees” or “habitat levees’, and can be collectively described as hybrid combinations of natural and built infrastructure that enhance coastal resilience to storm and coastal flooding protection, while also providing other benefits (Sutton *et al*. 2015).

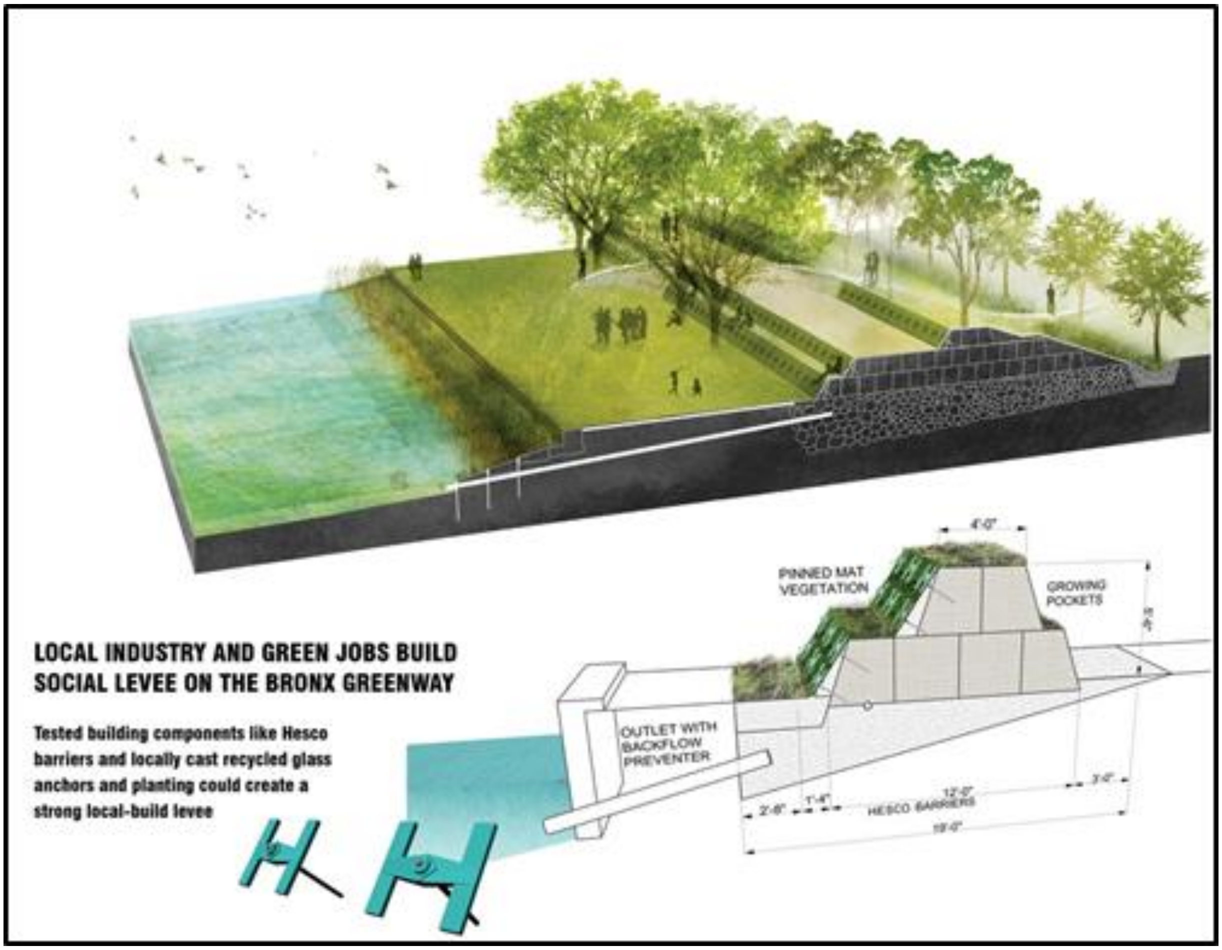

Figure 2.11. Conceptual multi-benefit horizontal levee, featuring social amenities including pedestrian and bicycle pathways. (http://www.loversiq.com/o/214876113/landscape/214876/).

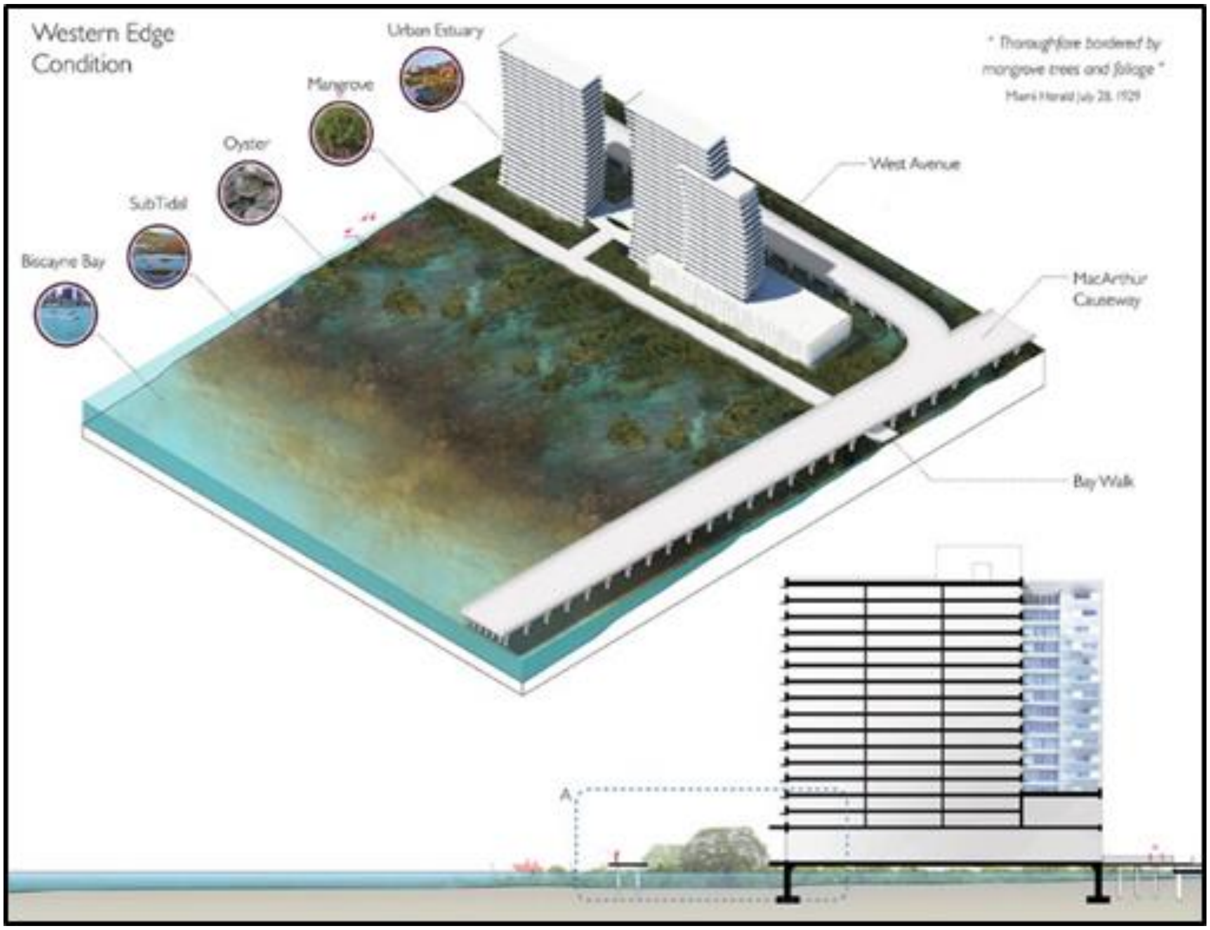

Figure 2.12. Conceptual multi-benefit horizontal levee, featuring a living shoreline of natural wildlife habitat plus social amenities including pedestrian and bicycle pathways for Miami Beach FL (https://www.vanityfair.com/news/photos/2015/11/miami-beach-rising-sea-levels-plan).

A local example of the multi-benefit potential of horizontal levees is the Ora Loma Project in Hayward (Ora Loma Sanitary District 2015). The project is based on a concept generated for San Francisco Bay (see Figure 2.13 below). The Project is designed to filter wastewater, provide habitat, and increase the resilience of the local shoreline to sea level rise. The project involves a basin that removes nutrients from wastewater while providing increased capacity to store stormwater during heavy rains. Wastewater that has undergone secondary treatment passes through the wetland and then through the levee to create habitat on the broad outboard levee slope. The surface and sub-surface filtering processes of the levee are expected to support native plants and purify the water enough to permit its safe discharge directly into San Francesco Bay. In the first year since its construction, the native vegetation planted in the treatment wetland and on the levee is meeting performance measures. Over the next 3-5 years, a UC Berkeley research team will evaluate the effectiveness of the project to treat wastewater as well as provide habitat. While horizontal levees provide resistance to sea level rise, they also adapt to it by creating migration space. Therefore, they can be regarded as a type of landscape adaptation.

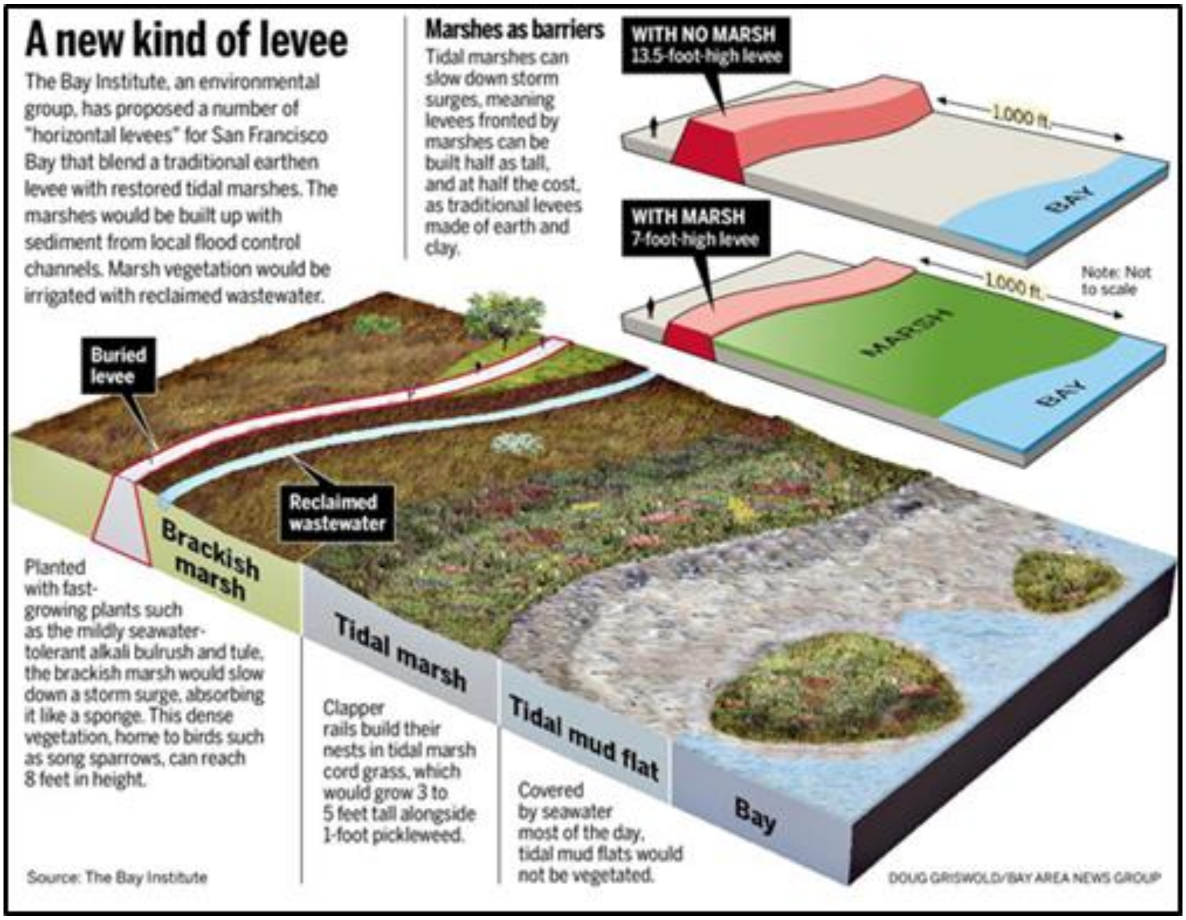

Figure 2.13. Multi-benefit horizontal levee conceptualized for San Francisco Bay, featuring a living shoreline of natural intertidal wildlife habitat plus a pedestrian and bicycle pathway (ESA PWA 2013, https://issuu.com/thebayinstitute/docs/slr_executive_summary-oro_loma_fina).

2.5.5 Containment at Bothin Marsh

There are various levees and dikes that historically have constrained tidal flooding at the Bothin Marsh Complex and its immediate environs (see Figure 2.14, below). They were constructed to support railroading, reclaim tidal marsh, contain dredged sediment, and provide flood control. The history of these features is provided elsewhere in this report (see Chapter 3). In addition to the levees, there are areas of artificial fill that provide some containment.

All of the exterior levees and dikes, except for the flood-control levees along the creeks draining to the Bothin Marsh (see levees shaded pink in Figure 2.14 below) are breached and can be overtopped by King Tides, due in part to wave run-up (personal observations of the authors). Even if their breaches were eliminated, none of these levees and dikes are high enough to resist tidal flooding beyond 2030, especially during King Tides or major storm events, when creek discharges and wave run-up are high.

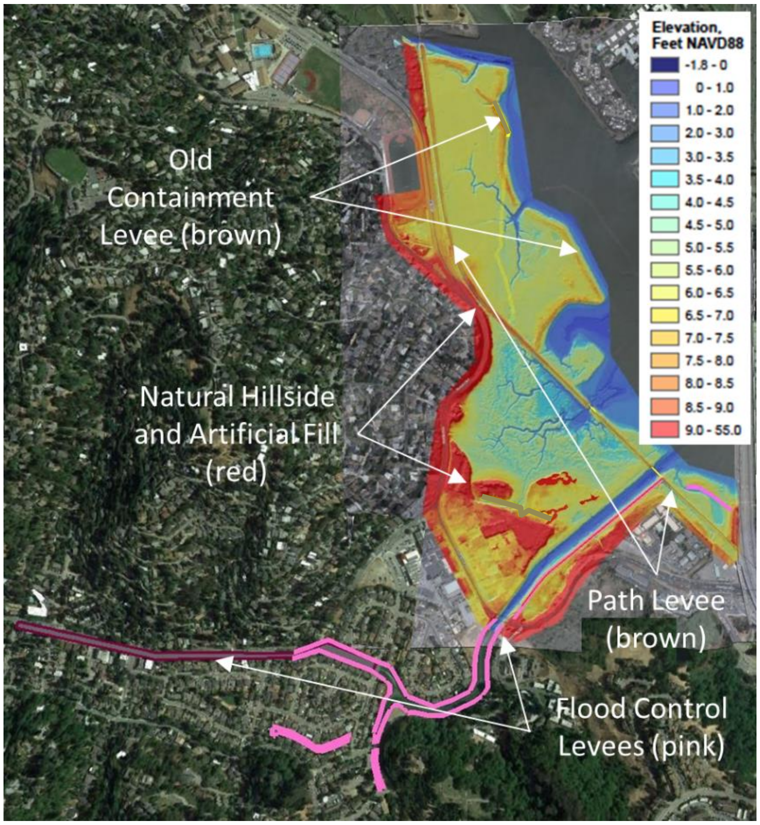

Figure 2.14. Example containment levees of varying age and purpose at the Bothin Marsh Complex, as evidenced by elevation and analysis of land use history (see Chapter 3).

2.5.6 Accommodation

Accommodation of sea level rise can be defined as the dedication of lands to the inland migration of tidal waters, as a well as the policies and financial mechanisms to achieve the dedication. The dedicated land is commonly called migration space.

There are many possible approaches to accommodation, or the provision of migration space, some of which are potentially suitable for the Bothin Marsh Complex.

The resources listed below provide national and statewide guidance on adaptation to sea level rise, including accommodation. Most of the national guidance is general and would need to be adapted to the local physical and social landscape. However, the general guidance provides many useful and creative ideas that can benefit local accommodation planning.

- NOAA: Adapting to Climate Change: A Planning Guide for State Coastal Managers (https://coast.noaa.gov/czm/media/adaptationguide.pdf).
- USEPA Adapting to Climate Change (https://archive.epa.gov/epa/climatechange/adapting-climate-change.html).
- Georgetown Climate Center: Adaptation Tool Kit: Sea-Level Rise and Coastal Land Use How Governments Can Use Land-Use Practices to Adapt to Sea-Level Rise (http://www.georgetownclimate.org/files/report/Adaptation_Tool_Kit_SLR.pdf).
- California Coastal Commission: Sea Level Rise Policy Guidance: Interpretive Guidelines. (https://documents.coastal.ca.gov/assets/slr/guidance/August2015/0_Full_Adopted_Sea_Level_Rise_Policy_Guidance.pdf).
- Coastal and Ocean Working Group, California Climate Action Team: State of California Sea Level Rise Guidance Document (2018 update forthcoming) (http://www.opc.ca.gov/webmaster/ftp/pdf/docs/2013_SLR_Guidance_Update_FINAL1.pdf
- California Energy Commission, Adapting to Sea Level Rise: A Guide for Coastal Communities.

(https://seymourcenter.ucsc.edu/OOB/Adapting%20to%20Sea%20Level%20Rise.pdf).

Managed retreat (USACE 2012) or managed realignment (Esteves 2014) is often cited as means of accommodation. These are broad ideas that require one or more of the following activities to achieve. The land use activities and their legal or economic instruments of achievement are grouped separately. This is not an exhaustive list. The very broad range of activities were filtered by their applicability to the Bothin Marsh Complex.

2.5.7 Legal or Economic Instruments

2.5.7.1 Transfer of Development Rights

A transfer of development rights (TDR) is a way for property owners to transfer development rights to one another. In the context of migration or tidal flooding, TDR can be used to move future development from migration spaces. TDR can also be used to preserve open space, thereby facilitating the implementation of other mitigation measures, such as wetlands development or other green infrastructure to further increase a community's resilience to coastal flooding. TDRs are usually administered through a local government zoning ordinance, with specific districts zoned to either give or receive development rights (American Planning Association 2006).

2.5.7.2 Purchase of Development Rights

Purchase of development rights (PDR) involves a local government or nonprofit purchasing development rights while the land remains privately owned. This restricts the future use of a property from certain types of development and is often used to preserve open space or farmland. In the context of coastal flooding, this can be used as a measure to prevent future development from occurring in migration spaces (American Planning Association 2006).

2.5.7.3 Rolling Easements

Rolling easements prohibit engineered barriers or other types of containment and involve removal of structures seaward of a migrating shoreline (EPA 2011). Rolling easements ensure existing migration space into the future. Structures that become threatened by tidal flooding are removed. Rolling easements can discourage future development in anticipated future migration spaces. As the shoreline continues to recede, the easement "rolls" farther inland. The intent of rolling easements is to allow natural migration to take place.

2.5.7.4 Fee-Simple Acquisition

Fee-simple acquisition involves the outright purchase of property and all associated development rights (Berger 2012). Fee-simple acquisition is often used when local governments purchase waterfront properties that are vulnerable to erosion and flooding. In the context of coastal flooding, the purpose of the acquisition is to remove or prevent future development in vulnerable areas and to reduce future damage from coastal flooding. Fee-simple acquisitions can be used in conjunction with other managed retreat policies to preserve open space, which in turn can be used to implement other mitigation measures, such as wetlands development or green infrastructure, to increase a community's resilience to coastal flooding.

2.5.7.5 Zoning in Migration Spaces

Zoning ordinances restrict allowable land uses for a defined area. Zoning may regulate land use kind, intensity, and density, and can regulate architectural design and other aspects of development. In the context of sea level rise and tidal flooding, zoning can prevent or limit development in migration spaces, ensure that new development does not increase the severity of flooding, and require that new and renovated structures incorporate flood-resilient designs and features. Local ordinances must, at a minimum, comply with federal requirements for developing within floodplains, and many zoning ordinances already include measures related to flood-hazard areas.

2.5.7.6 Development Fees in Migration Spaces

Development fees are one-time charges imposed by local governments on new development projects to cover costs for infrastructure outside the developed area. In the context of sea level rise, development fees can be used to remove containment structures in areas otherwise suitable for migration.

2.5.8 Land Use Activities

2.5.8.1 Infrastructure Relocation

Infrastructure relocation involves moving vulnerable infrastructure away from known or anticipated migration spaces. Relocation can be a viable option for many types of infrastructure, including roads, bridges, buildings, overhead utilities, and containment features such as levees and dikes. Moving infrastructure may involve physically relocating the existing infrastructure, constructing new replacement infrastructure, or otherwise shifting the function of the infrastructure to a different location.

2.5.8.2 Elevated Development

Elevated development involves physically raising infrastructure (e.g., on stilts/pilings or raised land) so that tidal waters can temporarily and harmlessly flow underneath or around (UNESCO 2002) without harming the structure. Elevated development can be included in the original design or added as a retrofit. Traditionally, only buildings are elevated, while the surrounding infrastructure (e.g., roads, walkways) is not. While a building may be protected from flood damage, access to it may be limited during a coastal flood. It is possible to raise surrounding infrastructure, including roads, bridges, walkways, and utility lines. A common example of elevated development is beach homes built on stilts, often with the first floor at a height of 10 feet or more above ground level. Elevating structures is a relatively easy feature to incorporate into the design of a facility or infrastructure during initial construction, but it is more challenging to incorporate as a retrofit. Physically raising a structure that is already elevated slightly (e.g. with a crawlspace) is more feasible than elevating “slab-on-grade” construction.

2.5.8.3 Floating and Floodable Development

Floating structures rise vertically on top of floodwaters instead of being inundated. The structures are prevented from moving horizontally by pilings or similar anchors that keep them in the same location and prevents them from floating away (UNESCO 2002). Only individual buildings are constructed on floating foundations. Floodable buildings experience minimal structural damage to being flooded. On a larger scale, floodable development can include structures and green infrastructure designed to capture, retain, and gradually release tidal water during ebb tide.

2.5.8.4 Movable Buildings

Movable buildings are designed to be easily relocated in advance of sea level migration. The most common movable buildings are trailers and modular buildings, which are moved by truck or train. These buildings are usually left on trailers or set on a concrete slab foundation.

2.5.8.5 Tidal Wetland Creation, Restoration, and Enhancement

Coastal wetlands provide more than $23 billion annually in storm protection (Anderson and Mulder 2008). They have significant value in protecting shores from erosion by anchoring sediments and dissipating the erosive energy of tidal currents, storm surges, wind waves (e.g., Shephard *et al*. 2011, Goals Project 2015). Communities can take steps to conserve, enhance, restore, or create wetlands in suitable intertidal areas. The conservation of tidal marshes can involve many scientific and engineering disciplines.

There is increasing concern that tidal marshes may drown due to rates of sea level rise that exceed rates of sediment accumulation and marsh accretion (Nuttle *et al*. 1997, Orr *et al*. 2003, Stralberg et al *et al*. 2011, Kirwan and Megonigal 2013, Mercury News 2016). There is a concomitant interest in developing methods to supplement natural tidal marsh accretion processes with suitable imported sediment (Roman and Burdick 2012), most commonly by the direct application of dredged sediment to the marsh surface (e.g., Marcus 2000, Schrift *et al*. 2008), or by redirecting fluvial sediment from nearby rivers and streams (e.g., SFEI 2015). The need to restore and sustain tidal marshes in San Francisco Bay as part of sea level rise accommodation and adaptation is well recognized (Goals Project 2015, San Francisco Bay Restoration Authority 2015), and is reflected in past efforts to conserve Bothin Marsh (e.g., Leventhal and Baye 2015).

2.5.9 Regional Initiatives

There are a number of regional projects converging on innovative designs for increasing the resilience of the natural and built shoreline landscapes of San Francisco Bay to climate change, especially sea level rise. Each effort intends to integrate landscape architecture, social science, and environmental science into model approaches and operational examples of sea level rise adaptation. The response of the regulatory and management agencies is uncertain, given that there is no legal obligation to adopt any of the findings or recommendations. However, it is likely that the projects will widen the field of view to recognize new opportunities and possibilities, while improving collaboration across disciplines and public agencies.

2.5.9.1 Flood Control 2.0 (http://www.sfei.org/flood-control-20)

Flood Control 2.0 is an innovative regional project that seeks to integrate habitat improvement and flood risk management at the Bay interface (SFEI 2017). The project focuses on helping flood control agencies and their partners create landscape designs that promote improved sediment transport through flood control channels, improved flood conveyance, and the restoration and creation of resilient bayland habitats. The project findings have been synthesized into an online “toolbox” that includes channel classifications and relevant management concepts for reconnecting the tidal marshes to their watersheds and creating a marketplace for tidal marsh restoration sponsors to find available dredged sediment, regulatory guidance, and benefit-cost analyses of current and alternative flood management practices.

2.5.9.2 Adapting to Rising Tides (ART) (http://www.adaptingtorisingtides.org/)

In 2010, the San Francisco Bay Conservation and Development Commission (BCDC) and the NOAA Office for Coastal Management (NOAA OCM) brought together local, regional, state and federal agencies and organizations, as well as non-profit and private associations for a collaborative planning project to identify how current and future flooding will affect communities, infrastructure, ecosystems and economy. Since then, the ART Program has continued to both lead and support multi-sector, cross- jurisdictional projects that build local and regional capacity in the San Francisco Bay Area to plan for and implement adaptation responses to sea level rise. The ART Program is integrating adaptation into local and regional planning and decision-making in multiple ways:

- Leading collaborative adaptation planning projects that build a comprehensive understanding of climate vulnerability and risk;
- Building regional capacity for adaptation by working with local, regional, state and federal agencies to find funding;
- Advocating for adaptation by communicating findings, issues, processes and needs to state and federal agencies.

2.5.9.3 Resilient by Design (RbD) (http://www.resilientbayarea.org/about/)

RbD is a collaborative research and design project that brings together local residents, public officials and local, national and international experts to develop innovative solutions to the issues relating to climate change. In a yearlong challenge, teams of engineers, architects, designers and other experts will work alongside community members to identify critical areas throughout the Bay Area and propose innovative, community-based solutions that strengthen the region's resilience to sea level rise, severe storms, flooding, and earthquakes. The result will be 10 implementable projects that offer an imaginative and collaborative approach to resilience.

2.5.10 Previous Adaptation Plans for Bothin Marsh

Multiple recent studies provide evidence of efforts to incorporate sea level rise forecasts into plans and management of Bothin Marsh or its associated infrastructure (ESA PWA and Wetlands Research Associates 2006, Leventhal 2015, Leventhal and Baye 2015, Marin County Public Works 2017, WRA Environmental Consultants 2017, WRECO 2017). In addition, OCOF can be used to visualize sea level rise at Bothin Marsh. No studies have been conducted regarding the possible effects of local shoreline modification on variations in tidal energy or sea level rise within Richardson Bay.

2.5.10.1 ESA PWA and Wetlands Research Associates 2006

The following italicized project description was excerpted from the public document. The terminology was edited to maintain consistency with the rest of this report.

> *The purpose of this study is to evaluate options for combining wetlands enhancement with flood management in Coyote Creek Lower Reach (i.e., the Coyote Creek Canal or tidal reach of the creek bayward of Highway 1), improving both flood management and habitat restoration. The project area includes Coyote Creek Lower Reach (between Highway 1 and the Bay Trail) and the north and south basins of Bothin Marsh. The main project goals were:*
>
> - *Reduce the need for ongoing maintenance dredging in Lower Coyote Creek;*
> - *Improve the habitat value of wetland and upland areas in the project area.*

There was no objective to address explicitly sea level rise, although that was a background consideration (Phil Williams, personal communication). Based on the constraints and opportunities identified in the study, it provides four conceptual alternatives (see Figure 2.15 below). All alternatives seek to increase tidal prism in the lower reach of Coyote Creek (i.e., the Coyote Creek Canal) to reduce the need for future dredging. Note that each alternative plan involves breaching the northern levee of the Coyote Creek Canal near its intersection with an earlier route of Coyote Creek (See Chapter 3 of this report), with the intent of draining Bothin Marsh into the Canal. This would reverse the natural drainage direction. The plans depend on the marsh being flooded by the tides through the existing inlet at the Bay Trail, northwest of the Canal, and draining during ebb tide through the proposed breach of the Canal levee.

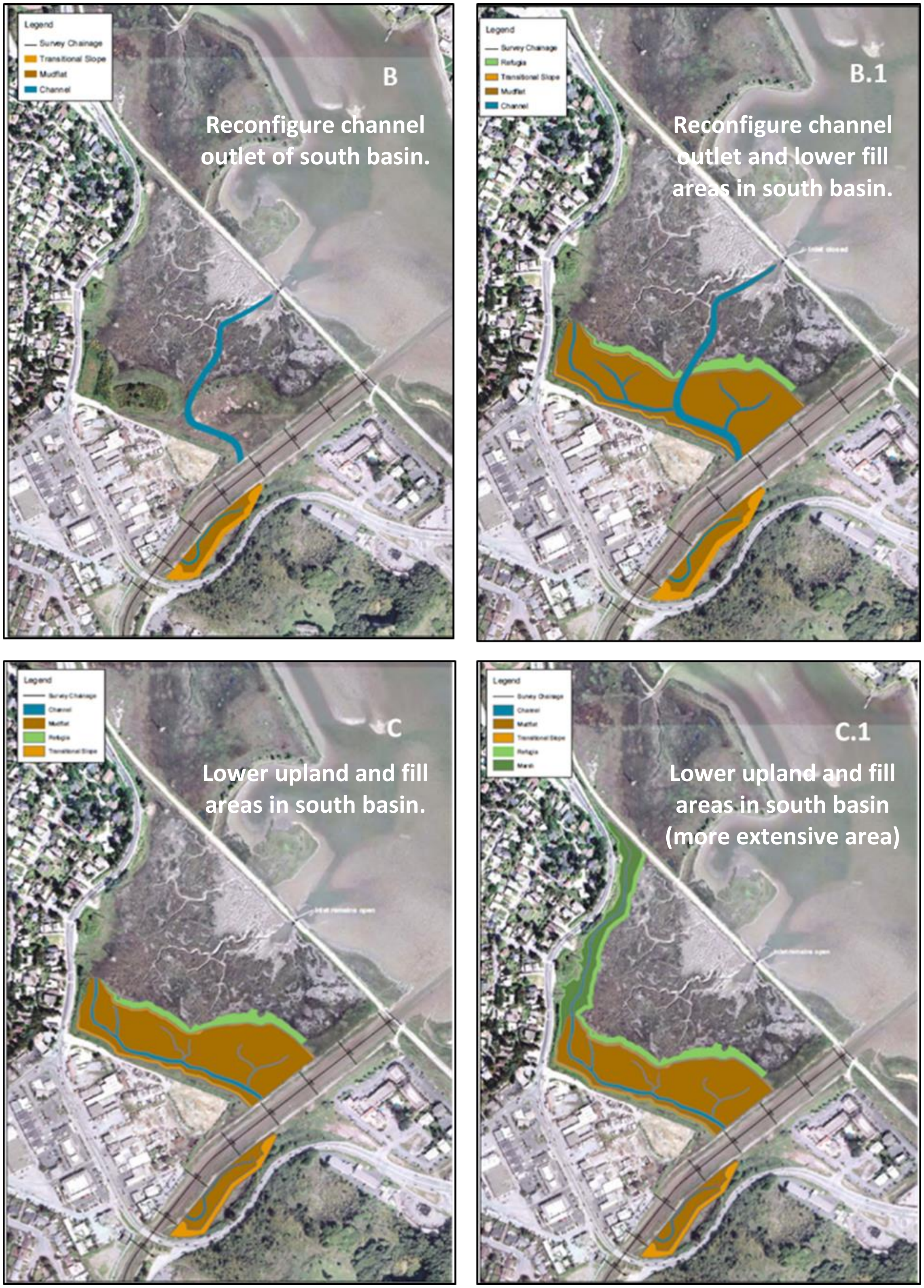

Figure 2.15. Four diagrams of conceptual plans to reduce the need for maintenance dredging of the Coyote Creek Canal by increasing its tidal prism while also improving aquatic habitats (PWA and Wetlands Research Associates 2006). Plans are described in text above.

2.5.10.2 Leventhal 2015

The following italicized project description was excerpted from the public document. The terminology was edited to maintain consistency with the rest of this report.

> *The primary purpose of this study was to assess the impacts of sea level rise along parts of the Richardson Bay shoreline and to discuss a range of potential engineering and planning alternatives to increase the level of flood protection under selected scenarios of sea level rise. Adaptation options include a number of possible alignment alternatives for containment structures along the shoreline edge. In each case, alternatives were developed to inhibit direct coastal flooding and protect the built infrastructure along the urbanized shoreline edge. Therefore, no alternatives were developed that involved retreating or relocating buildings or existing infrastructure. However, the costs developed for protection in-place can be used as a baseline to compare against other adaptation approaches, such as planned retreat and removal of structures or utilities and use of larger, landscape-scale, natural approaches. Several nature-based solutions (horizontal levees and engineered beaches) have been included where they fit the landscape. For the sea level rise impact projections in this study, values for years 2030, 2050, and 2100 were taken from the NRC guidelines (NRC 2012). It was assumed that planning on a 30 to 100 year period is appropriate for major sea level rise adaptation strategies, given the potential expenditure of funds and the lifecycle of most infrastructure improvements. The project noted that any dates are subject to significant uncertainty and should only be read as a very approximate guide to the future to allow for long-term planning horizons.*

One of the interesting analyses of the report is the assessment of minimum elevations of containment structures to prevent their overtopping by King Tides and to meet FEMA flood protection standards under different sea level rise forecasts (Table 2.4). As stated in the report, how high to build a barrier depends on several factors including the level of protection desired, costs, impacts of overtopping, and the critical importance of the assets being protected. The significant differences in barrier elevations (Table 2.4) can translate to large cost differences.

Year	Sea Level Rise Scenario (inches NAVD88)	Minimum Design Elevation (ft NAVD88) to Contain Annual King Tide	Minimum Design Elevation (ft NAVD88) to Achieve FEMA Certification
2030	12	9 - 10	13
2070	36	11 - 12	15
2100	60	13 -14	17

Table 2.4. Design elevations for containment features having different performance objectives, such King Tide containment of FEMA certification. (Leventhal 2015).

A variety of possible alignments of containment features were developed based on sets of reasonable assumptions about flood control needs (Figure 2.16). The alignments serve to illustrate an approach to land use planning and do not represent the findings of final engineering studies. It should be noted that the alternative alignments were developed without the benefit of more recent studies showing how containment in one area of an embayment can affect flood risks elsewhere in the same embayment (Holleman and Stacey 2014, Stacey 2017). The idea of preventing tidal excursion into upper Richardson Bay (see Figure 2.16D, and Kennedy 1957) probably has serious implications for flood risks in others parts of San Francisco Bay. Individual containment projects will need to be assessed in terms of their cumulative effects on sea level rise and tidal flooding at a variety of spatial scales.

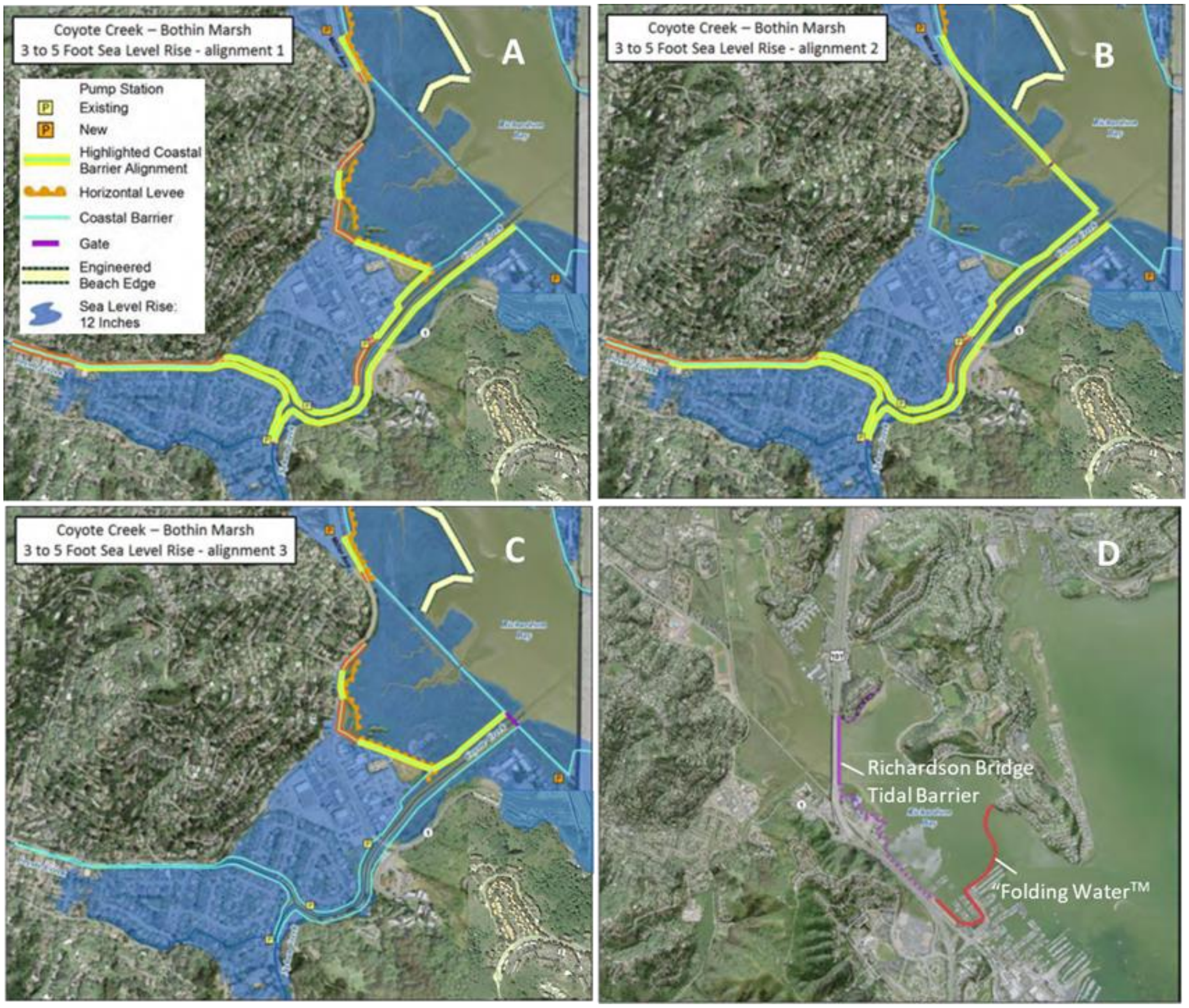

Figure 2.16. Example alternative alignments (A-C) for containment features at Bothin Marsh for a sea level rise of 3 - 5 feet NAVD88, plus (D) possible alignment of features affecting tidal containment throughout upper Richardson Bay (Leventhal 2015).

2.5.10.3 Leventhal and Baye 2015

This study generated conceptual landscape plans for enhancing the ecology of Bothin Marsh and its resilience to sea level rise using naturalistic adaptation features. The value of the plans is their innovation, building on experience with horizontal levees and overwash berms, both of which have historical, natural analogues at Bothin Marsh. In many ways, these conceptual plans build on the previous site-specific studies of Bothin Marsh while incorporating concerns about sea level rise. The design elevations of the features would be based on the best available local information on tidal elevations and sea level rise relative to NAVD88 (Roger Leventhal, personal communication). In the context of recent forecasts of sea level rise for San Francisco Bay (Griggs *et al*. 2017), these conceptual plans are probably viable for a timeframe of 50-75 years, although some significant shifts in relative amounts of low and high intertidal habitats can be expected, with lower habitat types becoming more dominant. When combined with containment features designed to protect the adjoining built environment, these naturalistic features could provide adequate flood control and conserve local habitats for decades. Addressing sea level rise in the longer term will likely involve more difficult landscape activities, such as managed retreat.

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Bothin Marsh Geomorphology, Ecology, And Conservation Options

Chapter 3: Environmental History of Intertidal Habitats in Richardson Bay with Emphasis on Bothin Marsh

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Chapter 3: Environmental History of Intertidal Habitat in Richardson Bay

3.0 Introduction

This chapter summarizes the environmental history of Richardson Bay (herein referred to as "the Bay") with a generally focus upstream or northwestward of the State Highway 101 bridge, with special regard for the study area encompassing the Bothin Marsh Complex (Figure 3.1). See the overall Introduction to this report for a more complete description of the setting.

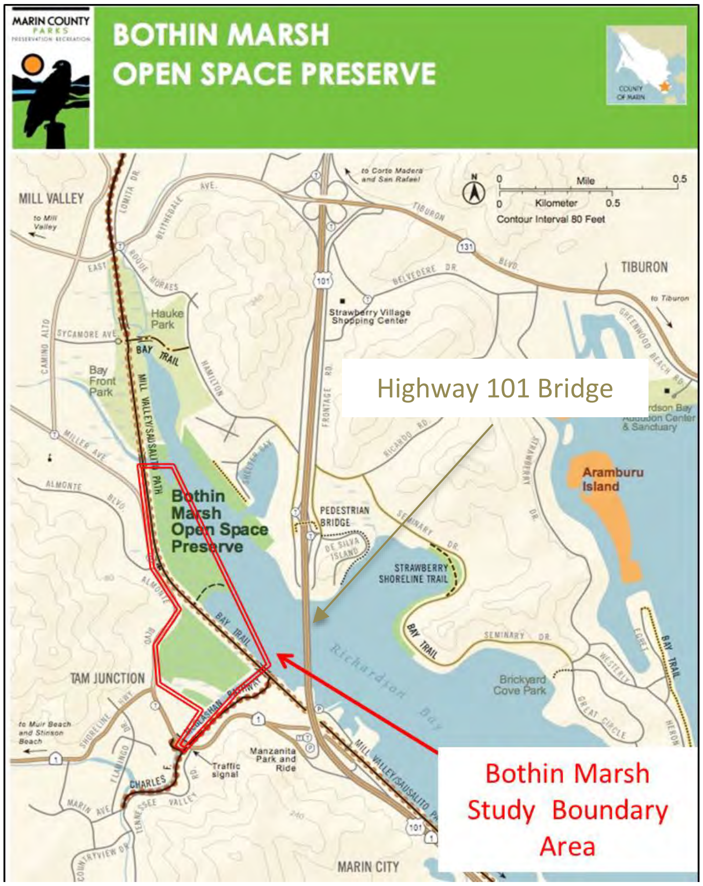


Figure 3.1. Location of Bothin Marsh Complex Study Area in upper Richardson Bay. Map courtesy of Marin County Open Space District.

This historical analysis documents changes in the distribution, abundance and general condition of intertidal habitat types, including their conversion from one type to another, due to natural processes and human intervention. This analysis is supported by the understanding of physical and ecological processes conveyed in Chapters 1 and 2, and draws on that understanding to infer the causes of documented environmental change.

3.1 Summary of Findings

The Bay and its marshes are still adjusting to major environmental changes caused by people since the late 1700s. These alterations of the landscape of the upper Bay have been ongoing and overlapping. The tidal marshes are sensitive to these changes. The marshes have never had a chance to adjust to one set of changes before another begins. They are still adjusting to changes that happened more than a century ago. Many changes have happened since then.

The timeline of environmental change in Richardson Bay (Section 3.4) can be separated into three approximate phases. Phase 1 ended in the 1950s. It was mostly about adding and expanding old world land use around the Bay, such as logging and grazing and residential development. These land uses increased erosion in the local watersheds and flooding along the bayshore. Phase 2 ended in the mid-1970s. It was mostly about dredging, diking, and filling the shallow subtidal and intertidal areas of the Bay, especially tidal marshes, to create marketable lands. Phase 3 is ending now. It's been about working with nature to manage the Bay for many competing objectives, including flood control, shoreline protection, recreation, and wildlife protection, in the context of modern environmental policies and regulations. The next phase will use the lessons of the past phases to address the challenges of climate change, especially sea level rise.

The following lessons have been synthesized from the accompanying detailed study of the environmental history of upper Richardson Bay.

- Altering one part of the Bay effects what happens elsewhere in the Bay. Ignoring this fact causes the alterations to have unexpected consequences and sometimes to fail expensively. Failed efforts to exploit the Bay for commercial or social interests are evident as eroded reclamation levees, piles of rubble, chronic flooding, damaged habitats, unwanted sedimentation, and a dependence on dredging.

- Major enterprises have come and gone, but their physical and ecological effects on the Bay persist in numerous ways. Logging and ranching forever changed the nature of vegetation and its effects on runoff and erosion in the watersheds around the Bay. Railroading and highway construction has left levees and berms and bridges that dissect the Bay and its marshes, forever changing how winds and waves and tidal waters move throughout the Bay and along its shores. Urbanization has altered the amount and chemistry of runoff entering the Bay. Dredging has rearranged the ancient and more recently deposited sediments of the Bay, while changing the way the Bay fills and drains. These alterations have created a mosaic of fragmented and damaged habitats, left remnants of historical habitats isolated from each other, and created opportunities for biological invasion, while threatening populations of native plants and animals.

- Early reclamation of tidelands during Phase 1 of the Richardson Bay Timeline of Environmental Change (Timeline) had the overall unintentional effect of moving the marshlands bayward. Reclamation of the historical Coyote Creek marshes in the 1870s, coupled with railroading across the Coyote Creek open embayment in the 1880s, initiated the process of turning marsh into land and the embayment into marsh. The railroad levee became the new foreshore. The construction of a reclamation levee along the historical foreshore of Almonte Marsh in the 1920s forced the sediment of the Arroyo Corte Madera del Presidio to bypass the marsh and be deposited in subtidal areas and new mudflats. Storm waves and flood tides moved some of the sediment from the flats to new marshland bayward of the levee. This fringe of new marshland was subsequently reclaimed with another levee in the 1930s. Marshland bayward of this new levee has continued to be nurtured with sediment from the Bay. Throughout this period, in the valleys and embayments of Coyote Creek and Arroyo Corte Madera del Presidio, marsh became land and the Bay became marsh, because of reclamation.

- Upper Richardson Bay is much smaller than it was at the time of Euro-American contact. Its extent has decreased by about 50%, due to reclamation of tidal marshes and flats, and artificial filling of shallow subtidal areas. Much of the reduction in size can be attributed to railroading during the late 1800s. It isolated marshland of Coyote Creek and Arroyo Corte Madera del Presidio from the Bay, especially as trestles were replaced with levees. But, the isolation accelerated after WWII, during phase 2 of the timeline, with aggressive reclamation of tidelands and shallow subtidal areas bayward of the railroad. The decrease in extent of the Bay is reflected in a decreased tidal prism. Although there are no data to calculate the historical loss in prism, it's evidenced by rapid in-filling of dredged areas and chronic shoaling elsewhere. There has been inadequate prism to scour the accumulated sediment to the historical water depths. The average depth of the upper Bay relative to high tide has decreased markedly since the first navigational charts of the mid-1800s.

- Alterations of the Bay have rearranged and redistributed the supplies of sediment from the local watersheds. Very little of the sediment has been exported from the Bay. It has been dredged to improve navigation, to build levees, and to turn the margins of the Bay into land. These major rearrangements of sediment have mostly ignored their net negative, long-term effects on flood control, navigation, and ecology.

- The disconnection of the tidal marshlands from their watersheds has been a very significant change in the overall mechanics of the upper Bay. The marshes owe their existence in large part to the supplies of fine sediment provided by their watersheds. Dikes and levees have increased the distance sediment must travel from the creek mouths to the marshes, which in turn has increased the likelihood that sediment will be delivered elsewhere, including subtidal sediment sinks created by dredging. Of all watersheds of Richardson Bay, the Arroyo Corte Madera del Presidio matters the most as a sediment source. It is by far the largest watershed with the greatest potential for erosion, given its geology, steepness, and rainfall. Its sediment supply is essential for the conservation of tidal flats and marshes of Richardson Bay.

- Alterations vary in their reversibility. Some historical alterations have been monumented by their incorporation into modern land uses. For example, marshlands reclaimed from the 1880s to the 1970s support commercial and residential development that will be difficult to protect from sea level rise. The railroad levee has become the very popular Bay Trail. It can be raised or realigned, but at considerable expense. In contrast, some historical levees are deteriorating on their own and some portions of these levees support popular foot trails or serve as high marsh refuge for wildlife, and therefore might deserve conservation. In-Bay dredged canals are filling with sediment, and in-bay spoil piles are eroding. The need for maintenance dredging in the Bay is decreasing, because deep draft boats are not using the upper Bay. If future flood control plans reroute Coyote Creek to accommodate sea level rise, the need for the Coyote Creek Canal may be nullified. The Canal could then remain as subtidal, or be converted to tidal flats or marsh.

- Sudden extreme events, natural or not, can have lasting environmental significance. Tidal habitats represent a rather sensitive balance between sediment supplies and tidal hydrology. A sudden change in one or the other can trigger major changes in habitat abundance and condition. For example, major storms can trigger landslides that produce large pulses of terrigenous sediment (Collins *et al*. 2001), which in turn can create deltas across diked baylands and tidal marshes (Ellen *et al.* 1988, Watson 2011). Overtopping of levees or their intentional breaching can suddenly transform diked baylands to subtidal or intertidal habitats. Conversely, the completion of a containment levee, the installation of a tide gate, or the creation of other restrictions on tidal flows can suddenly convert tidal habitat into non-tidal habitat, at a large scale. Decisions to accommodate sea level rise rather than contain it may be triggered by one or a series of catastrophic floods. Such events punctuate the environmental history of upper Richardson Bay

- The natural processes of tidal flat and marsh evolution and maintenance are ongoing. Where they have been allowed to operate long enough without disruption, tidal flats and marshes are evolving. This is evident in formerly diked areas that have been opened to the tides, such as North Bothin Marsh, and on the bayward sides of levees that are not directly attacked by wind-generated waves. Varieties of methods exist to enhance or even accelerate marsh evolution, by nurturing processes that govern conditions in upper Richardson Bay, as well as in the marshes.

3.2 Methods

This study of change in upper Richardson Bay followed a proven procedure to discover and compile historical environmental information. The procedure begins with a clear definition of its geographic focus, while recognizing that information from surrounding areas will be useful.

In general, the amount and diversity of information sources increases from the past to the present. The start of a timeline of environmental change is often fixed by the oldest available reputable sources of information that pertains the study area. For Richardson Bay, these sources are the accounts of ranching and timber harvest conducted during the early years of the Presidio de San Francisco and early mission period of the late 1700s and early 1800s. Written accounts about the earliest settlers in the region dating to the first part of the nineteenth century are readily available.

Environmental history is place-based, and therefore reputable maps are always informative. All maps are incomplete or factually wrong in some regards; however, so knowing the purpose of a map and the motivations and qualifications of its author and producer is important. In general, federal and state maps are the most reliable and best documented. Regional and local agency maps can be helpful but tend to be less well documented. Maps produced for commercial purposes, such as real-estate maps, tend to be very selective and somewhat biased in content and design. The accuracy of a map can vary among the features it shows. For example, many bayshore maps produced by regional and local interests to depict the built environment share a common map of the Bay and its marshlands as context, even if the contextual map is wrong. With the advent of automobiles, travel times decreased, and map scales decreased, such that maps of a given physical size showed more area in less detail.

For Richardson Bay, and for most of the California coast, the earliest reputable maps of tidal marshes and related environs are the Topographic Sheets and Hydrologic Sheets of the first Coast Survey. The Coast Survey was a federal program initiated in San Francis Bay in the mid-1800s to maps the waters and immediately adjoining lands for informing federal and state planning and management of coastal resources, especially with regard to navigation. The T-sheets and H-sheets serve as a proven foundation for assessing historical changes in near-coastal environments.

Aerial photography first became locally available in the early 1930s, and has increased in quality and abundance since then. Intervals of time covered by aerial imagery have decreased steadily. The advent of digital imagery has greatly increased the acuity and resolution of landscape images. New high-quality imagery of the entire focus area has become available every few years since the 1990s.

Written accounts by early settlers, local and regional published histories of places within the focus area, diaries and letters describing landscape condition, and landscape paintings of known origin and vintage can provide clues about changing local and regional conditions, and about the land uses affecting the changes. For example, reports on dairy and ranching operations, the amount of lumber removed from watersheds, records of local commerce can shed light on industries utilizing and changing the landscape.

Throughout the Bay Area, and certainly in Richardson Bay, early railroading had profound and lasting impact on tidelands because it often skirted or crossed them with levees that interrupted the flow of tidal waters. The railroads also spurred growth in industries and municipalities along the railways, and hence along the bayshore. Plans for railways and related constructions are often very well documented with reports and detailed maps of conditions along right-of-ways, including as-built conditions for engineered crossings of tidal sloughs and embayments.

As the Bay became more densely populated, and cities were incorporated, the amount of governmental planning of land use increased. Engineering reports on shoreline infrastructure and development became commonplace and dependable. With the advent of federal and state environmental policies and laws in the 1960-70s, the number of expert studies of past and present conditions increased. The number and breadth of academic studies of the Bay also increased, due in part to the needs of government agencies for science support, and to large number of nearby state colleges, major universities, and federal centers for environmental research. Many of the studies focusing on Richardson Bay include environmental histories, which can accelerate any new efforts to understand historical environmental change.

All of these kinds of sources of historical information were utilized in this study of the changes in tidelands and related environments of the Study Area and its environs in upper Richardson Bay. The sources were cross-referenced along a timeline extending from the late 1700s to the present. A weight-of-evidence approach was used to determine the location, timing, and characteristics of likely or known change. Changes are only recorded if they are well supported by multiple lines of evidence. The resulting Timeline of environmental change for upper Richardson Bay, including especially the tidal marshlands, is produced as a matrix that follows Tables 3.1-3.3, and the citations for this chapter. All measurements of area were made using Google Earth, and in some cases involved overlaying historical photographs and maps on Google Earth imagery.

3.3 Quantified Marshland Change

Tables 3.1 is a key to the abbreviations of place names referenced in Tables 3.2 and 3.3, as well as to the Timeline that follows these tables. Table 3.2 reports the amount of change in acres since 1851 for each component marsh of the Bothin Marsh Complex. Table 3.2 focuses on the conversion of mudflat to marsh in South Bothin Marsh. The changes at South Bothin Marsh illustrate how tidal habitats respond to changes in sediment supply, as affected by climate, weather, and land use. Measures of marsh area only include vegetated marsh plains and pannes between the foreshores and backshores. Tidal channels wide enough to be depicted by two banks on the historical maps (rather than by a single line) and areas of levees above tidal influence were excluded from the measurements.

Key to Abbreviations for Tables 3.2 and 3.3	
AA	Almonte Marsh
NBM	North Bothin Marsh
SBM	South Bothin Marsh
EBM	East Bothin Marsh
NMM	North Manzanita Marsh
HCCM	Historical Coyote Creek Marsh
CCE	Coyote Creek Embayment
CC	Coyote Creek
CCC	Coyote Creek Canal
RR	Railroad

Table 3.1. Key to abbreviations of place names. The key pertains to Table 3.2 and Table 3.3 (see immediately below), and to the following Timeline.

Table 3.2. Changes in area of tidal marsh of the Bothin Marsh Complex. Note the gain of about 3 acres of new marsh in South Bothin Marsh (SBM) during the 3-year period 1924-27. This may be alluvial fill that was mapped as marsh, but it nevertheless indicates the possibility of rapid change due to extreme events. The increase in acreage is mainly due to formation of the Coyote Creek alluvial fan in SBM after the severe storms of 1925 (See Timeline).

Year	AM (includes Tam Marsh) (ac)	NBM (includes Rectangle Marsh) (ac)	SBM (ac)	EBM (east of RR) (ac)	NMM (ac)	HCCM (west of SR 1) (ac)	HCCM (east of SR 1) (ac)	CC Embayment (ac)	Total tidal marsh (ac)
1851	49.6	0	0	0	15.8	76.1	(No SR 1)	open	141.5
1870	49.6	0	0	0		65.5	(No SR 1)	open	
1872	49.6	0	0	0	16.6	64.2	3.7	open	134.1
1883	49.6	0	0	0			3.7	47.6	
1889	50.0	0	2.5	0			3.7		
1899	51.7	0	17	0.1	7.3	28.6	3.7	40.5	108.4
1924	45.9	0	27.8	0.20	10.6	32.3	3.0	29.9	119.8
1927	41.6	0	33.4	0.20	13.2	37.6	3.1	21.6	129.1
1946	40.1	0	33.8	0.25	10.9	33.4	2.8	16.6	121.25
1950		0				30.2	2.2		
1952	38.7	0	35.4	0.9	6.0	0	2.2	12	83.2
1960	21.4	0.4	28.0	1.3	1.2	0	0.3	10	52.6
1965	17.5	2.9	26.1	0.8	2.1	0	0	9.5	49.4
1973	18.8	14.3	28.8	0.6	2.1	0	0	5.2	64.6
1976	18.8	14.1	28.0	0.7	2.2			5.0	63.8
1978	18.8	14.0	28.1	0.8	2.1			5.0	63.8
1987	18.4	15.6	28.1	0.9	2.4)			6.1	65.4
8/ 2005	18.2	15.4	29.6	0.9	2.2			3.5	66.3
8/ 2016	18.0	15.3	30.4	0.8	2.2			3.1	66.7

Table 3.3. Evolution of tidal marsh from mudflat at Coyote Creek Embayment (CCE). Since the embayment was created by construction of the railroad in 1883, 47.6 acres of mudflat has evolved into 44.5 acres of tidal marsh, which is presently mostly low marsh, at an overall rate of 0.67 ac/yr.

Significant Event	Year	CCE Mudflat (ac)	% Initial Mudflat	Period of Change (yrs)	Mudflat Change (ac)	Rate of Marsh Evolution (ac/yr)

First Coast Survey	1851	No RR Levee	NA	NA	NA	NA
Sierran hydraulic mining begins	1853	No RR Levee	NA	NA	NA	NA
1300' RR trestle constructed	1883	47.6 (time zero)	100	NA	NA	NA

Table 3.3 continued

Significant Event	**Year**	**CCE Mudflat (ac)**	**% Initial Mudflat**	**Period of Change (yrs)**	**Mudflat Change (ac)**	**Rate of Marsh Evolution (ac/yr)**
Sierran hydraulic mining ends	1884					
RR trestle shortened to 120' with more levee	1894					
None	1899	40.5	85	16	7.1	0.44
None	1924	29.85	63	25	10.6	0.43
Significant 1925 rains and flooding (L. Collins 2011), formation of CC delta	1927	21.6	45	3	8.25	2.75
None	1946	16.6	35	19	5.0	0.26
Upstream grading and channelization of HCCM	1952	12	25	6	4.6	0.77
Flooding	1955-6					
CC channelized upstream of Flamingo Rd	1959					
HCCM mostly gone; 5% SBM filled	1960	10.0	21	8	2	0.25
CC diverted from SBM; flap gate added to SBM inlet	1965	9.5	20	5	0.5	0.10
Seasonal desiccation and standing water changes distribution of plants colonization of SBM mudflat	1973	5.2	11	8	4.3	0.54
CCC dredged above SR 1	1974					
None	1976	5.0	10	3	0.2	0.07
None	1978	5.0	10	2	0	0
SBM flap gate removed; undersized inlet armored; bridge #2 installed over 26-ft inlet	1980-1?					
Extreme flooding with sediment pulse	1982					
Some post flap gate marsh converts to mudflat	1987	6.1	13	9	-1.1	-1.20
Flooding with sediment pulse	1998					

None	2005	3.5	7	18	2.6	0.14
Tides overtop CCC levee to and from SBM	2005-17					
None	2017	3.1	6	11	0.4	0.04
Totals	2017	3.1	6	66	44.5	0.67

3.4 Timeline of Environmental change

The Timeline covers the period between the early 1800s and the present. Both the amount of change and its abundant documentation are remarkable. However, the interval between noted years of information is generally much shorter after WWII. This reflects two factors: the relatively slow rate of change before WWII, and the relative paucity of information about that change. Nearly annual accounts of change are available in modern times. While there are gaps in documentation for some early causes of change, such as early reclamation and dredging, most of the changes caused by human intervention have redundant documentation from alternative perspectives. As stated in section 3.2 above, changes are only recorded in the Timeline if they are well supported by multiple lines of evidence. The dates of change are usually inexact, however, unless the changes were rapid and authoritatively documented, either in writing or through imagery.

3.4.1. How to Use the Timeline

The Timeline is constructed as a matrix in four columns as diagrammed below. The Timeline is accompanied by a set of numbered images and figures illustrating the changes noted in the Timeline. Column 1 designates the time period or year. Column 2 references the number(s) of the relevant supporting illustrations that follow the Timeline. The illustration number is typically noted on the lower left corner of the actual image. The third column is a quick reference to any key changes for the corresponding year or time period. The last column provides detailed notes from the sources of historical information, including citations. For convenience, the key to abbreviations (Table 3.1) is reproduced below.

Column 1	**Column**	**Column 3**	**Column 4**
Time Period or Year	Image Ref #	Key Changes	Notes Relevant to Geomorphic Conditions and Landscape Change

Key to Abbreviations for Tables 1 and 2	
AA	Almonte Marsh
NBM	North Bothin Marsh
SBM	South Bothin Marsh
EBM	East Bothin Marsh
NMM	North Manzanita Marsh
HCCM	Historical Coyote Creek Marsh
CCE	Coyote Creek Embayment
CC	Coyote Creek
CCC	Coyote Creek Canal
RR	Railroad

Table 3.1. Key to abbreviations of place names (reproduced from above for convenient use with the Timeline below).

Richardson Bay Timeline of Environmental Change			
Time Period	**Image Ref #**	**Key Changes**	**Notes Relevant to Geomorphic Conditions and Landscape Change**
Pre 1775	None	Landscape was managed by indigenous people	There were more than 5000 years of Coast Miwok settlement in Marin County prior to first European contact at Richardson Bay. The lands were managed in part by intentional small fires of varying frequency. (https://geog.sfsu.edu/sites/default/files/thesis/Peri2005-ArroyoCorteMaderaHabitatAssess.pdf). It is likely that the intentional fires did little to increase soil erosion and sediment supply to the Bay because the fires were not hot enough to create significant water repellency (hydrophobicity) in the soils as has been documented to occur in modern times in some regions of the Bay Area following intense wildfire (Booker, Dietrich & Collins 1993; Collins and Ketcham 2001). Native people were using the natural resources of the historical Coyote Creek Marsh. Nelson (1906) mapped shellmounds very near Almonte Marsh, in small alcoves at the base of hillsides west of present-day Tamalpais High School (Tam High), upstream of the tidal reach of Coyote Creek and of Tennessee Creek, and near the backshore of Manzanita Marsh. Sediment supply to the Richardson Bay from all sources, including the attending creeks, was probably low. Supply was less from the Coyote Creek watershed than from the Arroyo Corte Madera del Presidio watershed, because of its much less steep topography and smaller size. Arroyo Corte Madera might have had occasional punctuated periods of high supply associated with natural debris slides in steep headwater streams of Mount Tamalpais.
1775	3	European contact begins in Richardson Bay	The first European known to visit the present-day location of Sausalito was Don José de Cañizares, on August 5, 1775 (https://en.wikipedia.org/wiki/Sausalito, California). **Image Ref #3** shows a map of the San Francisco Bay produced by Cañizares during 1781. The map might portray the Coyote Creek Embayment at the head of Richardson Bay.
1776-1839	None	Cattle and sheep replace deer and elk as herbivores	During the Mission Period from 1776-1839, The missions in San Rafael (1817) introduced free ranging cattle in eastern and southern Marin County that may have entered the lands around Richardson Bay (http://www.cityofmillvalley.org/community/about/history.htm). The Mission also introduced horses and sheep. Coastal prairies were considered prime pasturage for cattle and sheep ranching because of their productive and nutritious perennial grasses (Burcham 1957: fort and Hayes 2007, Howard 1998). The change from deep-rooted perennial

		Euro-American land uses increase land erosion	grasses to the annual grasses with shallow roots that decompose during the wet season increases the potential for surface erosion and shallow landsliding (Prosser and Dietrich, 1995). The European settlers hunted the abundant mule deer and tule elk that were reported by Richardson to be in great abundance along Richardson Bay. In time, the introduced livestock replaced the native elk and deer as the dominant herbivores.
1792-1848	None	Europeans suppress use of fire as a landscape management tool	The use of controlled fires by Coast Miwoks was discontinued in favor of fire suppression by Euro-Americans who believed fire interfered with the needs for ranching cattle (http://web.sonoma.edu/cei/prairie/history/recent_history.html). This contributed to the dominance of annual grasses, and allowed the accumulation of fuels, which in some areas led to more intense fires, and potential increased water repellency and surface erosion. Reduced interception of rainfall from grazing and fire influences would have led to increased runoff and downstream impacts to channels, causing higher than previous rates of sediment supply to the Bay from bank erosion and streambed incision.
1816	None	Logging begins to contribute to local sediment supplies	Commercial logging began on Mt Tamalpais (https://geog.sfsu.edu/sites/default/files/thesis/Peri2005-ArroyoCorteMaderaHabitatAssess.pdf). This would have significantly increased sediment supply to local streams and increased runoff, especially from the steep headwater streams on Mount Tamalpais. Mechanical soil disturbance would have decreased soil strength, increased shallow landsliding and bank slumping along channels, and reduced interception of rain by the forest canopy. Increased runoff would have initiated chronic channel incision as another added source of sediment. Abundant literature on studies of channel width, depth, and velocity (hydraulic geometry) show that many of the channels throughout the Bay Area have incised their channels since European settlement.
1822	None		The development of the Richardson Bay began with the arrival of William A. Richardson in 1822, shortly after Mexico had won its independence from Spain. Richardson submitted a petition to the California Governor for a rancho across from the Presidio to be located at the headlands of the Golden Gate and to be called “Rancho Saucelito.” “Saucelito” is a misnomer for the California (Osio 1996) term “Sausalito” which refers to a small stand of willows. The presence of a sausal indicates the presence of a spring or small creek. Richardson founded the town of Sausalito by first establishing it as a fresh watering station for the many vessels and schooners entering the Golden Gate (https://en.wikipedia.org/wiki/Sausalito, California).

			Richardson Bay was also used as a relatively quiet anchorage in the lee of the Marin Headlands
1830	None		In 1918, the *Call Bulletin* published a personal description by Stephen Richardson, son of William Richardson, of the late-1830s Richardson Bay that was later excerpted by Annie Sutter for a 1987-88 publication of the *Marin Scope*: "My early life in Sausalito was perhaps the happiest time of my life. A horse trail ran from San Rafael to Sausalito, very much the same as the main highway goes today. The country was entirely untouched by man, and the wild oats grew shoulder high, in spite of the great herds of wild animals browsing in the fields. On an ordinary jaunt from Sausalito to San Rafael I would see enough elk, deer, bear and antelope to fill a good-sized railroad train. I never grew tired of riding through wonderful forest land and over ridges overlooking the sea." The land grant, which Richardson received in 1838 ("Rancho Saucelito"), totaled over 19,000 acres and extended from Richardson Bay to the sea. "The bay as my father knew it was a fairyland of enchantments . . . the waters had not been fouled by tailings from the mines, and were still crystal clear so that a pebble could easily be seen at a depth of 30 feet. The timber reached in many places down to the shore. The stillness was unbroken save for the shrill piping of the myriad shorebirds, and elk with huge branching horns, graceful antlered stags, and huge grizzly bears stood statuesque on the hillsides." As stated by Sutter: "Richardson's daughter wrote that she saw bands of elk, hundreds in a band, swimming from Angel Island to the shores, and remembers fields of yellow poppies stretching as far as the eye could see. However, all was not Paradise, as attested to by one visiting sailor who, in 1837, 'sailed for Whaler's cove . . . remained an hour or two . . . shot a rabbit and got most confoundedly poisoned by what is here called 'yedra' - (poison ivy).'" http://www.sausalitohistoricalsociety.com/marin-scope-columns/2013/5/6/early-life-in-sausalito.html The reference to the 30 feet of water clarity in Richardson Bay is remarkable, but not surprising for at least two reasons: (1) suspended sediment in Richardson Bay is more strongly influenced by supplies from local watershed and wind generated waves on the mudflats, particularly at the head of the Bay, than by the larger circulation currents moving in and out of the Golden Gate and the greater San Francisco Bay that carry sediments from Sierran

			sources as well as other adjacent Bay Area watersheds; and, (2) the late 1830s (the period referenced in Richardson's description) probably preceded in major changes in sediment supply caused by European land sues. According to Van Geen *et al.* (1999), significant erosional disturbances dating after 1830, but well before 1890, are evident in sediment cores taken from the mouth of Richardson Bay. Van Geen *et al.* suggest that both hydraulic mining debris and erosion in local watersheds contributed to increased sediment supply well before the turn of the last century. They suggest that after this early erosional disturbance occurred, sediment was distributed more evenly around the Richardson Bay, whereas prior to the disturbance, most of the sediment, particularly at the head of the Bay, was related to local watershed supplies. Local sediment supplies available for marsh building not only involved direct delivery of terrigenous sediment by the streams but would have also involved tidal supplies through and re-suspension of the sediment temporarily stored in the mudflats. During the summer, wind action affects circulation patterns in Richardson Bay, when northwest breezes tend to set up a clockwise circulation current in the Bay (Phillip Williams & Assoc., 1983). The average wind direction for San Francisco Bay is from north to south (http://windhistory.com/map.html#9.00/37.8109/-122.1369). Winds from the north might contribute to substantial intermixing of Arroyo Corte Madera del Presidio sediments with Coyote Creek sediments in the Coyote Creek Embayment. The pattern of sedimentation seen in cores from the mouth of Richardson Bay was considered by Van Geen *et al.* (1990) to be consistent with deforestation and the expansion of agriculture in the watershed of the San Francisco Estuary. Peterson *et al.* (1993), suggest that diking and filling of much of the salt marshes that once surrounded the Estuary resulted in an overall reduction in sediment filtering and trapping and therefore increased the amount of suspended sediment in the Estuary. However, Richardson Bay tended not to receive much of this sediment because of its position perpendicular to the flow of sediment through and around the larger Estuary (Phillip Williams and Associates 1983).
1834	None	Cattle ranching begins and local logging intensifies	Mexican land grants divide Marin County. Cattle and sheep ranching begins for hide and tallow trade and for dairy purposes. John Thomas Reed was granted Rancho Corte Madera del Presidio where wood was cut and transported to the Presidio in 1834. Reed named the City of Mill Valley. He built his sawmill on Cascade Creek (now Old Mill Park) to process the wood in the mid-1830s on land that was

			part of Richardson's Rancho Saucelito. The wilderness of what is now modern Tiburon, Belvedere, Corinthian Island and parts of Corte Madera and Mill Valley became the "Rancho Corte Madera del Presidio" - meaning literally where wood is cut for the Presidio. (http://www.cityofmillvalley.org/community/about/history.htm) To equip his mill, Reed had to trade the resources from his land, 300 elk skins, 20 bearskins and 200 cattle hides with the Russians at Fort Ross for a circular saw, a grist mill flour, guns and ammunition (https://www.mvhistory.org/history-of/history-of-early-mill-valley/).
1845	4	Homesteading begins near marshlands	Homesteading is establishing along the marshes of Richardson Bay. Homesteading practices at the time were associated with practices that disturb soils and make them highly erodible and likely to be carried off the hills and valleys by surficial flow, transporting the fine sediment to the bay. For example, water diversion for farming often required ditching and diversion, as well as small dams for water supply. These activities caused channel adjustments that created more sediment. Farming required plowing fields, and ranching/dairying activities required concentrating animals into small areas. These activities increased rates of local sediment delivery to Richardson Bay.
1848	None		Discovery of gold in the Sierra Nevada prompts the Gold Rush.
1849	None	Significant local creek flooding is likely	Based upon analysis of numerous local historical rainfall records (Goodridge 1996, Collins 2001), 1849 was a year that could have generated flooding in local watersheds.
1850	5	Coyote Creek embayment is entirely open to Richardson Bay	This early map of the Richardson Bay shows that Coyote Creek has an open embayment. However, marshes known to exist in Richardson's Bay were not depicted on this map. Prior to this time, there had been significant upland watershed disturbance in both Coyote Creek and Arroyo Corte Madera del Presidio watersheds. Rhodes suggests that most sedimentation in the Richardson Bay by this time was directly associated with Arroyo Corte Madera del Presidio Creek that poured storm sediments from Mount Tamalpais into the Bay (email communication from P. Rhodes to L. Collins, 3/30/2017). This creek was also known as Widow Reed Creek. The sediments from Arroyo Corte Madera del Presidio contributed to Almonte Marsh, (which was on the south side creek banks near the mouth of the channel to the Bay), but also the much larger marsh system extending up through most of the flats of Mill Valley along the main Arroyo and its tributary tidal sloughs. However, it is suggested that the mudflats within the Coyote Creek Embayment, might have supported a mix of sediments from both Coyote Creek and Arroyo Corte Madera del Presidio that were reworked by waves on the mudflats and then re-deposited on the Historical Coyote Creek Marsh.

1851	6, 7, 8, 9	First detailed coast and geodetic survey map showing HCCM is produced	**Image Ref #6, #7 and #8** show portions of the earliest highly detailed topographic map by US Coast Survey (T-Sheet 00334) of the Coyote Creek area (email communication from Phil Rhodes to L. Collins, 3/30/2017 & 4/21/2017). This map shows tree groves (probably willows) at the downstream ends of Coyote and Tennessee Creeks as they transition into tidal marsh. Both creeks have tidal reaches extending through the tidal marsh to Richardson Bay. The mainstem of Coyote Creek flowed into the landward or upstream boundary of a tree grove (sausal) before transitioning to the marsh. It is not clear that the creek passed through the grove as a single channel or a network of distributaries. It is expected that the grove existed on an alluvial fan of sediment deposited by the creek. A similar configuration is evident for Tennessee Creek. It also flowed into a tree grove while transitioning to the head of the marsh. The same western tributary of Tennessee Creek makes an abrupt eastward turn that might follow the subtle boundary of a transitional alluvial fan. Within the marsh, both Coyote and Tennessee tidal sloughs are highly sinuous. The 1851 map (**Image Ref #7**) shows the intertidal marshes extended upstream and downstream of the confluence of Coyote Creek and Tennessee Creek. Numerous tidal marsh pannes are evident along the foreshore of Almonte Marsh, as indicated in **Image Ref #7**. These pannes are indicative of a poorly drained area of marsh along the backside of an overwash berm. Summaries of historical wind speed and direction data available for the Sausalito Boat Harbor (https://www.meteoblue.com/en/weather/archive/windrose/sausalito_united-states-of-america_5393611) indicate that the foreshore of Almonte Marsh is perpendicular to winds from the southeast, which have a fetch extending the length of Richardson Bay. Although this is not the predominant wind direction, it tends to occur during the onset of Pacific storms. Storm waves and the surge generated by winds along this fetch create the largest waves at Almonte Marsh, and the overwash from these waves very likely explains the formation of this berm. The foreshores of other marshes along Richardson Bay are parallel to this fetch and do not show evidence of overwash berms. The MLLW contour, which marks the bayward margin of tidal flats, is also shown on **Image Ref #7,** and it indicates that flats extended from the south and western sides of Richardson Bay to the mouth of Arroyo Corte Madera del Presidio. Tidal flats extended 1800 feet bayward of the mouth of Coyote Creek, entirely filling the Coyote Creek Embayment.

			There were 35 years of logging on Mt Tamalpais and 17 years of cattle grazing in the vicinity prior to creation of the 1851 map (**Image #7**). Conditions in **Image #7** probably reflect a period of increased sedimentation at the head of Richardson Bay. The watersheds of Coyote Creek and Arroyo Corte Madera del Presidio account for 57% of the drainage area of the Bay. The Arroyo Corte Madera del Presidio accounts for 36%, is much steeper, has a maximum elevation of 2,536 ft, and contained most of the logging activity. It is therefore likely to have been the dominant source of terrigenous sediment. In contrast, maximum elevation of Coyote Creek is 1041 ft. **Image Ref #8** shows the combined drainage area of Coyote Creek and Tennessee Creek. Historical Coyote Creek Marsh (HCCM) had a drainage area of 3.40 square miles. As will be discussed further through the timeline, the modern drainage area of South Bothin Marsh (SBM) became significantly smaller after it was disconnected from Coyote Creek for the construction of the Coyote Creek Canal. The modern Coyote Creek Canal (CCC) marsh has a drainage area of 3.56 square miles, and modern South Bothin Marsh has a drainage area of 018 square miles. **Image #9** shows the historical marshland boundaries projected onto the 2017 Google Earth Imagery. **The historical** Coyote Creek Marsh covers ~76 ac, excluding the tidal channels that were large enough on the maps to depict both banks (as opposed to a single line). If these larger channels are included the aerial extent of marsh was ~92 ac. Unless otherwise noted, marsh area determinations did not include the area within channels that had both banks mapped. The portion of historical Almonte Marsh (AM) relevant to this study covered about 50 ac, and North Manzanita Marsh (NMM) (north segment that is subject to influences within the larger Coyote Creek Embayment and therefore relevant to this study) covered about 16 ac.
1852	None	Commercial logging in Mill Valley ends Probable local creek flooding	Commercial logging in Mill Valley ends (https://geog.sfsu.edu/sites/default/files/thesis/Peri2005-ArroyoCorteMaderaHabitatAssess.pdf). Although logging ends, the geomorphic impacts of related erosion and high sediment delivery to Richardson Bay will continue for years. Based upon analysis of numerous local Bay Area rainfall records (Collins 2001; Gilbert 1917), storms in 1852 could have generated flooding in local watersheds and caused large amounts of

			sediment to be delivered to Richardson Bay, particularly from Arroyo Corte Madera, because it contained most of the logging and is steeper that the other watershed.
1853	None	Hydraulic mining begins in Sierra Nevada.	Hydraulic mining for gold begins in the central Sierra Nevada watersheds draining to the San Francisco Estuary (https://www.sierracollege.edu/ejournals/jsnhb/v2n1/miningtechniques.html). Fine sediment from mining debris led to an increased rate of sedimentation and rapid marsh expansion into parts of Suisun Bay, San Pablo Bay, Central San Francisco Bay and South Bay (https://pubs.usgs.gov/pp/0105/report.pdf). However, the peak of hydraulic mining sediment delivery to these areas did not occur until after the 1880s (Gilbert, 1917). Although much of the San Francisco Estuary was affected by the delivery of hydraulic mining debris, the tidal circulation patterns near the Golden Gate prevented the sediment from entering Richardson Bay, except perhaps near its mouth (Gilbert 1917, Philip Williams and Associates 1983).
1856	10	Extensive Shallowing of Richardson Bay has occurred.	The position of the MLLW contour changes significantly between 1851 and 1856. The change indicates a large-scale shallowing of Richardson Bay during a 5-year period. This might reflect increased sediment supply from erosional land use activities in local watersheds exacerbated by the storms of 1852. As discussed earlier, inputs of sediment from hydraulic mining into the eastern, northern, and central areas of the San Francisco Estuary probably did not have a large impact on Richardson Bay, especially in its upper reaches. The shallowing was likely due to ongoing logging, grazing, road-building, and other land use practices associated with increased homesteading. The tidal marshes changed little between 1851 and 1856, except that Coyote Creek might have migrated or been physically moved to the southern edge of the willow grove at its transition to the tidal marsh. Other details of the tidal marsh channel system evident in the 1851 map (**Image Ref #6**) are missing in the 1856 map (**Image Ref # 10**).
1859	11		**Image Ref #11** for 1859 shows the same bathymetry as mapped in 1856 (**Image Ref # 10**) and similar channel and marsh conditions.
1860	None		Elk were completely eliminated from Marin County by this time (http://web.sonoma.edu/cei/prairie/history/recent_history.html) and had been replaced by cattle, which augmented the conversion of perennial grasslands to nonnative annual grasslands. As a result, the production of sediment from grasslands has been permanently higher than historical rates from both soil erosion and shallow landsliding (Collins *et al*. 2001).

1861	None	Probable local creek flooding	Based upon analysis of numerous local historical rainfall records (Goodridge 1996, Collins 2001; Gilbert 1917), the total rainfall for the winter of 1861-62 was the greatest of any year of record until perhaps the winter of 1982-83.
1867	None	Probable local creek flooding	Based upon analysis of numerous local historical rainfall records (Goodridge 1996, Collins 2001; Gilbert 1917), 1867 was a year that could have generated flooding in local watersheds.
1868	12	San Rafael road on marsh perimeter	The 1868 Detail of Sausalito Land and Ferry Company map (**Image Ref # 12**) is an early parcel map for the sale of tidelands to support developing Richardson Bay by extending large amount of fill from its perimeter. It shows San Rafael Road existing along the perimeter of the historical Coyote Creek Marsh. Although it shows significant changes in the channel planform, the channel and marsh mapping shown her is considered unreliable because the marsh shoreline and topographic mapping along the north and northwestern edges does not conform well with earlier and later maps. It is possible that this map is more diagrammatic than geographically accurate,
1870	13, 14, 15, 16, 17, 18	San Rafael Road exists along backshore of HCCM ~10.5 ac of 1851 Historical Coyote Creek Marsh eliminated at head of Coyote Creek (representing about 49% of original marsh).	Unlike the earlier 1868 map (**Image Ref # 12**), the 1870 No. 7 Salt Marsh and Tide Lands map (**Image Ref #13 and #14**) shows the proposed Coyote and "Saucelito" (sic) Canals and the proposed route of the North Pacific Railroad. Tidelands are divided into parcels and mapped for future sale. Canals are designed to access the reclaimed tidelands and drain Coyote Creek and Arroyo Corte Madera del Presidio. Interestingly, the middle portion of the proposed Coyote Creek Canal (CCC) aligns well with the existing Army Corps project constructed in 1965. The proposed railroad route does not align with the existing route of the Bay Trail, which is on a later railroad levee that formed the modern Coyote Creek Embayment. The State Lands Commission tidelands map (**Image Ref #15)** produced detailed soundings of upper Richardson Bay (email communication from Phil Rhodes to Laurel Collins, 3/30/2017). The map seems to verify the shallowing trend for Richardson Bay evident by comparing the 1851 map (**Image Ref # 6**) and the 1856 map **(Image Ref # 10**). This verification is indicated by the much narrower areas between the MLLW contours on opposing sides of the Bay, and that the MLLW contour extends only to an embayment south of Silva Island. The 1870 bathymetry of Richardson's Bay (**Image Ref #15, #16, and #17**) changed slightly since 1856. The 1870 MLLW boundary extends farther northward toward the head of Richardson's Bay, slightly past Silva Island.

			The 1870 map (**Image Ref #15, #16, and #17**) indicates that ~10.5 acres of marsh at the upstream end near the transition of Coyote Creek into the marsh was eliminated and that the San Rafael Road generally followed the perimeter of the marsh except for cutting off a landward portion of the marsh. This would have reduced tidal prism in the Coyote Creek Marsh, which would have initiated narrowing of the tidal marsh channels. Tidal prism is the volume of tidal flow moving in and out of a bay or tidal channel. A reduction in the tidal prism of a marsh causes its tidal channels to shoal and narrow because they have less volume of tide flow to convey. A shoaling or narrowing of tidal channels is therefore evidence of reductions in tidal prism. The road crossing at Tennessee and Coyote Creeks probably influenced the ability of the creeks to convey their sediment loads downstream. Whether these were bridges or fords are unknown. This map is considered to be a more reliable depiction of the upland MHHW boundary than the 1868 tidelands map, particularly since it indicates survey points along the marsh perimeter. However, the reliability of the depictions of Coyote and Tennessee Creeks above their confluence is uncertain. The map shows that houses existed upstream of the southwest corner of the Coyote Creek Marsh along Tennessee Creek and at the north hillslope between Coyote Creek and Almonte Marshes. Cattle ranching and/or crop farming were likely causing increases in sediment supply to the marshes, which supports the indications of increased sedimentation in Richardson's Bay. The tidal reach of Coyote Creek downstream of its confluence with Tennessee Creek shows substantial decrease in width, since early 1850s. The same is true of Arroyo Corte Madera del Presidio along northern edge of Almonte Marsh. For example, at the site equivalent to where Flamingo Road currently crossed Coyote Creek, the channel width in 1851 was roughly 125 ft. The 1870 map indicates that it narrowed to roughly 80 ft. These changes in channel width reflect the reduction in tidal prism due to marsh reclamation and road crossings. Similar changes in channel width are evident for the Arroyo Corte Madera del Presidio watershed. The 1870 map indicates a significant difference in the planform of tidal reaches of both Coyote and Tennessee creeks upstream of their confluence. **Image Ref #16** shows a detail of Tennessee and Coyote Creeks. **Image Ref #17 and #18** show comparisons of channel position during and prior to 1870**.** By 1870, the Coyote Creek channel had been truncated where the 10.5 ac of marsh had been reclaimed. The cause of this reclamation is not known. It may have involved diking, filling, or a combination of both. The San Rafael Road was likely on an elevated berm but it is upstream of the truncated marsh.

			The sinuosity of the middle portion of tidal reach of Tennessee Creek upstream of its confluence with Coyote Creek had been significantly altered, yet its uppermost tidal reach remained the same.
1872	19, 20	SR 1 on levee across HCCM exists near shoreline	The 1872 US Coast and Geodetic Survey T-5929 **(Image Ref #19 and #20)** used the previous 1851 map information for the depiction of topography, channels, MLLW, and marsh. The only apparent updates are to the roads and agricultural activities. Interestingly, the homesteaders often located their crops on small alluvial fans at the base of tributaries rather than the main valley floors. Under natural conditions, the direction of flow down a fan is variable over time. Streams moving back and forth over the fan depositing their bedload build alluvial fans. When bedload supply is particularly high, many distributaries channels can form that effectively dispersing the sediment and building the areal extend of the fan and its elevation. When a stream has a limited supply of bedload, the flow may become confined to a single-thread channel that cuts into the fan and then re-disperses the stored sediment farther downstream. To tame the channel and to reduce the amount of flooded or saturated soils, farmers often diverted creeks into a single ditch along the middle or more commonly to one side of the fan or to the edge of the valley flat, often connecting the channel to another ditch that diverted the mainstem of the creek from the middle of its valley to the side. This maximized the area for crops and minimized the need for stream crossings. Diverting the flow into straight ditches increased flow velocity, which caused the beds and banks of the ditches to erode. The deeper ditches confined larger flows, which increased the bed erosion. This channel incision undoubtedly increased sediment supplies downstream to the remaining Coyote Creek Marsh and to Richardson's Bay. Such channel incision was likely also occurring in other local watersheds. **Image Ref #19** shows the new presence of Shoreline Road that crosses the eastern portion of historical Coyote Creek Marsh. During the 1870s, the San Rafael Road was the main wagon road between Sausalito and San Rafael (email communication from Phil Rhodes to Laurel Collins, 3/30/2017). The newly constructed State Route 1 (SR 1) along the marsh foreshore was most likely on an elevated levee or berm with a bridge crossing the mouth of Coyote Creek. It might have eliminated about 1.3 ac of the marsh, but was very likely the beginning of significant reductions in tidal prism landward of SR 1.

			The amount of historical Coyote Creek Marsh (1851) that became sandwiched between SR 1 and the marsh foreshore was ~3.7 ac.

<table>
<tr><td>1873</td><td>21,
22,
23</td><td>4000-foot-long RR trestle construction across Richardson’s Bay from Strawberry Point to Sausalito.</td><td>Based on AB Dickinson (1967) as explained by personal email from P. Rhodes ((4/21/2017):
North Pacific Coast Railroad (NPRR) was the first railroad in Richardson Bay and existed from 1871 to 1902;
The NPRR was incorporated in December 1871.
Ground-breaking at Sausalito for the NPRR was 12 April 1973;
The Daily Alta California Newspaper, 23 August 1873, reported that construction was to begin on 4,000-foot long Richardson Bay trestle;
The Daily Alta California Newspaper 15 November 1873 reported that construction of the trestle was nearing completion.
This bridge would have been the first major construction to impact wind fetch, wave generation, and local tidal circulation currents in Richardson Bay. The extent of these impacts is unknown and their effects on sedimentation within the Bay are unknown. However, it seems possible that the trestle might have interrupted wind fetch, and reduced propagation of large waves and re-suspension of mudflat sediment in the upper Bay.

The 1873 Map T-01302 (Image Ref #21) uses information from 1851 T-sheet (Image Ref #6 and #7) and does not show any obvious differences in channel planform, MLLW contour, or marsh features. The marsh pannes, however, are not depicted. This is likely an artifact of the map rather than a change in actual conditions.

The Arroyo Corte Madera Creek del Presidio shown in the Almonte Marsh detail, Image Ref #21, shows roads and agricultural activities that would likely have been influencing upland runoff and tidal processes, including changes in water and sediment supply.

The 1873 T-01302 Marin County Map (Image Ref #22) shows the same SR 1 crossing at the mouth of Coyote Creek Marsh as the 1872 T-5929 map (Image Ref #19). The new SR 1 bypassed the older road that followed the shoreline above high tide near the head of the marsh. Image Ref #22 also shows the proposed railroad from Strawberry Point to Sausalito and Image Ref #23 shows the first trestle that crossed Richardson Bay from Strawberry Point to Sausalito, well southwest of Coyote Creek.</td></tr>
<tr><td>1875</td><td>24</td><td></td><td>According to Dickinson (1967) NPRR service started from Sausalito to Tomales, 11 January 1875, using the 4,000-ft trestle extending from Sausalito to Strawberry Peninsula. This 1875</td></tr>
</table>

			map (**Image Ref # 24**) does not show a railroad across Coyote Creek Marsh and does not show sufficient detail to describe any marsh or channel changes since previous years.
1883	25	1310-foot-long trestle of NPRR crosses Coyote Creek Embayment, influencing ~47.5 ac of shallow mudflat RR levee across Almonte Marsh mutes the tides across 42.5% of Almonte Marsh	The NPRR constructed a new main rail line from Sausalito to Corte Madera includes trestle across the southern shallows of Richardson Bay, just bayward of the historical Coyote Creek Marsh (P. Rhodes personal communication). Construction began on the new railroad line on 28 April 1883 (Dickinson 1967). Based on subsequent maps (see **Image Refs #40 and #41**), the length of the original trestle was about 1,310 ft and spanned about 2,160-ft of the Bay. At its western side, it had ~47.6 ac of shallow mudflat of the Coyote Creek Embayment. The trestle was anchored at either end by a new levee totally about 850 ft in length. These berms essentially reduced the opening of the embayment by 850 ft. This effectively narrowed the western side of the embayment by about 61%. The trestle had closely spaced piers. It and the adjoining levees would have caused wave heights to be reduced on the landward side and may have also affected tidal circulation, which in turn would have promoted entrapment of sediments delivered by Coyote Creek, plus sedimentation of tidal sediments within the embayment landward of the trestle. These factors would have caused the quiet embayment landward of the trestle to shoal as tidal flat, and initiate the bayward expansion of the existing tidal marsh. The new rail line extended on a new levee across the eastern portion of Almonte Marsh, cutting off ~22.5 ac (~42.5 %) of the marsh from direct access to tidal flows from Richardson's Bay. The marshland removed from direct tidal access can experience muted tidal action, meaning the high tides are lower and the tidal flow velocities are reduced, relative to other nearby marshland with direct tidal access. Marshland can experience tidal muting because its source of tidal water, such as the mouth of a tidal channel, becomes restricted, or because a levee or berm increases the distance between the marshland at its source of tidal water. The location of the levee across Almonte Marsh can be seen on **Image Ref #40 and #41**. **Image Ref #25** does not show the changes occurring in the marshes, but it does show a major road along the perimeter of the historical Coyote Creek Marsh, and an unimproved road leading upstream along Tennessee Creek to Tennessee Valley, located across the Tennessee Creek watershed divide. Road construction could have caused an increase in sediment supply to the creeks and thus to the quiet embayment caused by the new trestle.

1884	26, 27	Hydraulic mining in Sierra Nevada ends	Hydraulic mining is halted in the Sierra Nevada (https://calisphere.org/exhibitions/14/environmental-impact-in-the-gold-rush-era/). Service started on the new rail line between Sausalito and Corte Madera constructed in 1883 on 28 April 1884 (email from P. Rhodes 4/21/2017). **Image Ref #26** shows extensive wetlands still exist west of the railroad and SR 1 but does not show the railroad trestle. **Image Ref #27 shows the** fill for the railroad levee along the southern alignment near North Manzanita Marsh, but not along the northern alignment near Almonte Marsh.
1889		Mill Valley branch of RR caused tidal prism to be muted over 50% of original (1851) AM.	The Mill Valley Branch rail line that went to the lumber mill near downtown Mill Valley was completed 13 October 1889 (Dickinson 1967). As a result, an additional ~4 ac of Almonte Marsh sandwiched between the Mill Valley and San Rafael Branch lines became subjected to muted tides. Total aces of tidal marsh influenced by muted tidal action equaled ~ 26.5 ac. This represents about 50% of the original (1851) Almonte Marsh area.
1890s	28, 29, 30	Probable local creek flooding	**Image Ref #28, #29, and #30** show photographs of conditions near historical Coyote Creek and Almonte Marshes during the 1890s. Service on Mill Valley rail line started 17 March 1890. Based upon analysis of numerous local historical rainfall records (Goodridge 1995, Collins 2001; Gilbert 1917), 1890 was a year that could have caused local flooding and therefore generated pulses of sediment to Richardson's Bay from local watersheds.
1892	31, 32, 33	Tennessee and Coyote Creeks appear ditched to sides of their valleys	The 1892 Map by Dodge (**Ref Slide #31**) appears to use much of the same mapping information shown in the 1873 Marin County map (**Image Ref #22**) for the depiction of historical Coyote Creek and Almonte Marshes. It incorporates the No. 7 Salt Marsh and Tidelands Sales Map (**Image Ref #15),** to show potential bayland parcels. It therefore cannot be used for assessing mars, and channel change. It does show new information pertaining to the alignment of railroad and its branches to Mill Valley and San Rafael. The 1892 Tamalpais Land and Water Co. Map (**Image Ref #32 & #33**) show changes in the alignments of Coyote Creek and Tennessee Creek, but cannot be used for assessing changes in their width. The map shows that Tennessee and Coyote Creeks rerouted into ditches at the sides of their valleys. In addition, the 1892 map shows a new northward bend in Coyote Creek just upstream of the mouth of the tidal reach of the creek. There is no clear explanation for

			this new bend but one possibility is that it was associated with constriction that might have happened upstream of the SR 1 bridge. The Mill Valley Lumber Company was founded by Captain Robert Dollar to provide lumber for a booming steamship business. The lumber company became a focal point for growth for San Francisco after the 1906 quake and fire (http://www.marinij.com/article/ZZ/20060402/NEWS/604029992). It is unclear if this meant that logging activities resumed on Mount Tamalpais. It seems that the lumber company relied on the railroad to transport products to market rather than commercial navigation of Richardson Bay.
1894	34, 35	RR trestle made smaller, reducing size of inlet of Coyote Creek embayment to 125 ft Probable local creek flooding	Based upon analysis of numerous local historical rainfall records (Goodridge 1995, Collins 2001; Gilbert 1917), 1894 was a year that could have generated flooding in local watersheds and pulses of sediment to Richardson Bay. **Image Ref #34** is a 1913 geologic map that relies on Coast Survey mapping done in 1894-95 to depict marshlands. It shows very broad tidal channels through the interior historical Coyote Creek Marsh. It also shows the confluence of Tennessee and Coyote Creeks to be in a similar location as shown in **Image Ref #33 (**from 1892**)**. The map indicates that the railroad across the Coyote Creek Embayment has a double track south of the Mill Valley Junction by this year. The rail line changed ownership and became the Northwest Pacific Railroad (NPR). The older railroad levees that anchored the railroad were widened to accommodate two lines, and they were lengthened, which shortened 1310-ft trestle to 125 ft in total length. The rail line was converted from narrow gage to standard gage (5/30/2017 verbal communication NWPRR Historical Society). Picture 1 in **Image Ref #35** shows the resized railroad levee in Sausalito. Detailed mapping of the upgraded railroad levee and trestle at the Coyote Creek Embayment is shown in T-Sheet 5929 (**Image Ref #64**). The much shorter trestle and much longer levee substantially altered the hydrological connection between Richardson's Bay and both the Coyote Creek Embayment and its watershed. The 1894 restricted inlet to the Coyote Creek Embayment likely caused: 1) a reduction in tidal prism to the embayment; 2) near elimination of wind-generated waves within the embayment; and 3) a greater potential for flooding upstream of SR 1 when high tides coincided with large rain storms and flood flows from Coyote Creek. These factors would tend to increase sedimentation within the embayment.

			Picture 2 of **Image Ref #35** shows the junction of the Mill Valley and San Rafael rail lines along Almonte Marsh. The marsh along the west side of the Mill Valley branch appears dryer, perhaps due to the muted tides caused by the Railroad levee constructed along the eastern foreshore of the marsh in 1883.
1898	36, 37		The Mill Valley Branch of the rail line pictured in **Image Ref #36** was taken in 1898 and shows sparse development in the background hills. It seems likely that the previous undated picture 2 photo of **Image Ref #35** post-dates **Image Ref #36** because it shows much more hillside development. The Mill Valley branch further dissected Almonte Marsh, restricting tidal flow to the marshlands on the western side of the tracks to small culverts beneath the railroad levee. This further reduction in tidal prism and resulting poor drainage caused the former channels on the west side of the tracks to become pannes or potholes. Much of the marsh vegetation in the backshores of Almonte Marsh during this time appears to be dominated by pickleweed or other low-growing, salt-tolerant vegetation. **Image Ref #37** shows what appears to be a narrow channel in the mudflats connected to the inlet to the Coyote Creek Embayment at the recently shortened trestle. This image also shows an area of light shading at the flatlands between Coyote Creek and Tennessee Creek. The shading is consistent with reflection off standing water. The area may be ponded due to flooding or irrigation. The tides are low in this image, suggesting that any flooding upstream is not tidal. The abandoned 4000-ft-long railroad trestle across Richardson's Bay between Strawberry Point and Sausalito can be seen very faintly in the background of **Image Ref #37**.
1899	38, 39, 40, 41	~32 ac of tidal marsh above the confluence of Coyote and Tennessee Creeks is eliminated The total loss of marsh by 1899 is 42% of the original 1851 HCCM acreage	The 1899 UC Coast and Geodetic Survey Map T-02485 (**Image Ref #38)** shows that the tidal marshland within the lower reaches of the Coyote and Tennessee Creek valleys had been reclaimed. The tidal channel of Coyote Creek upstream of its confluence with Tennessee Creek appears to have been rerouted into a ditch at the north side of its valley. Tennessee Creek still exhibits naturalistic meanders for a short distance upstream of its confluence with Coyote Creek, but farther upstream it appears to have been routed into a ditch running down the middle of its valley. These are substantial changes in the plan form of the creeks since 1892. It is likely that the channels were undergoing continuous change. For example, sedimentation might cause them to abandon their ditches and reoccupy older channel courses, and then again be subjected to ditching.

		South Bothin Marsh begins to evolve within the Coyote Creek Embayment	The width of Tennessee Creek at the present-day crossing of Flamingo Road decreased in width from about 80 feet in 1870 to about 23 feet by 1899. The channel is in a slightly different position than previously mapped in 1892. This 1899 map shows Tennessee and Coyote Creeks mapped as a single line upstream of their confluence with each other. Previously they were mapped as double lines. This indicates that channel narrowing continued and was primarily due to reduced tidal prism and possibly to a lesser degree, increased upstream sediment supply. Marsh is not depicted upstream of the confluence of Tennessee and Coyote Creeks. There is no map evidence of natural or artificial filing of the valley above the confluence with sediment. one possibility is that either the construction of SR1 elevated levee plus the increasingly narrower Coyote Creek channel and the smaller inlet created by the shorter railroad trestle across the Coyote Creek embayment caused the tides to be more muted, so much so that the tides could not reach upstream beyond the confluence. Alternatively, a levee might have been placed along the lower meander of Tennessee Creek that extended to the Coyote Creek confluence. In either scenario, ~33 acres of the historical Coyote Creek Marsh were eliminated. By 1899, only about 32 acres (42%) of HCCM remained. Between 1856 and 1899, Coyote Creek Marsh expanded into the Coyote Creek Embayment. About 7 ac of mudflat evolved into tidal marsh. This was the beginning of what is now referred to as South Bothin Marsh. The railroad also reconfigured the marshlands. About 10.5 ac of the North Manzanita Marsh were enclosed by the railroad and thus became part of the Coyote Creek Embayment. About 6.5 ac of the North Manzanita Marsh remained open to Richardson's Bay. As of 1899, South Bothin Marsh totals ~17 ac, including the ~6.5 ac of newly formed marsh plus the addition of ~10.5 ac of the North Manzanita Marsh. In total, ~49 ac of tidal marsh existed in the Coyote Watershed upstream (west) of the railroad tracks. Almonte marsh slightly increased in area to ~52 ac by expanding northward into the Arroyo Corte Madera del Presidio, as the channel narrowed and migrated northward. The east side of Almonte Marsh and North Manzanita Marsh were the only remaining segments of marsh with full access to tidal waters unimpeded by the railroad or other infrastructure. In other words, it had a fully functioning tidal prism.

1900	42, 43		The 1900 photo in **Image Ref #42** shows the double rail system and its levee that replaced the 1300-ft-long trestle along the Coyote Creek Embayment. This supports the proposed date of 1894 as stated by historians at the NWPRR historical Society (5/30/2017 verbal communication to L. Collins). The Tam Valley Sale map (**Image Ref #43**) shows the layout of the former Coyote Creek marshlands upstream of the Tennessee Creek confluence. The rendering seems to indicate a levee or wall that might be associated with the 1870 loss of ~10.5 acres of marsh (see **Image Ref #16 and #17**). The image also shows a break in slope near Spruce Street, which probably represented the toe of an older alluvial fan built by Coyote Creek. The tidal transition zone, where the sausal had been located, was between Poplar (previously Oak) and Spruce Streets. Based on the 1851 map (**Image Ref # 6**), the head of tide within the creek was just slightly upstream of Poplar Street Field observations from 2017 indicate that the present-day head of tide might be only slightly further downstream, near Laurel Way (previously Main Street). This is based upon cursory reconnaissance observation. The correspondence between historical (1851) and present-date head of tide suggests that the historical muting of the tide has been relieved by the construction of the Coyote Creek Canal and upstream flood control channel.
1901	44	Increased subtidal area	The 1901 Nautical Chart (**Image Ref #44**) shows that the subtidal area of Richardson Bay (i.e., the area below the MLLW contour) has slightly expanded westward along the centerline of the Bay and northward since 1870. These subtidal areas evidently deepened. It reasonable to speculate that the tidal prism of the Bay as a whole was adequate to remove the sediments that had accumulated along the Bay bottom during the period of intensive logging, grazing, and other forms of agriculture.

1902-03 1903	45	Narrow gage RR converted to standard gage Electric train third rail system begins	Service ends for the 4000-ft railroad trestle spanning Richardson Bay between Strawberry Point and Sausalito. It is not clear when the trestle was removed. As the wooden railroad trestles across tidal flats and marshes deteriorated they were largely replaced with levees fill. Tidal flow was not initially impeded as much as it was later when levees replaced the trestles. This conversion is not always dated but some of it might have been done when the Richardson Bay line was electrified in 1902-03 with a "third rail" system of the North Shore Railroad which took over the rail line some tie in 1902 (Phil Rhodes email to L. Collins 4/21/2017). Road Map of Marin County (**Image Ref # 45**) indicates that the watershed south of Tennessee Creek was called Elk Valley (now called Tennessee Valley) and that Coyote Creek Valley was called Coyote Hollow. A "Milk Ranch" was located near the former backshore of historical Coyote Creek Marsh.
1904	None	Probable local flooding	Based upon analysis of numerous local historical rainfall records (Goodridge 1995, Collins 2001, Gilbert 1917), 1904 was a year that could have generated flooding in local watersheds and pulses of eroded sediment into Richardson Bay.
1905	46		This 1905 Map of the San Francisco Entrance (**Image Ref #46**) shows the same channel and marsh features as the 1899 T-sheet 0214785 (**Image Ref #38).**
1906	47		A 1906 photo of Richardson Bay looking eastward shows the sparse development of the land around the Bay (**Image Ref #47**). On December 18, 1906, voters decided to create a new high school called Tamalpais (Tam High). About 2.8 acres were purchased for $2,800, plus an additional ~5 acres of marshland for $509. The railroad soon added a special stop on its line to service the school.
1907?	None		Northwestern Pacific Railroad was incorporated 7 January 1907 as an amalgamation of several railroads including the North Shore. Initially it was owned by Southern Pacific (SP) and Santa Fe railroads. Santa Fe later sold their interest to SP (Dickinson 1967).
1908	48, 49, 50		First building at Tam High was Wood Hall, constructed in 1908 (**Image Ref #48 & 50**). http://thetamnews.org/lifestyles/tamalpais-high-school-an-architectural-history/ These photos also show the railroad levee that restricted the flow of tidal waters to and from the marshes west of the tracks, which likely resulted in reduced marsh surface sedimentation, greater desiccation, and probable subsidence of the marsh surface.

			The Marin County Water Map (**Image Ref #49**) does not show changes in marsh or tidal channels. It does however depict the 1870 loss of ~10.5 ac marsh in the Coyote Creek drainage.
c. 1910	51		The c. 1910 photo (**Image Ref #51)** shows that the marshes along the various embayments of the Sausalito shoreline have not been filled landward of the railroad levee. They were all filled at later times.
1915	52, 53, 54		The 1915 USGS topographic map of San Francisco and Vicinity (**Image Ref #52)** cannot be used to assess channel and marsh change since it has a range of mapping dates from 1894 to 1913. It shows the same channels that were indicated on the 1894-1895 US Coast Survey map shown in **Image Ref #34**. The 1915 photo of Tam High (**Image Ref #53**) shows a portion of Almonte Marsh that documents the muted tidal conditions created by the railroad levee of the Mill Valley branch line. The photo shows a former 1851 tidal slough along its landward bend that used to be at least 45 ft wide, but by 1915 had substantially narrowed and shoaled. The 1915 San Francisco Entrance map (**Image Ref #54**) cannot be used to assess tidal channel or marsh change because it shows the conditions based on the 1899 mapping and bathymetry.
1916	55		The NPR map shows a portion of Arroyo Corte Madera del Presidio tidal channel that was influenced by the railroad levee. This is the same channel bend that can be seen in **Image Ref #57**. In 1851 the channel was at least 220 ft wide in this vicinity, but the bridge over it in this 1915 map is only 106 ft long. The 1851 channel demonstrated a fairly consistent width upstream and downstream of the bridge location. The Mill Valley branch of the railroad had been constructed in 1889, but the San Rafael branch was constructed in 1883. If it is assumed that the Arroyo Corte Madera del Presidio bridge was reconstructed in 1894, while the single rail track was converted to double, the channel must have lost 114 ft of its width between 1895 and 1851 (43 years). This represents an average rate of narrowing (or infilling of the marsh) of about 2.6 ft/yr. Undoubtedly the railroad levee of the San Rafael branch muted the tidal flows in this reach of the Almonte Marsh. The tides were even more severely muted in the marshes west of the Mill Valley branch line, where tidal access was only through a 10 in x 12 in x 35 ft box culvert (**Image Ref 55)**.

			The train depot on the Mill Valley Branch at Tam High was called High School, while the depot on the San Rafael-Sausalito line, south of Tam High was called Almonte.
1917	None		"… contractors completing the portion of road between Manzanita street, near Waldo station, and Coyote Creek bridge is one of the problems that is occupying the attention of the state highway engineers (03/31/1917). https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=SN19170331.2.5&srpos=9&e=-------en--20--1--txt-txIN-Coyote+Creek%2c+Mill+valley-------1 Note that Waldo station is near Manzanita Marsh, as shown in **Ref Image 61**.
Early 1920s	56	c. early 1920s artificial levee for power poles in AM and HCCM	Levee construction started to appear west of the Mill Valley railroad branch in Almonte Marsh. Based on 1923 photos and 1924 Coast Survey maps (**Image Ref #56 and #62**), it appears that an artificial levee was constructed during this time in Almonte Marsh and Coyote Creek Marsh to protect a power line corridor. It is not clear exactly when the power poles were placed in the marsh but it is estimated that it was around the mid 1920s. The power poles are indicated on a US Coast and Geodetic map dated 1927 (**Image Ref #64**).
1923	57	Only 50% of Almonte Marsh remains west of the RR	Sports fields, buildings, and artificial fill have been constructed on the west side of the Mill Valley railroad branch on Almonte Marsh by the end of 1923. The Garcia Associates letter of 12/16/16 states that the railroad tracks across Bothin shoreline might have changed from trestle to berm between 1923 and 1949. The evidence presented in this 2018 Watershed Sciences report indicates otherwise, that it happened long before in 1883 in South Bothin Marsh and Almonte Marsh. The photo shows that new marshland has in-filled the original 1851 channel of Arroyo Corte Madera del Presidio. It also shows about 6 ac of marsh had been eliminated near Tam High School. Maps indicate that it is likely that an additional 2 ac of Almonte Marsh had been eliminated west of the San Rafael Road (presently Homestead Blvd).
1924	58, 59, 60	Total area of AM ~35.5 ac and ~99 ac of marsh forms bayward of a c. 1920 levee	Using combined information from the 1924 map (**Image Ref #58**) and the 1923 photos that show development of Tams High School in the former Almonte Marshlands (**Image Refs #56 & #57**), it appears that by 1924 at least 19.5 ac of Almonte Marsh west of the San Rafael branch line tracks had been eliminated by placement of berms and artificial fill.

		Area of shallow mudflats in Coyote Creek Embayment is 63% of original size.	**Image Ref #58** shows a possible cable crossing or pier to deep water at the southern edge of the railroad levee at Manzanita Marsh. **Image Ref #59** shows ~10 ac remaining of Almonte Marsh west of the railroad tracks. This remnant likely had very muted tides because tidal access was only through small culverts beneath the tracks. About 36 ac of marsh existed east of the San Rafael branch rail, of which ~12 ac were relatively new marsh, having formed new shoreline since 1899. The approximate estimates for eliminated and remaining Almonte Marsh include the 1851 tidal channels that were previously wide enough to be mapped as double lines rather than single. The amount of shallow mudflats in the Coyote Creek Embayment west of the railroad tracks decreased to ~30 ac from ~40.5 ac in 1899, representing 63% of its original extent (~47.5 ac). In the 1924 map (**Image Ref #58**), an artificial levee c. 1920 is shown along the entire bayward shoreline of both Almonte Marsh and the newly forming South Bothin Marsh. In Almonte Marsh the levee would have reduced direct tidal access to the marsh from the Bay. Tides would have accessed the marsh from the banks of Arroyo Corte Madera del Presidio. This would have reduced the potential for the reformation of the natural overwash berm that characterized the 1851 foreshore of Almonte Marsh. By 1924, Arroyo Corte Madera del Presidio, near its railroad crossing, as seen previously in **Image Ref #55,** had narrowed to about 65 ft from its original (1851) width of 230 ft. In South Bothin Marsh (**Image Ref # 60**), the c. 1920 levee closely followed the perimeter of Shoreline Highway. Only a small portion of the original HCCM had its foreshore open to the tides. Tides west of SR 1 probably had become severely muted as indicated by the increasing narrowness of the remaining tidal marsh channels. It is not clear how much the SR 1 Bridge might have affected the upstream tidal prism because accurate maps of channel features for this time period were not found. East of SR 1, ~12 ac of new South Bothin Marsh evolved into the embayment between 1899 and 1924. Coyote Creek extended its tidal channel about 650 ft eastward within newly built marshland.

			By 1924, the total amount of tidal marsh west of the railroad levee in the Coyote Creek drainage was about 58 ac. This included ~12 ac of newly forming South Bothin Marsh, ~10.5 ac of the former North Manzanita Marsh, ~32 ac of the historic Coyote Creek Marsh west and ~3.5 ac east of the SR 1. The ~43.8 ac of marsh that had been eliminated from the HCCM were likely used for dairy and agricultural purposes. These are land uses that tend to generate considerable amounts of eroded sediment. It has not been determined if the head of Richardson Bay was dredged this early. It seems the only dredging conducted by this time was to build levees for marsh reclamation. There is no apparent map evidence at this time that commercial or other kinds of ship travel was impeded by shoaling of the Bay or that there was a need for commercial marine transportation at the head of the bay. Access to the railroad and SR 1 reduced the need for commercial maritime navigation. It is assumed that the primary need for maintaining navigability was for access by dredges that were busy creating levees to convert marshlands to future developments.
1925	61		The hiking map of Marin (**Image Ref # 61**) shows that hiking trails led from both Coyote Creek and Tennessee Creek to the Pacific Ocean. The trail along Tennessee Creek was already a road through the length of Tennessee Valley and half way into Elk Valley (presently Tennessee Valley), leading to and from Tennessee Cove. Construction of this road would have increased sediment supply into Tennessee Creek and thus into the Coyote Creek Embayment.
1926	62, 63		The 1926 Coast Survey Chart (**Image Ref #62**) does not show relevant information to assess and landscape change. The photo (**Image Ref #63**) shows an aerial view of Almonte Marsh and the once greater extent of the Mill Valley marshland.
1927	64, 65, 66, 67	Area of shallow mudflats in Coyote Creek Embayment is 45% of original size Coyote Creek delta/alluvial fan forms in Coyote Creek embayment	Almonte Marsh continued to expand northward into Arroyo Corte Madera del Presidio as the channel narrowed and migrated westward, eroding some of the pre-existing 1924 shoreline, including a portion of the c. 1920 levee along the creek mouth. **Image Ref #64** shows the “bulb” of Almonte Marsh that comprises the inside of a large meander bend of the Arroyo Corte Madera del Presidio at its north end. The bulb can also be seen clearly in the previous photo, **Image Ref #63.** The c. 1920 levee might not have been high enough to prevent overtopping by waves at high tide. It was probably only built high enough to potentially facilitate construction of the power line corridor. Small tidal channels extended through the levee as the marsh prograded eastward.

		East Bothin Marsh starts to form North Manzanita Marsh expands	**Image Ref #65** shows the total area of Almonte Marsh east of the tracks. In 1927, it covered ~38 ac, only a couple of acres less than it covered in 1924. The small muted tidal area west of the tracks also decreased in size by ~1 ac for development. This small remnant of muted marsh is here referred to as Tam Marsh, which for the purposes of this study is considered part of Almonte Marsh. A remnant piece still exists today but is not property of Marin County Parks. This remaining marsh segment was not indicated on the 1927 map (**Image Ref #64**). This 1927 map (**Image Ref #64**) is the first to indicate the power line corridor and location of the power poles that extend through Almonte and North Bothin Marsh. It is assumed that a boardwalk was constructed contemporaneously, although it might have been constructed somewhat earlier in the 1920s because the levee that was placed to facilitate construction appears on a 1924 map (**Image Ref #58**). Based upon the differences in the 1923 and the 1927 maps, the Coyote Creek Embayment seems to have experienced rapid conversion from mudflat to marsh, while the width of Coyote Creek within the embayment narrowed substantially (**Images Ref #66 and #67**). **Image Ref #66** shows the amount of mudflats in the Coyote Creek Embayment west of the railroad tracks had decreased from ~30 ac in 1923 to ~21.5 ac in 1927, representing 45% of its original 1851 extent, which was ~47.5 ac. By 1927, the sharp bend in the Coyote Creek tidal channel upstream of the SR 1 Bridge had been straightened, and ~2 ac of marsh had been eliminated along the southern bank of the bend. About 150 ft upstream of the bridge the channel abruptly changed in width from about 73 ft to about 23 ft. Near the present-day Flamingo Road crossing, the channel was mapped as a single line rather than a 25-foot-wide channel. The remaining historical Coyote Creek Marsh was ~40 ac, but had muted tides and might have been a mixture of muted tidal and non-tidal seasonal wetlands. By 1927, the tidal channel of Coyote Creek had built a fan along the backshore of South Bothin Marsh and thus extended its mouth northeastward almost 700 ft relative to its 1924 position. The width of the channel South Bothin Marsh before its northward extension narrowed to about an average of 40 ft where previously it had been more than 160 ft wide. By 1927 South Bothin Marsh had growth to ~33.5 ac. Historical Coyote Creek Marsh, was now

			comprised of ~3 ac east of SR 1 and ~37.5 ac west of SR 1. The total amount of tidal wetland in the Coyote Creek watershed west of the railroad levee was therefore ~74 ac. To the east of the railroad tracks, East Bothin Marsh developed ~0.2 ac of fringing marsh along the outboard toe of the railroad levee. North Manzanita Marsh expanded northward ~13 ac. At some point perhaps around 1927, the original San Rafael Road that roughly traced the backshore of the historical Coyote Creek Marsh became Tennessee Road on the east side of the marsh, Marin Ave to south, SR 1 to the west, and Almonte Blvd north of SR 1 (**Image Ref #67**).
1929	68	Sediment supply to Bay likely increases from post-fire erosion caused by Tamalpais/Mill Valley Fire	It is reasonable to assume that the 1929 Mount Tamalpais fire significantly increased the supply of sediment to Arroyo Corte Madera del Presidio and thus to upper Richardson Bay, in the vicinity of Almonte Marsh. The fire burned 2,500 ac of the creek's watershed over a three-day period, July 4-6, in an area prone to fire-induced erosion (Spittler 1988).
1931	69, 70, 71	Redwood Bridge over Richardson Bay opens Period of filling of Richardson Bay begins	The first Richardson Bay vehicle bridge was originally constructed of redwood and called the Redwood Bridge and opened in November 1931 (**Image Ref #69**). The drawbridge section near the northern edge of the bridge provided a 40-foot wide channel to access the head of Richardson Bay during high tide. It was seldom used during low tide. A view of the bridge construction at low tide can be seen in **Image Ref #70**, with South Bothin Marsh in the background. During the 18-year period from 1931-1949, the drawbridge opened only six times (Information sign of Marin County Parks at Bothin Marsh). The northern anchor and ramp of the bridge required extensive filling of the Bay north of De Silva Island (see **Image Ref #68**). This marked the beginning of ongoing and extensive filling of the Richardson Bay for decades, both upstream and downstream of the Redwood Bridge, including many parts of the Sausalito shoreline. A remnant of the c.1920 artificial levee associated with the power transmission corridor along the foreshore of Almonte Marsh is evident in **Image Ref #71.** Toward its southern shore the levee appears to be breached or eroded away and water can be seen to the base of the power pole nearest to the railroad levee.

1932?	72, 73	Fill placed in the northern upper Richardson Bay Additional levee construction AM	**Image Ref #72** shows the sinuosity of Coyote Creek in its embayment and that the creek transported sufficient sediment from its watershed to continue building an alluvial fan/delta and contributing to the formation of mudflat and tidal marsh. Two levees of different age can be seen that parallel the long North-South axis of Almonte Marsh, c. 1920 and c. 1930. Several other levees of the same possible vintage can be seen in the historical Coyote Creek Marsh and South Bothin Marsh. One is inboard of the foreshore and the others are on the west side of SR 1. These levees are mapped in yellow on a 1946 photo (**Image Ref #73)**. Very minor commercial development had occurred by 1932 along SR 1, mostly at the northern edge of South Bothin Marsh. Extensive artificial fill had been placed for the northern span of Hwy 101 beyond the Redwood Bridge. It can also be seen that sediment had started to accumulate at the southern piers of the bridge downstream of the mudflat channel leading from the opening to the Coyote Creek Embayment. This sediment is likely derived from Coyote Creek Marsh; the sediment transported from Arroyo Corte Madera del Presidio is more likely upstream and in the deep channel beneath the drawbridge.
1936	None	Impact of shoaling on navigation noted for upper Richardson Bay	This narrative was extracted from the Sausalito News (No. 3, 17 January 1936): "The story of a once useful waterway gone to waste by becoming more shallow with the passing years and how it can be converted into a useful harbor that will spell prosperity for this end of Marin was told to U. S. Army engineers at War Department hearing in the City Hall on Wednesday afternoon. And, there was revived the plan studied 25 years ago [1911] or so to cut a ship canal through a gap in the hills to the Pacific Ocean at Tennessee Cove, a scheme that sounds almost fantastic at first blush but which, upon careful study, appears quite feasible and at the same time would offer a means of scouring a channel through the sixty to eighty feet of mud that fills Richardson Bay except for the shallow covering of water at high tide." file:///Users/laurelco/LAUREL03/Bothin%20Marsh/Bothin%20Literature/Sausalito%20News%2017%20January%201936%20%E2%80%94%20California%20Digital%20Newspaper%20Collection.html In this excerpt referencing 60 to 80 feet of mud, it is assumed to be referring to the total amount of bay mud above underlying bedrock in Richardson Bay. The idea of cutting a new opening to the bay through Tennessee Valley was presumably not further pursued. This proposal clearly was not carried forth but it is interesting to note that it was initially proposed in 1911.

1937	None	Golden Gate Bridge built	Completion of the Golden Gate Bridge (it was started in 1933) initiates a building boom that leads to the need for additional highway construction in Sausalito and Mill Valley. The increased development in the Coyote Creek and Arroyo Corte Madera del Presidio undoubtedly increased the local sediment supplies to upper Richardson Bay.
1940	None	Electric rail service ends and freight service begins	Electric rail and passenger service to Mill Valley ends 1 October 1940 (P. Rhodes 4/21/2017 email). The rail line begins to support freight service in 1940's(P. Rhodes 4/21/2017 email). Richardson Bay Cleanup Set: Sept 14, 1940: " Richardson Bay is going to be cleaned up. All the old windjammers and discarded steamer hulks that have been reposing quietly in the shallow bay graveyard will soon be pulled forth and destroyed completely. Notice was given yesterday by the United States Army engineers that on next Tuesday, bids will be received for the removal of the hulks. "The wrecks which it is proposed to do away with include the former steam schooner Helene and the remains of the barkentine Echo, which last year was burned to the water's edge by the Richardson Bay Yacht Club and which since that time has given the Coast Guard boys several uncomfortable hours chasing its drifting carcass down . . ." (Newspaper clipping at California Room, Marin Civic Center Library).
1942	None	Artificial fill increases in Richardson Bay	Wartime ship construction began in Sausalito at what was then known as Marinship. An estimated 838,763 cubic yards of earth and rock were excavated from Pine Point, Waldo Point and nearby areas. The resulting fill was spread using heavy equipment across the shoreline and tidal mudflats at Sausalito to create new land on which the various buildings of the shipyard were rapidly constructed (https://en.wikipedia.org/wiki/Marinship).
1945	None		The Sausalito News (No 30, 26 July 1945) reported that: "Richardson Bay Dredging Urged by State Chamber. A region-wide program for the early development of six north coast harbors to stimulate postwar expansion of commerce, industry, fishing, lumber shipments and other activities that will increase the wealth of this region has received the backing of the North Coast Council of the California State Chamber of Commerce. Proper maintenance and dredging of the channel in Richardson Bay as far as the Marinship yards is the council's goal for Sausalito, it was stated. This channel is rapidly filling, It was reported to the council by President Harry Braun, and Director J. Herbert Madden of the Sausalito Chamber of Commerce, who requested the state body to aid in helping to alleviate the local condition." Sausalito News (March 1, 1945) reported: "For the third time in recent years the Richardson Bay drawbridge was raised to allow passage of the dredge Liberty to dig out the yacht harbor

			Marvel Mar and to begin work piling up land behind the cottages to make more land available for development. The dredge was expected to operate for two weeks (included in 4/21/2017 email from P. Rhodes). This article refers to previous dredging in Richardson Bay but documentation of it has not been found.
1946	73, 74, 75	Sediment deposition continues at southwestern piers of Redwood Bridge	The 1946 aerial photo (**Image Ref # 73**) further reveals the extent of additional levees that might have been constructed c. 1920s and 1930s in the historical Coyote Creek and South Bothin Marshes and during the 1930's in the Altamonte Marsh. Artificial filling had continued in the Coyote Creek watershed, particularly along SR 1. **Image Ref #74** shows that by 1946 Almonte Marsh was about 1.5 ac smaller than it was in 1927. This is due to marsh erosion along the inside bend of the large downstream meander of the Arroyo Corte Madera del Presidio. A portion of the c. 1920 levee was eroded away at the channel bend as well as at the southern end of the marsh, where the c. 1930s levee and the c. 1920s levee converged. The Tam Marsh diminished in size by 1 ac due to artificial fill. **Image Ref #75** shows that by 1945, the historical Coyote Creek Marsh had decreased to about 33.5 ac on the west side of the road and on the east side it decreased to about 3 ac. Given the number of levees and distance from the tidal source, and narrowness of the remaining tidal channel of Coyote Creek, it is likely that much of the Historical Coyote Creek Marsh west of SR 1 was converting to a mixed brackish tidal/seasonal marsh due to the diminished tidal prism. The tidal flats of Coyote Creek Embayment decreased in size to ~16.5 ac (35% of its original 1851 acreage). The size of the South Bothin Marsh increased its size from ~33 ac in 1927 to ~34 ac. The total amount of tidal marsh in the Coyote Creek watershed west of the railroad levee totaled ~70.0 ac. It is apparent in these images that sediment accumulated downstream of the subtidal channel of Coyote Creek at the Redwood Bridge. The evidence is the sizable sediment bar at the southwest pilings. It seems likely that, as Coyote Creek extended itself eastward and then northward within the Coyote Creek Embayment, sediment transport from the creek into the bay via the subtidal channels accelerated. East Bothin Marsh had slightly increased in size from ~0.2 ac in 1927 to ~0.25 ac in 1946.
1949	76	Redwood Bridge decommissioned.	Redwood Bridge over Richardson Bay was decommissioned in 1949 (information sign along Bothin Marsh, Marin County Parks). A cable crossing is shown to cross Richardson Bay to

		New concrete bridge built for Hwy 101	either side of the Redwood Highway 101 Bridge and portions of Manzanita and South Bothin Marshes (**Image Ref # 76**).
1950	77, 78, 79	ACMdP straightened upstream of railroad bridge	Increased artificial fill along SR 1 is evident in **Image Ref #77**. The fill reduces the Historical Coyote Creek Marsh to ~30 ac on the west side of SR 1 and to ~2 ac on the east side. South Bothin Marsh had ~4 ac of artificial fill but it also continued to prograde toward the railroad levee within the Coyote Creek Embayment resulting in only a slight increase in total tidal marsh acreage to ~33.5 ac. **Image Ref #78 and #79** shows increasing fill near the Tam Marsh and the area of marsh between the Mill Valley and San Rafael branches of the railroad at Almonte Marsh. **Image Ref # 79** provides unobstructed detail of Almonte Marsh, revealing a new straight canal cut through a former meander in Arroyo Corte Madera del Presidio upstream of its railroad bridge.
1952	80, 81	Less than 3% HCCM remains east of SR1 as land development accelerates Only 54% of former marshland west of SR1 remains	**Image Ref #80** shows the conditions of the study area in 1952 and **Image Ref #81** shows polygons that indicate change in marsh acreage since the mid to late 1940s. Almonte Marsh increased to ~39 ac following 1946. About 37 ac were east of the RR levee. This was probably mostly due to the extension of the northern bulb at the bend in Arroyo Corte Madera del Presidio. The muted tidal marsh south of Tam High decreased in size from ~3 ac to ~1 ac. It is worth noting that the material dredged during the straightening of Arroyo Corte Madera del Presidio west of the railroad bridge was spread discontinuously to either side of the new channel, without blocking tributary tidal marsh channels, rather than being used to construct containment levees. Less than 3% of the historical (1851) Coyote Creek Marsh existed in 1952, represented by the ~3 ac marsh remnant just east of SR 1. Development had begun to spread across the remaining Historical Coyote Creek Marsh west of SR 1. Coyote Creek and Tennessee Creeks in the historical marsh upstream of SR 1 become completely ditched. These activities surely increased sediment supply to Coyote Creek, South Bothin Marsh, the enclosed embayment, and Richardson Bay. The reduced tidal prism caused by upstream marsh reclamation decreased the power of the ebb tidal flows to move sediment through the tidal channels to Richardson Bay. This coupled to the increase in sediment delivery promoted sedimentation within the Coyote Creek Embayment.

			A network of gullies is apparent in the steep, small tributaries of the northern hillsides in the Coyote Creek watershed. The existence of these gullies supports the contention that earlier heavy grazing led to increased runoff and erosion that augmented the terrigenous sediment supply to the Bay. **Image Ref #80** shows colonies of cordgrass moving out onto the mudflats of the embayment. Total acreage of marshland west of the railroad levee (South Bothin Marsh plus historical Coyote Creek Marsh) was reduced to ~37.5 ac, about 54% of its size in 1946. Marsh expansion in the Coyote Creek Embayment caused a reduction in the total acres of mudflat from ~16.5 ac in 1946 to ~12 ac in 1952. North Manzanita Marsh and East Bothin Marsh had merged by 1952 in area of marshland covering ~7 ac, but individually they had ~6.0 ac and ~0.9 ac, respectively. The North Manzanita Marsh portion of this marshland became smaller as levee building and artificial filling proceeded at is southern edge.
05/28/ 1953	None	Dredging operations resume in Richardson Bay	The Sausalito News, #22, 28 May 1953 reported that: "Richardson Bay Bridge [Redwood Bridge] was closed last night at 10 o'clock and traffic was rerouted for about 40 minutes . The bridge was closed to allow a dredge to pass through to the Zaro Yacht Harbor, where dredging operations are being resumed." https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=SN19530528.2.6&srpos=6&e=-------en--20--1--txt-txIN-dredging+richardson+Bay-------.
10/01/ 1954	None	Dredging continues in upper Richardson Bay	Sausalito News, #39, 1 October 1954) reported "dredging operations were started this week north of the Richardson Bay bridge to accommodate the equipment, which will be used for construction of the new Richardson Bay bridge. Construction of the new span is expected to start within the next week or two." https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=SN19541001.2.5&srpos=1&e=-------en--20--1--txt-txIN-dredging+richardson+Bay-------1.
Dec 1955	82 83	Significant flooding throughout the Bay Area due to intense rain	Flood at Arroyo Corte Madera del Presidio was caused by 9 inches of rainfall over the watershed that resulted in a peak discharge of 1400 cfs at the Camino Alto Bridge (USACE 1968). Flooding was widespread and ultimately led to the start of many flood control projects that straightened and diverted channels throughout Marin County.

			Specific areas of flooding can be seen in Tam Valley in **Image Ref #82 and #83**. (Madrone Assoc. 1975).
1956	84	Concrete Hwy 101 bridge construction begins Containment levee started east of AM shoreline	A new concrete Richardson Bay Bridge was under construction during 1956. This may have permanently isolated and diminished portions of North Manzanita Marsh. **Image Ref #84** shows that a new levee was constructed of dredge spoils well over 600 feet offshore of the Almonte Marsh. It is presumed that this levee was being constructed to contain dredge spoils and thus reclaim an area of mudflat and shallow bay for development. It would have substantially reduced tidal prism in the upper Richardson Bay, interfered with the generation of wind-generated waves along the fetch of the Bay, and ironically would have led to a greater need for maintenance dredging in the boating channel. The inset photo in **Image Ref #84** shows the kind of junk materials that were used for constructing many of the levees and artificial berms in the Bay. Materials similar to these can be found in South Bothin Marsh today, although the date(s) of their placement is uncertain. The photo also shows the amount of filling that has begun and was being planned for the Bay waterfront in Sausalito.
1957	85, 86, 87	Increased shoaling of Richardson Bay due to continued losses in tidal prism and likely increases in local sediment supply	The Independent Journal (1/2 6/1957) published a map of the planned dredging and development of Richardson Bay (**Image Ref #85**). It shows a canal cutting through the northern bulb of Almonte Marsh and another canal cutting through South Bothin Marsh. It also shows the area of a cable crossing that extends farther west of the alignment of the Redwood Bridge that was shown in the 1949 bathymetric map (**Image Ref #86**). The significance of this difference is not known. **Image Ref #86** shows that upper Richardson Bay had shoaled since1949. The tidal flats had extended southward, as indicated by the southward migration of the MLLW contour, toward the Richardson Bay Bridge. This shallowing was likely caused by a multitude of factors including reduced tidal prism due to marsh reclamation and artificial filling of the Bay, increased sediment supply from the 1955 flooding, and from ongoing local land use disturbance. **Image Ref #87** shows changes in the position of the MLLW contour between 1851 and 1956. Two principal periods of shallowing of the upper Bay were 1851-1856 and 1901-1956. Shorter episodes or even brief pulses of terrigenous sediment due to especially wet winters,

			major storms, wildfires, and bursts of land development may have punctuated both periods. However, sediment supply during the first period was due mainly to land uses, such as grazing and logging, in the local watersheds. The latter period was dominated by the interference with tidal processes, such as construction of levees, channelization of tidal channels, and dredging that decreased the tidal prism of the upper Bay and thereby increased the tendency of the tidal flats and marginal marshlands to expand. The earlier period of increased sediment supply might have been followed by a period of near recovery to pre-existing depths in upper Richardson Bay, if the tidal prism had been maintained. The chronic shoaling that resulted from the loss of tidal prism might only be reversed by maintenance dredging or long-term sea level rise.
1959	None	Coyote Creek concrete channel constructed upstream of Flamingo Road	To protect the housing developments on the historical tidal marshlands of the original Coyote Creek Marsh, which evidently had only been slightly raised by fill and might also have been influenced by subsequent subsidence, the USACE devised a flood control plan that involved an engineering project along the lower 7,100 feet of the Coyote Creek channel (USACE 1959). The project entailed installing a concrete-lined channel for approximately 3,000 feet upstream of Flamingo Road, and dredging the downstream 4,200 feet of earthen channel (ESA-PWA 2012). The project was motivated in part by the historic flooding of 1955. However, the alignment of lower portion of the project, called for the Coyote Creek Canal, which agrees closely with development plans dating back to 1892 (see **Image Ref #31**).
1960	88, 89	Fill provided for Shelter Cove Near elimination of North Manzanita Marsh Channelization of ACMdP through Almonte Marsh Near constant dredging of Richardson Bay	Richardson Bay Master Plan was adopted (Independent Journal ref from 7/15/1969). **Image Ref #88** shows that new fill had been place at the head of Richardson Bay for the Shelter Cove development, northwest of the fill that had been placed earlier for the north span of the Highway 101 at Richardson Bay Bridge. New dredge spoil deposits can be seen along the south edge of the 1956 containment levee. Marin News (10/29/1960) reported that the U. S. Army Dredge Hardin' “has finished its week - long 24-hours-per-day churning around Richardson Bay and the Sausalito side of San Francisco Bay. Object was the cleaning and dredging of ship channels in Richardson Bay, which the Harding affected on schedule. The non-stop shift started Monday morning, Oct. 17, and was concluded Monday morning, Oct. 24. According to Army Engineer in Sausalito the Harding steamed off for Mare Island on Tuesday.” (https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=SN19601029.2.36&srpos=5&e=-------en--20--1--txt-txIN-dredging+richardson+Bay-------1

		Exterior containment levee constructed. Appearance of North Bothin Marsh	By 1960, Almonte Marsh had decreased in size to ~21.5 ac, 62% of its size in 1952, or 41% of its maximum size in 1899. About 20 ac were east of the railroad levee. This was due to continued flood control canal construction in Arroyo Corte Madera del Presidio that extended a diversion canal through Almonte Marsh, isolating the northern bulb of the marsh. The bulb, as defined by the large eastern bend in the channel, had been a natural feature of the channel that naturally expanded northward as the channel migrated. The larger southeast migrating bends in the lower tidal reaches of Arroyo Corte Madera del Presidio, at least historically included sand bars and beaches exposed at low tide, and natural levees along the banks. They increased the overall ecological diversity in the tidal landscape. They were mapped in the 1851 Coast and Geodetic Survey map (**Image Ref #7 and #9**). The flood control canal for the Arroyo Corte Madera del Presidio was much narrower and straighter than the original natural channel. It lacked the capacity to convey the tidal prism of the original tidal marsh landscape. Its straightness increased the delivery of terrigenous sediment to the shallow subtidal areas of the Bay, bypassing the remnant marshlands. The tidal flow and sediment distribution of upper Richardson Bay were completely and permanently altered in a way that would tend to increase its modern tendency to shallow. **Image Ref #89** shows the extent of filling by 1960 as evidenced in **Image Ref #88** and the other aerial images shown. About 1 ac of new marshland can be seen inside the southern corner of an incomplete containment levee. It was located just south of the main canal dredged for navigation, just east of the c. 1920 levee on Almonte Marsh, and it had at least three openings to allow dredges and barges to enter and exit from different directions. The new marshland forming along the interior (landward or western) margin of the incomplete containment levee is here referred to as North Bothin Marsh. The effects of this incomplete levee on tidal circulation and sedimentation in upper Richardson Bay are unknown. It is likely to have diminished the heights of wind-generated waves trained on the foreshore of Almonte Marsh. It may have reduced the exposure of the foreshore sediment delivered to the upper Bay from the Arroyo Corte Madera del Presidio. The deepened areas of the Bay from which the dredged materials were removed to build the levee served as sediment sinks, reducing the availability of sediment to sustain tidal flats and marshes.

			Image Ref #88 also shows further filling and grading of North Manzanita Marsh and South Bothin Marsh. **Image Ref #89** shows that North Manzanita Marsh has ~1 ac of marsh remaining that is part of the Bothin Marsh complex. About 2 ac of the marsh have become isolated to the south. Less than ~0.5 ac of Manzanita Marsh remaining to the north had started merging with East Bothin Marsh. About 1.0 ac was excavated as a deep pond, possibly to capture road runoff. East Bothin Marsh had grown only slightly, from ~1 ac to ~1.3 ac. South Bothin Marsh had been graded and filled just west of the historical 1851 foreshore, and along the southern bank of the lower tidal reach of Coyote Creek, near its mouth in the Coyote Creek Embayment. New containment levees were being constructed for additional reclamation farther into the marsh. About 9.0 ac of South Bothin Marsh was lost to artificial filling. The marsh also continued to prograde into the Coyote Creek Embayment, gaining ~2.0 ac. Overall, South Bothin Marsh decreased in size to ~28.0 ac, about 79% of its 1952 size. The tidal flats of the Coyote Creek Embayment were furthered reduced by conversion to tidal marsh. Since 1952, the embayment decreased in size from ~12 ac to ~10 ac, which was about 19% of its maximum size. The fan of the Coyote Creek tidal channel within the Coyote Creek embayment appears to have been straightened or ditched, perhaps to increase its capacity to convey floodwaters from upstream, and to promote expansion of its fan. Grading for suburban development on the historical tidal marshlands west of SR 1 appears to have been completed. Additional grading and artificial fill are evident east of SR 1, leaving a small remnant (~0.3 ac) of tidal marsh at the north edge of the original (1851) foreshore. By 1960, construction of the concrete flood control channel of Coyote Creek upstream of Flamingo Road is apparently complete.
1963	90	Elimination of the northern bulb of AM begins	Dredging activity had started to remove the remaining northern bulb of Almonte Marsh. **Image Ref #88** shows a dredge in the process of excavating the marsh bulb. The spoil material may have been used as fill for the Shelter Cove development to the immediate east.
1964	91	Construction of the CCC for flood control begins in SBM	Sausalito News published this report (21 October 1964): “Demolition of the Poplar Street Bridge, which crosses Coyote Creek in Mill Valley, continued last week despite protests from merchants who were nearly cut off from their customers, and the attempt of Tamalpais Fire Chief Herbert Owen to prevent the bridge's destruction. The operation is part of the Coyote

			Creek Flood Control project." (https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=SN19641021.2.68&srpos=1&e=-------en--20--1--txt-txIN-Coyote+Creek%2c+Mill+valley-------1). By 1964, lower Coyote Creek downstream of SR 1 was relocated to its current, straightened alignment as the Coyote Creek Canal. Dredged material was placed on the marshes to the north of this canal, severing the tidal connections between South Bothin Marsh and Coyote Creek except during extreme high tidal or flood conditions (ESA and PWA 2012). A flap-gate had been installed under the railroad levee at the inlet to the Coyote Creek Embayment and operated from 1964 to 1980 (ESA-PWA 2012). The flap gate allowed overflow waters from the creek and local runoff to exit the embayment into Richardson Bay during low tide, but prevented tidal waters from entering the embayment. Isolation from the tides and from the creek allowed the embayment to desiccate during the dry season. The desiccation would have caused the organic faction of the sediments to oxidize, reducing their bulk density and thus lowering the elevation of the land through subsidence. **Image Ref #91** shows areas of likely artificial fill placed on South Bothin Marsh along the alignment of the future Coyote Creek Canal. The purpose of this fill is uncertain, however it seems possible that it was placed to backfill areas along the levees of the future flood control canal. Containment levees for reclaiming Richardson bay just south and east of the Richardson Bay Bridge are visible at the bottom-center of **Image Ref #91**.
1965	92, 93	CCC constructed Rubble and debris piles placed in SBM Tidal flap gate placed at SBM limits tides to the embayment	**Image Ref #92 shows that c**onstruction of the Coyote Creek flood control project had begun. It extended into South Bothin Marsh and into the developing East Bothin Marsh to straighten tidal reach of Coyote Creek channel into a trapezoidal canal with levees on its banks extending to the railroad levee. The north bank appears to have had a continuous levee, while the south bank might have only had a levee on its lower half and a short distance downstream of the SR 1 bridge. A new 105-foot-long railroad bridge was constructed over the new Coyote Creek Canal. The drainage area of South Bothin Marsh was now only ~0.18 ac due to the canal isolating the marsh from the Coyote Creek watershed. A maintenance plan was developed for continued dredging of the channel. The design capacity of the canal was to carry a 20-year storm from the watershed. The discharge of a 20-

		Interior containment levee constructed at AM Early development of North Bothin Marsh bayward of Almonte Marsh	yr storm was reported to be 1,075 cfs in 1959 (USACE 1959) and 1,952 cfs in 2005 (PWA 2005). The base height of the Coyote Creek Canal was below MLLW and the Canal was excavated straight through the adjoining mudflats beyond the railroad levee to the subtidal Sausalito Canal on the east side of the Richardson Bay Bridge. This was done to connect the subtidal Coyote Creek Canal to the main northwest trending deeper dredged Sausalito Canal. This configuration promoted the transport of sediment from the Coyote Creek Watershed to the ebb flows of the Sausalito Canal that could carry the sediment toward San Francisco Bay. However, the net direction of fine sediment transport is more likely toward upper Richardson Bay, due to dominant direction of flood tide and wind-generated waves, typical of such estuaries with small fluvial discharges. The connection of the two Canals seems to have increased the need for dredging the Sausalito Canal, while isolating South Bothin Marsh from its terrestrial sediment supply provided from the Coyote Creek watershed. **Image Ref #93** shows that the former outlet of the Coyote Creek Embayment was made smaller, further limiting the tidal prism, and hence its sediment supply to South Bothin Marsh. It appears that the inlet involved a new approximately 26 ft-long bridge with an accompanying tidal flap gate of unknown dimension. This new bridge and flap gate replaced the 125 ft-long trestle. The flap gate eliminated tides from entering Coyote Creek Embayment. It only allowed floodwaters that overflowed the Coyote Creek Canal and other runoff from local urban drains to exit the embayment at low tide. The aerial photos indicate that the mudflat channel leading away from the east side of the opening became very narrower. It was not dredged and its small size was evidence of very reduced and discontinuous flow from the embayment. This elimination of tidal action within the embayment also eliminated tidal sedimentation, except during extreme flood events that overtopped the railroad or Canal levees. South Bothin Marsh became sediment-starved with no sufficient mechanism to gain elevation. Coyote Creek was unable to continue building its fan within the embayment. The conversion of the embayment into a floodwater storage basin would have caused seasonal changes in salinity from nearly fresh to brackish during winter to saline or hypersaline in late summer, due to the basin's desiccation. Repeated wetting and drying would have oxidized the organic faction of the sediments, causing the basin to lose some height, while increasing the acidity of the sediments, and thus causing some metals,

			such as iron, to mobilize. The wetting and drying can also cause elemental mercury to transform into the biologically active and toxic methylmercury (Yee *et al*. 2008). The Coyote Creek Embayment, including the abandoned truncated segment of the former Coyote Creek channel, was slightly reduced in size from an estimated ~10 ac in 1960 to ~9.5 ac by 1965, representing about a 20% reduction from its original 1883 size. By 1965, ~4 ac were eliminated in South Bothin Marsh mostly due to the excavation of previously vegetated marshland to create the Coyote Creek Canal, reducing the total acreage of the marsh to ~26 ac. Concrete rubble and other urban debris was placed on the South Bothin Marsh in and around the abandoned former Coyote Creek channel near its mouth and alluvial fan, and along the northwest backside of the northern flood control levee. This might have been done to fill former Coyote Creek channel of the diked marsh to buttress the backside of the new canal levee and to prevent headward erosion into its backside from the former truncated Coyote Creek; or, it was simply the disposal of unwanted materials, reflecting a general regard for diked marshes as disposal areas. A new interior containment levee was constructed on the Richardson Bay mudflats between the Almonte Marsh foreshore and the more eastern 1960 containment levee. North Bothin Marsh would form within this new interior containment levee. Almonte Marsh had changed in size very little since 1960. About 1 ac had developed near the north end of the new interior containment levee. It had minor erosion near at its north foreshore and minor expansion of its eastern foreshore, before the construction of the interior containment levee. It covered ~19 ac, of which ~1.5 ac was Tam Marsh, and ~17.5 ac was east of the railroad levee. About 3 ac of the new North Bothin Marsh formed at the northwestern area of the intersection of the 1960 exterior containment levee and the railroad levee. East Bothin Marsh expanded bayward very slightly. The area that had been merging with North Manzanita Marsh became isolated from the rest of East Bothin Marsh by the Coyote Creek Canal and hereafter is considered part of the North Manzanita Marsh. The total size of east Bothin Marsh therefore decreased by ~1 ac.

			North Manzanita Marsh covered ~2 ac due to the addition of a small portion of East Bothin Marsh, and construction of pond that might have functioned as storm runoff retention for the highway.
1966	94, 95, 96, 97	Continued formation of North Bothin Marsh Filling of San Francisco Bay curtailed by passage of the state McAteer-Petris Act and formation of the San Francisco Bay and Conservation and Development Commission	**Image Ref #94** shows that recent dredging and filling was widespread throughout upper Richardson Bay during the 1960s. The photo shows that the Coyote Creek Canal was not yet fully complete. Its banks appear wavy, not yet straight or parallel to each other. A vehicle trail leading to the areas of rubble disposal and in the diked South Bothin Marsh can be seen along the north bank of the Canal. The excavated runoff retention pond can also be seen along the remnant shoreline of North Manzanita Marsh. An earlier image (see **Image Ref #92)** shows dredge material being placed within the cell of the interior containment levee. Marshes forming within this cell and along either side of its levee are referred to as North Bothin Marsh. The containment cell was partially filled with material dredged from Shelter Bay and the subtidal channel of Arroyo Corte Madera del Presidio. **Image Ref #95 shows** canals that had been dredged and containment levees that had been constructed for the disposal of dredged sediment, the formation of the bar near the southern piers of the Redwood Bridge. The upper part of Richardson Bay had become completely altered. The historical navigational Chart 5532 (**Image Ref #96**) fails to show many of these changes. However, it does show a narrower MLLW boundary than the previous 1957 chart (**Image Ref #86**) and it only extends to south side of the Richardson Bay Bridge rather than slightly upstream as it did previously. Dredging is required to maintain these areas. Sediment supply from the CCC can actually be seen in the picture (**Image Ref #95**) as murkier water traveling to the Sausalito Canal. **Image Ref #97** shows some of the additional artificial filling that was occurring south of the Richardson Bay Bridge. These changes in the upper Bay have reduced its tidal prism, which in turn has affected the distribution and extent of mudflats and the power of wind-generated waves, which in turn has affected sediment delivery to the Bothin Marsh complex. By 1966, a trend toward net shoaling of the Bay is clearly evident.

			It should be noted that essentially no sediments have been exported from the upper Bay. Sediment provided from the local watersheds have been accumulating in local subtidal and lower intertidal areas. Dredging in these area has been used to construct local levees to contain other locally dredged sediment. These containment cells would later be breached. The increasing sediment pile within the upper Bay has been naturally and artificially redistributed within the Bay. A reasonable inference is that, in the absence of interference, the shoaling of the Bay would have generated new tidal flats and new tidal marsh, and would have supported the evolution of high marsh from low marsh.
Post 1966	98		**Image Ref #98** was taken sometime after 1966 as indicated by the development of more marshland and filling within the small Rectangle Marsh (considered part of North Bothin Marsh) south of Almonte Marsh but within the north side of the exterior containment levee. The new interior containment levee can be seen just beyond Rectangle Marsh. Levee construction was eliminating portions of SBM on its southeast corner.
1967	None	Coyote Creek Canal completed	Flood Control work was fully completed for Coyote Creek in 1967. The Coyote Creek Canal requires regular maintenance dredging to retain its design capacity. About 14,000 cubic yards of sediment were removed in 1965, and an unknown amount was removed in the fall of 1974 (Madrone Associates 1975).
1968	99	Hotel constructed on artificial fill [;aced on former NMM	**Image Ref #99** coarsely shows marsh and land development around upper Richardson bay since 1952 and 1968. Some of the larger changes depicted include the dredged areas of the Bay, Arroyo Corte Madera del Presidio, and Coyote Creek Canal. The developed areas are shown as a purple tint and purple stippled areas indicate excavations from dredging of the Bay and loss of marshland such as at Manzanita Marsh. Although urbanization has surely increased the amount of runoff with the creeks, the tidal channels are all much smaller than their historical counterparts, demonstrating the former importance of tidal prism, not upland streamflow, to support the wider and deeper channel of the historical marshes. Construction of a Howard Johnson Hotel was completed on artificial fill that had been placed on a former area of North Manzanita Marsh.
1969	None	Extension of Sausalito Canal proposed and the Richardson Bay	The Independent Journal (03/07/1969) reports a measure on the voter ballot endorsed by the Marin Conservation League would extend the Sausalito Canal 2.5 miles from the Army Corps of Engineers turning basin to the Mill Valley small craft harbor, which was under construction, with costs shared by the City of Mill Valley and property owners along the Canal, who had

		Channel Dredging District formed	formed the Richardson Bay Channel Dredging District to assess themselves for the project. Independent Journal (07/15/1969) reports a proposal to develop Richardson Bay's "cluttered" waterfront at Manzanita and Waldo Point were presented to Planning Commissions
1970	100	Rail line converted to a pedestrian path sometime after 1970s (?)	**Image Ref #100** shows that the clearance for boat and ship traffic below the San Rafael Bridge at high tide is 56 ft wide by 39 ft high. It also shows the existence of the CCC but seems to rely upon and show the same bathymetry as from 1966. According to Garcia Associates' letter of 12/16/16, after the railroad was fully decommissioned sometime after the 1970s, it was converted to a pedestrian path (CMDPW, 2016: 2). It is not known if this reference is to an earlier trail predating the 1981 Bay Trail.
1971	None		Rail line across Bothin Marshes begins freight service (P. Rhodes verbal communication and 4/21/2017 email Phil Rhodes).
1973	101, 102, 103	Early breaches occur through NBM interior containment levee Advent of the US Clean Water Act regulating the dredging and discharge of fill into waters of the US including Richardson Bay and its tidal marshes Interior dredge spoils observed in NBM	**Image Ref #101** shows that some colonies of vegetation appear to have coalesced in South Bothin Marsh as compared to the aerial photo of 1952 (**Image Ref #80**). By this time the marsh had been disconnected from the Coyote Creek watershed for 9 years. The photo shows that the Coyote Creek Embayment is able to drain at low tide, but the fully diked Almonte Marsh has abundant standing water. Only the highest areas of dredge spoils and the levees appear above water surface. The fringing tidal marsh along the foreshore of Almonte Marsh has expanded bayward. The higher areas of disposed dredged sediment in Almonte Marsh appear to support vegetation except in areas where sediment disposal is very new. The seasonal wetting and drying of this basin would have caused seasonal changes in salinity from nearly fresh during winter to saline or hypersaline in late summer. Repeated wetting and drying would have oxidized the organic faction of the sediments, causing the basin to lose some elevation, while increasing the acidity of the sediments, and thus causing some metals, such as iron, to mobilize, causing to transformation of elemental mercury to toxic methylmercury (Yee *et al*. 2008). These conditions were unfavorable to vegetation, and caused much of the basin to remain barren. Other notable changes by 1973 include further hotel development on the portion of South Bothin Marsh that had been leveed in 1966, and new levee construction to reclaim areas landward of the commercial district along SR 1. The exterior containment levee had been excavated by a dredge digging a borrow ditch for building the new interior containment levee. Maintenance dredging was conducted in the upper portion of the Coyote Creek Canal one year after this photo was taken.

			According to ESA-PWA & WRA (2012) the containment cell "at the north end of Bothin Marsh (referred to in this report as Almonte Marsh) was not reconnected to the tides until sometime in the 1970s or 1980s, when a number of breaches opened up in the north side of the berm to allow tidal access". **Image Ref #102** shows the same area as **Image Ref #101** but 3 days later. The more recent image shows a possible breach of the interior containment levee in about the middle of the Almonte Marsh foreshore. It is not known if this happened naturally or purposely. *T*he breach occurred where the mudflats were deepest within the containment cell. It appears that water has drained somewhat from the marsh. The former foreshore of the historical Almonte Marsh is also evident. A very high area of dredge spoils is evident along the western edge of the marsh that might be much older than the other dredging spoils. Based on field investigations for this report, these older spoils contain abundant broken shell of subtidal mollusk infauna mixed with silts and clays, and were placed on the historical tidal marsh rather than on dredged sediment. The material is not from an Indian shellmound. These spoils are evident in earlier images (see **Image Ref #73** from 1946). It seems likely that they were dredged from the Coyote Creek Embayment during the construction or reconstruction of a railroad trestle and possibly deposited for a possible staging area for trestle construction. **Image Ref #103** shows polygons representing the areas of components of the Bothin Marsh complex. The areal extent of Almonte Marsh, including Tam Marsh, decreased slightly to ~19 ac. East of the railroad levee, ~13.5 ac of marsh were subjected to cyclic wetting and drying. Tam Marsh decreased slightly in size, as did the north end of Almonte Marsh, as a result of levee construction. North Bothin Marsh increased in size to ~14.5 ac from dredge spoils developing wetland vegetation, some growth on fringing marsh of the levees, and ~0.5 ac Rectangle Marsh expansion, although the northeast corner of the marsh had started to erode. East Bothin Marsh slightly decreased to ~0.5 ac. The size of North Manzanita Marsh did not change. Although many levees had been constructed to contain dredge sediment and thus reclaim much of upper Richardson Bay, the required dredging and disposal of sediment into the areas bounded by the levees had not been completed due to challenges under the 1965 McAteer-

			Petris Act and the 1972 federal policies and laws regulating and generally preventing such activities.
1974	104, 105	Maintenance dredging CCC Small breach at NE corner of NBM	Madrone Associates (1975) reported that maintenance dredging of Coyote Creek was conducted in December of 1974 to remove cordgrass, pickleweed and salt grass that was expected to gradually reestablish. The emergent plants were acting as silt traps, accelerating siltation of the canal and reduction of flood control capacity. The mode of dredging was the dragline, which typically scrapes off a layer of mud and plant material, including most roots, and disposes it in waiting trucks. The project design called for a 4:1 sloping shoreline (Madrone Assoc., 1975). **Image Ref #104** shows the 1973 breach and an additional breach at the northeast corner of the interior containment levee of North Bothin Marsh. Standing water appears high in Almonte Marsh perhaps from relatively recent rainfall. It is not sediment-laden because features beneath the water column can be seen such as the remnant channels. Conversely, Coyote Creek Canal has turbid water that has formed a plume at its outlet and is intermixing with water in Richardson Bay. It appears that there is a moderate flood tide moving up the Bay because the turbid water from Coyote Creek is being pushed up the bay toward Bridge 2 of South Bothin Marsh. This photo shows evidence that Coyote Creek has ample suspended sediment supply that gets transported to Richardson Bay. It also indicates that there is a mechanism for sediment distribution into South Bothin Marsh during flood tides if the flap gate was not present. It is presumed that if the design capacity guidelines are maintained, a greater than 20-year recurrence interval terrestrial uplands flood would be required to deposit sediment on South Bothin Marsh unless it coincides with an exceptionally high tide. In South Bothin Marsh there is a general zone of numerous large patches of mudflat and colonies of sparse vegetation. Its upper boundary is the shoreline that predated the flood control project (1965) that is pickleweed-dominated and its lower boundary is a more densely vegetated area of cordgrass that colonized the mudflats of the embayment. A new small breach at the northeast corner of North Bothin Marsh can be seen on the interior containment levee that brings tides to the small section of marsh near the power pole, which borders Arroyo Corte Madera del Presidio and has levees on 3 other sides.

			In **Image Ref #105,** the tide looks relatively high in Richardson Bay but Almonte Marsh looks dry, or at least has a lower water level, which indicates its limited tidal connection. The water level in the Coyote Creek Embayment appears to be the same level as the tides, which indicates that either there was sufficient rainfall and urban runoff to the embayment it fill it and keep it from draining at high tide or that tidal waters had overtopped the Coyote Creek Canal levees or that the flap gate was not fully functioning. In South Bothin Marsh the image shows a transitional zone with numerous large patches of mudflat and sparse vegetation. Its upper boundary probably defines the lower boundary of the shoreline of the older pickleweed-dominated marsh that predated changes caused by the flood control project in 1965. Its lower boundary is established by the greater abundance of cordgrass and darker colored vegetation in the photography. The eroding northeastern corner of Rectangle Marsh can also be seen in this image. It is likely that the deep dredging for the borrow ditch reduced the amount of toe support at the foot of the levee, subsidence and insufficient fill height of the levee contributed to its erosion.
1975	106	Bothin Marsh area purchased for conservation	The Trust for Public Land purchased the Bothin Marsh area in 1975 from the railroad (https://www.savesfbay.org/bothin-marsh). The navigational chart of **Image Ref #106** does not show any shift in the position of the MLLW contour downstream of Richardson Bridge from the previous 1970 version of the chart (**Image Ref #98**). It does however depict the MLLW contour (boundary of the mudflats) and the Sausalito Canal to the head of Richardson Bay and Arroyo Corte Madera del Presidio. The inner containment levee was also mapped and a note was added about the Richmond Bridge being under construction.
1976	107, 108	Formation of large bar at mouth of ACMdP	It is a low tide in the 1976 photo shown in **Image Ref #107**. Yet standing water can be seen in the deeper mudflat area that has become a small embayment in North Bothin Marsh. A large depositional bar at the mouth of Arroyo Corte Madera del Presidio has formed at the ebb lee of the abandoned exterior containment levee. The levee contributes to shallowing the middle of Richardson Bay while the Sausalito Canal through its continued dredging helps transport the sand-sized bedload of Arroyo Corte Madera del Presidio farther down the bay. The borrow ditch on the west margin of the Bay, without continued dredging, functions as a sediment trap. A plume of turbid water can be seen emanating from the lower Richardson

			Bay moving upstream into the deeply dredged segments of Shelter Cove and the north side of Rectangle Marsh. **Image Ref #108** shows polygons representing the areal extent of the different marsh units. Almonte Marsh maintained its total size of ~19 ac with ~13.5 ac subject to desiccation, and ~4.0 ac that were covered with vegetation. The vegetated portion of the marsh had been reduced to small isolated fragments of higher marsh that had developed on the older dredge spoils near the railroad levee near the southern edge of the historical Almonte Marsh shoreline. The marsh channels in Almonte Marsh were too far from the tidal inlet in North Bothin Marsh to be influenced by tidal prism. North Bothin Marsh had a very minor decrease in total marsh area (~14.0 ac) due to a small amount of erosion of Rectangle Marsh. The area subject to seasonal desiccation in NBM developed a ~2.5-ac inner bay, while ~4 ac was still subject to desiccation. Vegetation expanded on the dredge spoils to ~4.5 ac and fringing marsh was ~1.0 ac. The width of the small breach in the inner containment levee that appears in 1973 was now about 16 ft. Its 1973 width appeared to be about the same but it might not have been very deep, perhaps it was more a surficial channel that developed on a low spot by water overtopping the levee. East Bothin Marsh and North Manzanita Marsh had very small increases in size, ~1.0 ac and ~2.0 ac respectively. South Bothin Marsh and the Coyote Creek Embayment both decreased slightly in size, 28.0 ac and 5.0 ac respectively. South Bothin decreased due to additional fill in its southeast corner and the embayment decreased due to slight expansion of vegetation from South Bothin Marsh.
1978	109		Changes in size of the different marsh segments, shown in **Image Ref #108**, were relatively minor although there was a general tendency of vegetated marsh expansion along the dredge spoils in Almonte and North Bothin Marsh and shrinking of the desiccated areas. The North Bothin Marsh embayment decreased in size to ~1.5 ac. The c. 1930 levee dividing Almonte and North Bothin Marshes had a breach that connected tidal flow between them. The breach in the inner containment levee of North Bothin Marsh widened, allowing a greater amount of tidal prism into North Bothin Marsh. The width of the

			breach widened to ~26 ft. It is not known if the breach in the c. 1930s levee happened naturally or if it was man-made. The channel in Almonte Marsh widened and eroded headward since it had more tidal flow. The overall size of Almonte Marsh stayed the same but the vegetation on the dredge spoils expanded to ~4.5 ac and the desiccated area decreased to ~13.0 ac. The size of South Bothin Marsh stayed the same but because there was different reflectance of vegetation and mudflats in the 1978 photo, it was possible to map a transition zone between the embayment and the slightly higher, predominantly vegetated marsh. The latter was ~19.0 ac. The transition ecotone was ~9.0 ac. It was characterized by numerous low areas subject to ponding interspersed with mudflats that were subject to long periods of desiccation. The mudflats were interspersed with patches of sparse vegetation, most likely cordgrass.
1981	None	MCOSD acquires Bothin Marsh Bay Trail & bridges built with grade control at Bridge 2 Tidal flap gate possibly removed creating a 26 ft span of the inlet to the Coyote Creek embayment Bridge 1 rebuilt	Marin County Parks and Open Space District formally acquires the marsh and easement across the old railroad tracks (https://www.savesfbay.org/bothin-marsh). The Mill Valley-Sausalito multi-use path, here called the Bay Trail, has an approved 20-foot improvement width that consisted of a 10-ft wide asphalt concrete path with 5-ft wide earthen shoulders on each side. ESA-PWA and WRA (2012) report that around 1980 improvements were made to the railroad line to incorporate the Bay Trail. At this time the flap gate at Bridge 2 outlet of Coyote Creek Embayment was replaced with an approximate 26-foot span footbridge, returning a limited amount of tidal prism to South Bothin Marsh. Based upon following images of 1982 and 1983 (**Image Ref # 110 and #111**) the Bay trail appears to have been constructed between 1981 and 1982. After the trail was completed, the inlet of South Bothin Marsh at Bridge 2 had a rock-armored base for grade control. This feature remains today and limits daily tidal connection to the Coyote Creek Embayment and South Basin Marsh. Bridge 1 over the Coyote Creek Canal was partially rebuilt, having a span of about 105 feet.
1982	110	Probable local flooding and high sediment loads from local landsliding	The two basins of Almonte Marsh and North Bothin Marsh are both flooded in **Image Ref #110** but they can still be distinguished by the slightly higher elevation c. 1930s levee that is covered by vegetation. The small breach of the inner containment levee shows the small channel that connects tides of North Bothin Marsh to Almonte Marsh. At the north end of

		associated with intense and prolonged rainfall	Almonte Marsh, sediment rich water of Arroyo Corte Madera del Presidio Canal can be seen entering the head of the Bay. In this same image, sediment laden-water can be seen moving out of Coyote Creek Canal, mixing with the flood tide of the bay and then moving toward the inlet of the Coyote Creek Embayment at Bridge #2. This exemplifies how locally derived sediment supply is redistributed on the marsh. If the creek were connected directly to South Bothin Marsh it would be functioning more naturally as a delta of its local watershed. Based upon analysis of numerous local historical rainfall records (Collins 2001; Gilbert 1917), the storms of the 1st week of January 1982 generated flooding in local watersheds throughout Marin County (Blodgett and Chin, 1989) and stream discharges were accompanied by very high sediment loading due to the initiation of numerous landslides and high rates of stream erosion throughout Marin County. Many streams had record flooding in the County. The photograph in **Image Ref #110** was taken January 7th.
1983	111	Paths along Coyote Creek Canal	The photograph in **Image Ref #110** shows conditions at either flood tide, or shortly after, when Arroyo Corte Madera del Presidio is the predominant sediment source in the head of Richardson Bay compared to the relatively clear waters of Coyote Creek Canal and the Bay itself. Sediment-rich water can be seen in a plume emanating from the Arroyo Corte Madera del Presidio that flows toward the inlet of North Bothin Marsh toward the levee breach of the inner containment levee. This is likely an important supply of suspended sediment to the marsh. The bar that has grown at the north side of the remaining exterior containment levee appears larger and emerges above the water level. It clearly captures and stores a significant amount of fine-grained bedload from Arroyo Corte Madera del Presidio. The Bay Trail appears to be fully constructed on the railroad levee and two pathways appear to be improved along the banks of the Coyote Creek Canal. Although a boardwalk already existed along the south bank of the canal it is not clear if there was an additional one along the north bank or just a pathway. The sediment supply from the Arroyo also contributes to growth of the fringing marsh along the outboard side inner containment levee. The dredged borrow pit that parallels its base, however, prevents it from prograding along a gentle uniform gradient that might eventually form if dredging of the bay bottom in this area is not renewed.

08/15/ 1984	None	Houseboats required to have sewage hookups in the Bay	Key step was taken in regulating sewage outfall from houseboats in Sausalito. Sewage hook-ups to be required in the future. Source: Independent Journal article at California Room, Marin Civic Center Library. This indicates that local water quality and its influence on wildlife might have improved following the mid 1980s.
1987	112	Effects of Bridge 2 flap gate removal evident	By 1987 the effects of removal of the flap gate could be seen in the landscape of South Bothin Marsh. Depicted in **Image Ref #112** are polygons representing the different marsh segments relative to the 1987 conditions. In the Coyote Creek Embayment the water elevation once again changed daily with the tides and the adjacent mudflats were no longer seasonally desiccated. The transition zone that was shown in **Image Ref #109** that was comprised of patchy mudflats and sparse vegetation was narrower than in 1976 but its upper boundary was still at the same location. The transition zone filled with more vegetation (probably cordgrass) along its lower boundary. The lower boundary was able to trap sediment more effectively where vegetation was more dense and closer to the source of sediment as it moved inland through the inlet. This filtering mechanism essentially cleans the water as it moves toward the higher elevations of the marsh that still remained sediment depleted because of the muted tidal prism moving through the small inlet of Bridge 2. Its 26-foot-wide opening and shallow depth limit the amount of tides and length of time that tides can reach the slightly higher, backshore areas of the South Bothin Marsh. Hence, the areas of pickleweed and their foreshore that predated the flap gate have a lower rate of sedimentation than the areas near the embayment that support cordgrass. The Coyote Creek Embayment increased over 1 acre in size becoming ~6.0 ac and the South Bothin Marsh totaled ~27 ac. Along the north bank of the Coyote Creek Canal path, the location where there was a pathway seems to have become compacted, depressing its elevation where it subsequently started to hold water, resembling a ditch. North Manzanita Marsh and East Bothin Marsh increased very slightly and were ~2.5 ac and ~1.0 ac respectively. In North Bothin Marsh the width of the tidal inlet increased to 32 feet from its 26-foot width in 1978 when it first started forming. Such an increase in width indicates a substantial increase in the amount of tidal prism reaching both North Bothin and Almonte marshes since they interconnect through two small channels by this time. The small embayment within North Bothin Marsh had a very slight decrease in size and was ~1.5 ac as surrounding land became more vegetated. It is very likely that the embayment became increasingly shallower

			from the sediment supply that was associated with intermixing of the tides with sediment from the adjacent watersheds. The fringing marsh of North Bothin and the rectangle Marsh both prograded increasing their size to ~1.5 ac and ~2.5 ac respectively. The vegetated area increased and was ~10.0 ac. In total North Bothin Marsh was ~15.5 ac. Since North Bothin Marsh was bringing more tidal prism to Almonte Marsh, the formerly desiccated mudflats in Almonte Marsh started re-establishing vegetation. Almonte Marsh was a total of about 18.5 acres, including the ~1.5 ac of Tam Marsh and ~17.0 ac of marsh east of the Bay Trail. Some very minor marsh erosion occurred along the bank of Arroyo Corte Madera del Presidio. A very small channel breach appeared in the containment levee at the northern portion of Almonte Marsh. Its channel leads to a small area of high dredge spoils rather than to the larger marsh.
1995	113	Upper Richardson Bay above 101 Bridge named Pickleweed Inlet by USGS Mudflat expansion near ACMdP	The navigational Chart 5532 shows the MLLW boundary from the 1975 Chart 5532 (**Image Ref #106**) projected onto the 1995 chart. A comparison of the 1975 and 1995 boundaries indicates that the Sausalito Canal MLLW boundary widened slightly south of Richardson Bay Bridge where it also developed a more uniformly shallow depth of about 1 foot above MLLW. Upstream of the bridge, where it was now named Pickleweed Inlet, the MLLW boundary narrowed by 1995. This indicates continued sedimentation of the headwaters of Richardson Bay and much of it is likely associated with the high sediment supplies of the 1982 flood event that had high sediment loading from Arroyo Corte Madera del Presidio. No new dredging seems to have occurred between 1975 and 1995.
1996	None	101 Bridge retrofitted	Richardson Bay Bridge had extensive retrofitting at this time (illustrative sign along Bothin Marsh Bay Trail, Marin County Parks). It is not clear how this may have affected conditions in Richardson Bay near the bridge.
1998	None	Probable local flooding	Based upon analysis of numerous local historical rainfall records (Collins 2001; Gilbert 1917), 1998 was a year that could have generated flooding in local watersheds.
1999	114	Urbanization along much of head of bayshore Area of mudflat equals area of subtidal in upper Bay	The topographic map of **Image Ref #114** shows the intensive increase in urban development at the head of Richardson Bay. The map demonstrates that the only large remaining marshes north of Richardson Bridge are those along the western shoreline and are associated with Arroyo Corte Madera del Presidio, Almonte, and South Bothin Marshes. Upstream of the Richardson Bridge the amount of open water is practically equal to the amount of remaining marsh, roughly 0.17 square miles, whereas in 1851, the amount of marsh was larger, roughly 0.53 square miles, compared to the amount of open water, which was ~0.38 square miles. In the absence of dredging most of the Richardson Bay would be above MLLW.

			Urban development abuts remaining marsh and bay shoreline. The urban area has changed the way runoff from the uplands is routed to the lowlands through pipes and canals, along roads and structures, and where it picks up, transports and deposits sediment. In general, the urban changes provide more runoff more quickly, which exacerbates the amount and speed at which flooding occurs downstream. These problems will be exacerbated with rising sea level because there is negligible space for terrestrial stream flow to spread onto a floodplain as it meets the future rising tides at increasingly higher elevations farther back into the valley.
2005	115	Significant sedimentation in subtidal area bayward of mouth of ACMdP	The size of the different marsh units by August 2005 are shown in **Image Ref #115**.l Almonte Marsh filled with more vegetation and the channel that was connected to the breach in inner containment levee of North Bothin Marsh enlarged, bringing slightly more tidal prism to Almonte Marsh. Total acreage was slightly smaller in Almonte Marsh, ~17.9 ac, due to marsh erosion at the north end along Arroyo Corte Madera del Presidio and widening of the channel. North Bothin Marsh stayed nearly the same size, ~15.5 ac, loosing a bit of its fringing marsh on the outside on the containment levee, which slightly decreased (~1.3 ac). The inner bay got smaller, decreasing in size to ~0.5 ac, while the vegetated marsh on the interior of the containment levee expanded. It was ~11.0 ac. The width of the breach in the containment levee increased to about 42 ft. Since the 2005 image was taken during low tide, it is possible to see the changes along the bottom of Richardson Bay. North of the channel breach of the inner containment levee, the borrow ditch appears to have shallowed from sedimentation, while south of the breach the borrow ditch is maintaining more depth due to the ebb tides that flow from Almonte and North Bothin Marsh through the breach. The large bar that formed at the outlet of Arroyo Corte Madera del Presidio started to show some erosion along both its east and west sides as flow diverges during the ebbing tide and flows to either side over the bar. On a rising tide it appears to flow southeastward over the bar. The sediment on the bar is being reworked and redistributed, with some amount likely moving upstream and reaching portions of Almonte Marsh. The deeply dredged area of the turning basin (for the dredge) just north of Rectangle Marsh also appears to have shallowed.

			The channel exiting the Coyote Creek Embayment of South Bothin Marsh shows some change where it has created a small shoal and a subtle delta fan at the outlet of Bridge 2. This indicates that there is some sediment being removed from the embayment during ebb tides and it seems to be from the channel network that appears to be deepening while the marsh surface gains in elevation from sediment deposition. The grade control at the bridge outlet also causes a steep drop to the bay during low tides, which exacerbates the formation of a plunge pool at the end of the grade control of the inlet, which might eventually lead to undermining and destabilization. If the bed at the inlet incised, the lower elevation tides would start to influence South Bothin Marsh and drainage velocities might increase. As it stands, such a sudden change in slope from the grade control structure is a fairly unnatural feature in mudflats. At South Bothin Marsh, the transition zone of patchy areas of mudflat and sparse vegetation seemed to expand to ~7.0 ac with an increasing amount of mudflat broken up by corridors of vegetation following the slightly higher banks along some of the larger channels in the marsh. In general, the density of channels leading to the Coyote Creek Embayment has been very high during all years, with channels too numerous to map in South Bothin Marsh. The marsh vegetation continued to expand toward the Coyote Creek Embayment reaching ~22.8 ac. The total amount of marsh and patchy mudflats was ~29.6 ac, which was more than 3 acres larger than in 1987. This embayment lost ~2.6 acres to vegetation during the same time period. On the south bank of the Coyote Creek Canal a ditch-like feature appeared parallel to the channel banks. There are three possible hypotheses about the origin of the ditch. One is that there used to be a paved pathway that was removed, leaving a low area (communication from Veronica Pearson, Marin County Parks). Another hypothesis is that there was a pathway that became compacted, and a third hypothesis is that is that there was an earlier because vegetation did not grow beneath the former alignment of the boardwalk that inhibited vegetation growth beneath it and that it was moved that was moved prior to 2005. East Bothin Marsh stayed the same size (~1.0 ac) and North Manzanita Marsh eroded slightly, decreasing its size and was ~2.0 ac.
2013	116, 117. 118. 119	Net historical decrease in the area of Richardson Bay	A comparison of the historical 1851 head of Richardson Bay marshes to modern conditions of 2013 is provided in **Image Ref #116**. Separate analyses are done for the whole Bay and its smaller southern arm that extends between Sausalito and Strawberry Point to Mill Valley. The Bay as a whole has 80% less marshland. It has 14% less mudflat and subtidal area. It’s 27%

		study area as a whole is 27% Net decrease in the southern arm of Richardson Bay with the Bothin Marsh Complex 50% AM eastern breach continues to widen	smaller overall. The Mill Valley arm has 74% less marsh, 30% less mudflat and subtidal area, and is 50% smaller. This means there is greater loss of total area in the southern arm that includes the Bothin Marsh Complex. The reduced size of the southern arm of Richardson Bay plus its shoaling means that its has lost tidal prism, at least in the upper area near the Bothin marshes. Since there are no historical measure of tidal range or velocity, the loss in tidal prism is unknown, However, large-scale restoration of tidal marsh would increase the prism and reduce any need for dredging. A storm drain map created by the Marin County Geographic Information Systems Department in **Image Ref # 117** shows the drainage network that leads to South Bothin and Almonte Marsh. The accuracy of the GIS map relative to the characterization of artificial paths, pipelines, and ditches does not seem to be fully depicted or relative to the Map Key, however, the map does seem to show a complex network of channels and drains and indicates whether they are perennial, intermittent or ephemeral. The 3-dimensional projection **in Image Ref # 117** of the stream network provides a perspective of the two different drainage areas of Coyote Creek Canal and South Bothin Marsh, which prior to 1965 was connected to the Coyote Creek watershed. The Coyote Creek Canal has a drainage area of ~3.6 square mile. The drainage area of South Bothin Marsh (unless the creek has a large flood coinciding with high tide) has been reduced to ~0.18 square mile due to the levees along the Canal. The numerous small headward tributaries drain open space lands that still have natural processes that provide sediment to the channels of the valley bottoms that are highly altered. Generally, the lower valley bottom channels are highly confined, either within pipes, between concrete walls, or between buildings that inhibit natural channel features such as meanders, sediment bars, and floodplains. The lower valley main channels essentially function as water and sediment chutes to the Canal where dredging is required to maintain flood protection of the valley bottom. Tidal water extends over 3,600 ft up-valley from SR 1 bridge. Based upon previous analyses by USACE (1959) the properties on the low lying parts of the valley floor are only protected from flooding of Coyote Creek when it has discharges of less than a 20-year recurrence interval and this is under the sea level conditions that existed in the mid-1960s. The projected sea level rise of 55 to 65 in (4.5 to 5.5 ft) by 2100.

			Image Ref #118 shows a parcel map of the Bothin Marsh Complex and surrounding areas, possibly representing ownership in 2013. Most of South Bothin Marsh, north of the north bank of Coyote Creek Canal and a portion of Richardson Bay extending to the Sausalito Canal is owned by the Marin County Open Space District. There is a small inholding near the southwestern boundary that belongs to CalTrans. The Bay Trail, a small section of marsh along the south bank of the Coyote Creek Canal, and the Sausalito Canal appear to be managed or owned by the County. The portion of Almonte Marsh, referred to as Tam Marsh, and the area of North Manzanita Marsh are not owned or managed by the County. **Image Ref #119** shows a 2013 LiDAR digital elevation model referenced to NAVD 88 that was provided by the Marin County Department of Public Works. The levees of dredge spoils that were initially placed on mudflats along the northeastern bank of Coyote Creek Canal have subsided. As a result, there is an increasing connection of tides between the lower Coyote Creek Canal and Coyote Creek Embayment. The map elevations indicate that the Bay Trail is generally between +7 and +7.5 ft NAVD 88. It is therefore subject to annual flooding from King Tides over some segments of the Bay Trail each year. When these high tides flow over the Bay Trail the large volume of water at the start of the ebb tide flows from the Coyote Embayment over the subsided levee of the north bank of Coyote Creek Canal, which is lower than the Bay Trail, and then into the Canal. At the start of ebb tide, since the Canal drains faster than the Embayment, water flows from the Embayment to the Canal. The outlet of the embayment at Bridge 2 is too small to drain at the same rate as the Canal at Bridge 1. At the upper northwest bank of the Canal, a small channel coveys flood tides into a shallow basin bounded by the old alluvial fan and artificial fill that separates the basin from the rest of the backshore of South Bothin Marsh. During the highest tides and terrestrial flood flow conditions, most of South Bothin Marsh and Coyote Creek Canal would merge together as open water, leaving a few of the artificial fill areas of demolition debris as isolated high points that may function as refugia for wildlife. The LiDAR map also shows the very low elevation of Rectangle Marsh and the areas near the embayment of North Bothin Marsh. It also demonstrates the lack of channel network in Almonte Marsh that would benefit from increased tidal connection to supply sediment to the

			backshore. The breach in the levee at north Bothin Marsh is twice the width of the South Bothin Marsh inlet at Bridge 2. Width of the breach of the inner containment berm at North Bothin Marsh measures to be about 50 feet compared to its 2005 width of 42 feet. If it continues to widen it will bring more tidal sediment into the backshores of sediment-starved Almonte Marsh. The LiDAR map also show the low elevation of land along the commercial district of SR 1. Much of the Coyote Creek valley floor toward the western boundaries of the Historical Coyote Creek Marsh have been affected by subsidence of the fill and marshlands on which they were developed, which increases the threat of flooding from projected sea level rise.
2016	120, 121, 122	Incipient breaches at north bank of CCC have slightly enlarged	The areas of marshland for 2016 are shown in **Ref Image #120**. In general there has been relatively little measureable change since 2005. South Bothin Marsh increased very slightly to ~13.4 ac as vegetation colonized more of the Coyote Creek Embayment and fringing marsh of Coyote Creek Canal. Two small channels have enlarged slightly on the north bank levee of Coyote Creek Canal. One is very close to the railroad levee, and the other is about half way up the canal. These channels help drain the high overflow tides that move from Coyote Creek Embayment into the canal. Coyote Creek Embayment decreased to a ~3.0 ac. East Bothin Marsh decreased very slightly and had about 1.0 ac and North Manzanita stayed the same at ~2.0 ac. Almonte Marsh has decreased slightly to 18.0 ac, primarily due to erosion of its north side. North Bothin Marsh decreased very slightly and had ~15.3 ac, due mostly to erosion of the fringing marsh of Rectangle Marsh along the outside of the south side of the inner containment levee, and along the south side of Rectangle Marsh. A geomorphic map of the South Bothin Marsh in **Ref Image #121** highlights some key features of the vegetated marsh, adjacent surroundings, and the unvegetated intertidal ecosystems pannes, tidal channels, mudflats, and bay. The map primarily depicts a time sequence of marsh growth as influenced by the activities of artificial filling within the former Coyote Creek embayment and reclamation of the former Historical Coyote Creek Marsh. Although the colored polygons represent the extent of marsh over different time periods, they also represent the actual amount of existing vegetation at the time of the 8/2016 base map image. Thus it is important to emphasize that the pattern does not represent the age of the existing vegetation on the marsh but the temporal pattern of marsh migration. Therefore, the

			coverage of vegetation during the historical time periods might also have been more dense within the different bands of color, but appear to be diminished due to increases in size of pannes and channels during 8/2016. A single white line represents the 1851 shoreline. Light grey areas are essentially the unvegetated intertidal areas. Artificial fill that was placed in front of the 1851 shoreline is shown as dark grey and has a mix of vegetated land and commercial development. Artificial levees, dredge spoils, and a combination of the two are shown as various shades of pink, while red polygons represent demolition debris and concrete rubble. Colored polygons (other than light and dark grey polygons) represent areas with vegetation. The Bay Trail, shown as a light pink polygon, is a partial exception since some portions of the levee are paved, bare ground, or rocky slope. Dark green polygons represent transitional high marsh vegetation to artificial fill that is above MHHW. Its distribution represents a mix of time periods. Most of the other polygons are linked to a time period over which vegetation colonized the mudflats in Coyote Creek embayment as it adapted to various perturbations such as changes in the size of the tidal inlet, diversion of Coyote Creek, installation and subsequent removal of a tidal flap gate, and rising sea level. Bright green polygons represent the extent of marsh by 1899. The dark blue polygons represent the position of the Historical Coyote Creek in 1960 before it was diverted a few years later. The surrounding polygons of yellow (1978), blue-green (1946), and dark purple (1952), and light purple (1960) show the migrating extent of marsh along its delta/alluvial fan and quieter perimeter waters of the embayment. After the construction of the flood control canal and installation of the tidal flap gate, the areal extent of marsh colonization diminished and progressively slowed between 1965 and 1978. The time intervals are represented by olive-green (1965), olive-brown (1973), light-green (1976) and yellow-green (1978) polygons. The olive-green and olive-brown areas might approximate the areas that were most subject to seasonal periods of standing water and desiccation while the flap gate was in place. It might have been removed during 1981 and the areal coverage of vegetation became smaller for a short time due to drowning . Polygons colored green (1987), burgundy (2005), and rusty orange (8/2016) represent marsh colonization after the 26-foot wide inlet was opened to the Coyote Creek embayment. The amount of vegetation colonization within the embayment appears to be decreasing, and the

			channel network and panne density (amount of channel per unit area) appears to be slightly increasing during the last decade. This likely reflects the influence of increased submergence from rising sea level and insufficient sediment supply. Rectangle Marsh and East Bothin Marsh do not reflect any notable marsh colonization since 1987. **Ref Image #122** shows a geomorphic map of the North Bothin and Almonte Marsh marsh complex using the same legend key for polygons representing intertidal vegetation and significant adjacent vegetated levee features above MLLW. Unlike South Bothin Marsh, it does not have a high density of channels and pannes. Almonte Marsh and North Bothin Marsh are separated by the c. 1930s levee (rosy pink polygon) shown as a narrow band near the power line boardwalk (red line). The pattern of Marsh colonization of Almonte Marsh shows the progressive bayward migration in from of the 1851 foreshore (white line). The light-blue band reflects the location of the 1851 overwash wave-formed berm at the foreshore. The bright green polygon shows the extent of marsh growth by 1899 and the 1927 marsh extent is represented by the teal color. The exterior levee (medium pink) on Almonte Marsh was placed on the 1946 marsh, about 20-25 ft inland from its foreshore. Some of it was preexisting from 1930s but upgraded and extended in 1965. Dredge spoils, shown as salmon pink polygons, were placed at the north end of Almonte Marsh between 1965 and 1973 but the west dredge spoils might be as old as the original railroad construction of 1883. The levee on North Bothin Marsh constructed in 1965 on mudflats is shown as fuchsia pink. Dredge spoils, were added at the south end sometime between 1965 and 1973. The conversion from small mudflat embayment to marsh with tidal channels within North Bothin Marsh has been fairly rapid since the initial levee breach in 1974. The only notable marsh colonization between 1946 and 1976 was on the outboard side of the levee. The south corner of the marsh near the intersection of the Bay Trail and the exterior levee appears to be loosing vegetation while a relatively newly formed panne increases in size. This is likely reflecting insufficient tidal prism and sediment supply. The geomorphic map clearly shows the low drainage density in 2017 of the North Bothin/Almonte Marsh complex.
2017	123, 124, 125	Evidence of loss of high elevation marsh within SBM	The photograph in **Ref Image #123** show a very high tide where water is pouring out of South Bothin Marsh over the low north bank levee of the Coyote Creek Canal. This represents what will become an increasing condition with sea level rise, and will likely change much of the tidal dynamics of the marsh. This photo shows that if Coyote Creek were at a very large flood

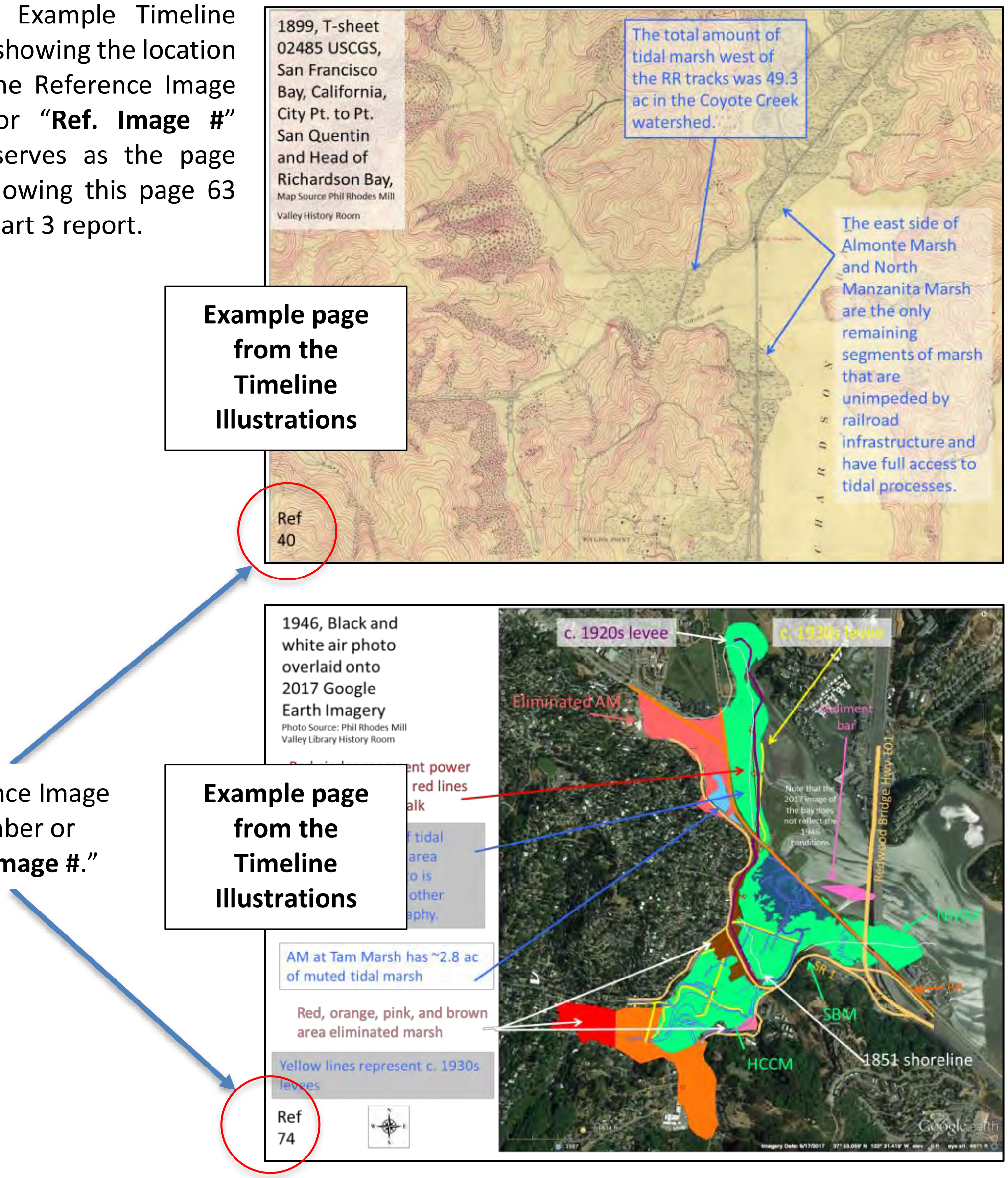
		and due to sea level rise	stage during a similarly high or higher tide, the Bay Trail, the small outlet of Coyote Creek Embayment at Bridge 2 and the structure of Bridge 1 would impede the escape and conveyance of floodwaters to Richardson Bay. The tidal choking of the basin creates a net water surface slope toward Coyote Canal can be seen while South Bothin Marsh drains during the higher stages of extreme high tides. **Ref Image #122** shows several photographs that demonstrate some of the characteristics of South Bothin Marsh including sediment-rich water of Coyote Creek, areas of backshore that still desiccate due to the muted tide caused by the constricted inlet at Bridge 2 inlet, channels deepening and marsh building in the Coyote Creek Embayment, and tidal connection between the Coyote Creek Canal and South Bothin Marsh during a lower tide than the one shown in the previous **Image Ref # 124**. The original rocky railroad levee of the Bay Trail continues to separate South Bothin Marsh from North Bothin Marsh at almost all tidal stages. The undersized, South Bothin Marsh tidal inlet that has armored grade control continues to choke tidal flows, creating muted tides that delay flood/ebb peaks within the tidal basin, relative to the Bay. It establishes visible, turbulent water surface slopes between the tidal basin and the bay at the inlet during ebb tides that creates scour at the outlet **Ref Image #125** shows a comparison of the modern and historical marshes of the Bothin Marsh Complex in the context of each other and their watersheds. Only Almonte Marsh overlaps with the extent of the 1851 historical marsh. The total amount of combined area of all the modern marshes is ~66.7 ac. The original combined extent of historical marshes was 141.5 ac, of which HCCM had 761 ac. ~18 ac of AM exists of its ~50 ac. It is the only historical marsh remaining in the study area. The extent of historical marshes is within the future extent of sea level rise.

3.5 Timeline Illustrations

The following pages contain the graphs and images used to illustrate the Timeline presented above. There is one illustration per page. The second column of the Timeline refers to the images as Reference Image Numbers, or “**Ref. Image #.**” The Reference Image Numbers are also provided in the lower left corners of the illustrations, to facilitate easy cross-referencing between the Timeline and its illustrations. The illustrations are numbered consecutively, such that the “**Ref Image #**” also serves as the page number. This is shown kin Figure 3.2 below.

It should be noted that not every image is used in the Timeline.

Figure 3.2. Example Timeline illustration showing the location of the of the Reference Image Numbers, or “**Ref. Image #**” That also serves as the page number following this page 63 of the this Part 3 report.



Reference Image Number or “**REF Image #.**”

Bothin Marsh Preserve and Project Boundary

Map Source: https://www.marincountyparks.org/~/media/Images/Departments/PK/Open%20Space/Bothin%20Marsh/Map%205Bothin073114.pdf

Location of Bothin Marsh Open Space Preserve is shown in green. The double red line shows the project area for modern tidal Bothin Marsh, the focus of this memorandum. The historical analysis extends beyond the boundaries of the project area to understand the context of landscape change

Ref 1


Bothin Modern Marsh
Location Names for Historical
Tracking and Analysis
Map Source: Google Earth Imagery 8/14/2016
Marsh names and abbreviations:
AM = Almonte Marsh (includes Tam Marsh)
EBM = East Bothin Marsh
HCCM = Historical Coyote Creek Marsh (not shown)
NBM = North Bothin Marsh (includes Rectangle
NMM = North Manzanita Marsh
SBM = South Bothin Marsh
Tidal flood control channels:
ACMdP = Arroyo Corte Madera del Presidio Canal
CCC = Coyote Creek Canal
CCr = Coyote Creek
Bridges:
Bridge 1 = ~105-foot-long footbridge over CCC
Bridge 2 = ~27-foot-long footbridge over Coyote Creek Embayment
Shoreline Bridge = Highway 1 Bridge over CCC
Richardson Bay Bridge = Redwood Highway Bridge 101 concrete bridge
Other Features
Hwy 101 = Highway 101
RR = Railroad right-of-way (later becomes Bay Trail Bay)
Bay Trail = Mill Valley Sausalito Path (former RR)
SR 1 = State Route 1
Bay Trail = Mill Valley Sausalito Path, also known as Bike Path
Ref 2
Bothin Marsh Study Boundary Area
Arroyo Corte Madera del Presidio Canal
Almonte Marsh AM
Richardson Bay
Tam Marsh part of AM
Bay Trail
North Bothin Marsh NBM
Richardson Bay Bridge
Rectangle Marsh part of NBM
Coyote Creek Embayment
North Manzanita Marsh NMM
South Bothin Marsh SBM
East Bothin Marsh EBM
Bridge 2
Richardson Bay Bridge along Hwy 101
Bridge 1
Shoreline Bridge along State Route 1 SR1
Coyote Creek Canal CCC
Google

1781, Cañizares Map of San Francisco Bay

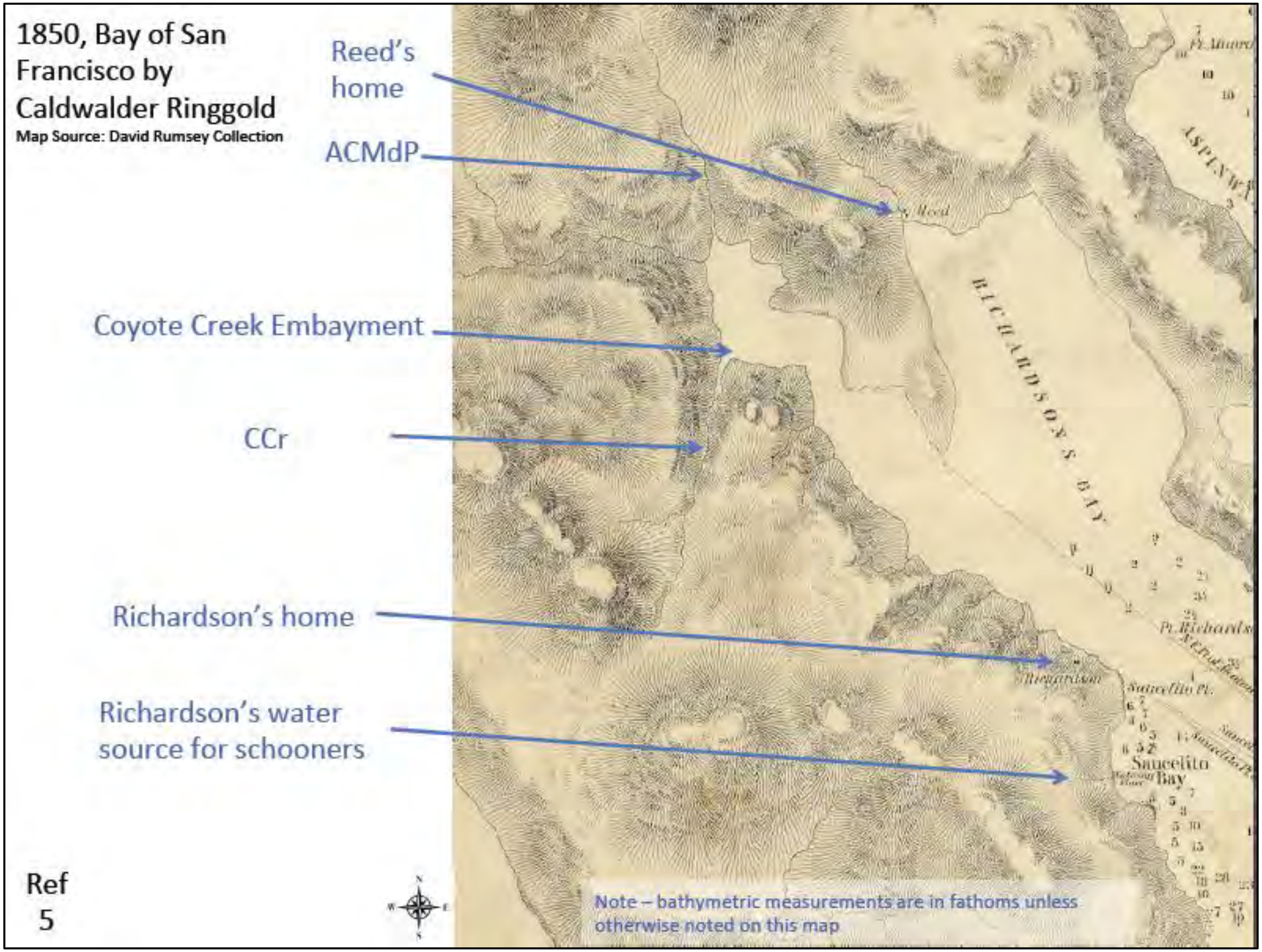
Map Source: https://commons.wikimedia.org/wiki/File: 1781_Ca%C3%B1izares_Map_of_San_Francisco_Bay.pdf

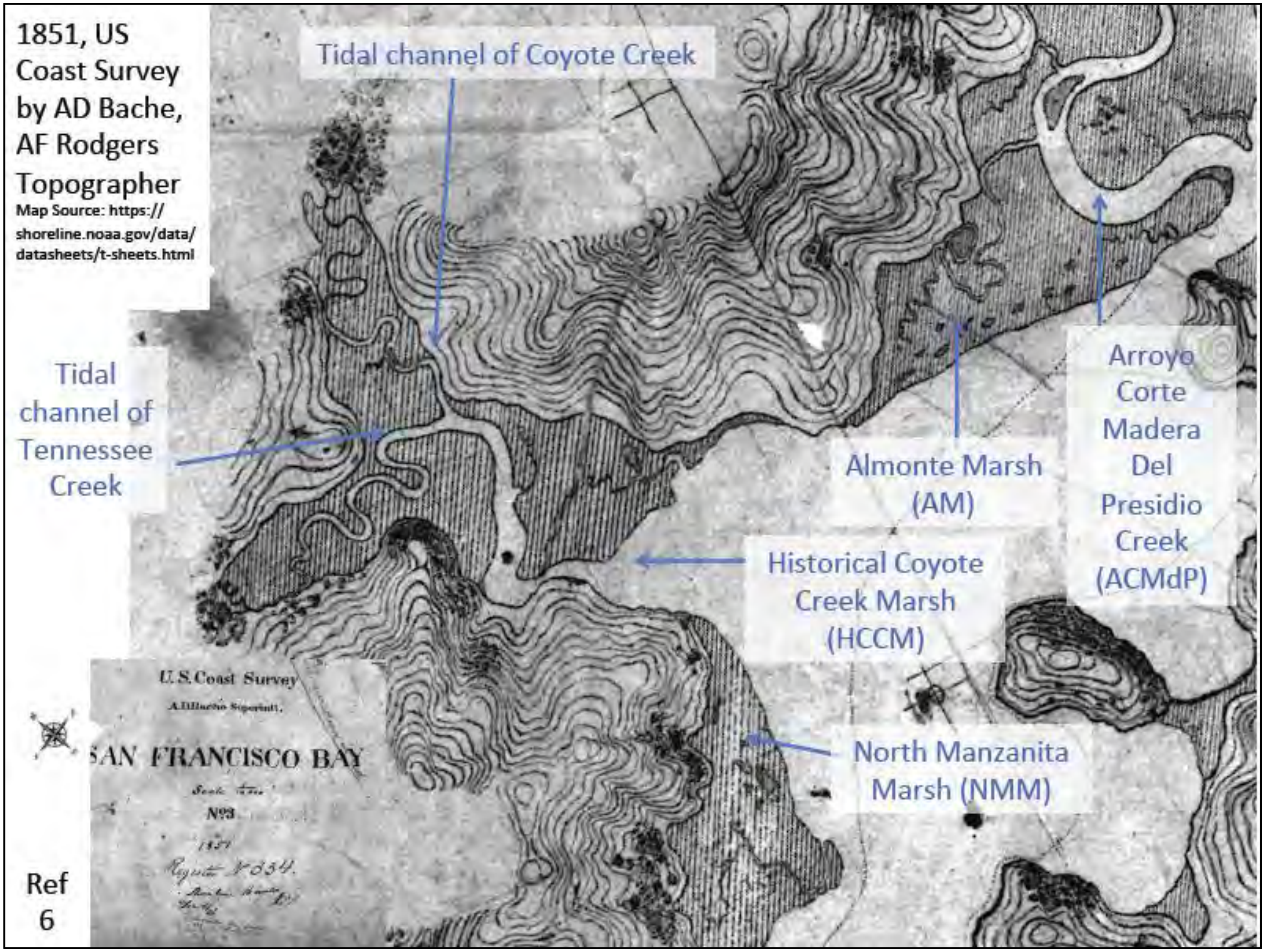
Possible embayment of Coyote Creek can be seen between the E and D symbols on the map.

B. Point Reyes	M. San Joaquin river	X. Mission Dolores
C. Point Bonita	N. Sacramento river	I. Fort Point
D. Lime Point	Q. Oakland, etc.	Z. Point Lobos or Pt. of the Guardian Angel
E. Richardson's Bay	S. Coyote Point	e. Golden Gate
F. Belvedere	T. Mission Creek (Channel Street)	f. Angel Island
H. San Pablo Bay	V. Presidio	g. Alcatraz
Y. Petaluma Creek		

Ref 3

This anonymous painting of Wm. Richardson's home c. 1845 is from the Bancroft Library. It appears in Jack Tracy's book, Moments in Time.


1850, Bay of San Francisco by Caldwalder Ringgold
Map Source: David Rumsey Collection
Reed's home
ACMdP
Coyote Creek Embayment
CCr
Richardson's home
Richardson's water source for schooners
Ref 5
RICHARDSON'S BAY
Saucelito Bay
Note – bathymetric measurements are in fathoms unless otherwise noted on this map

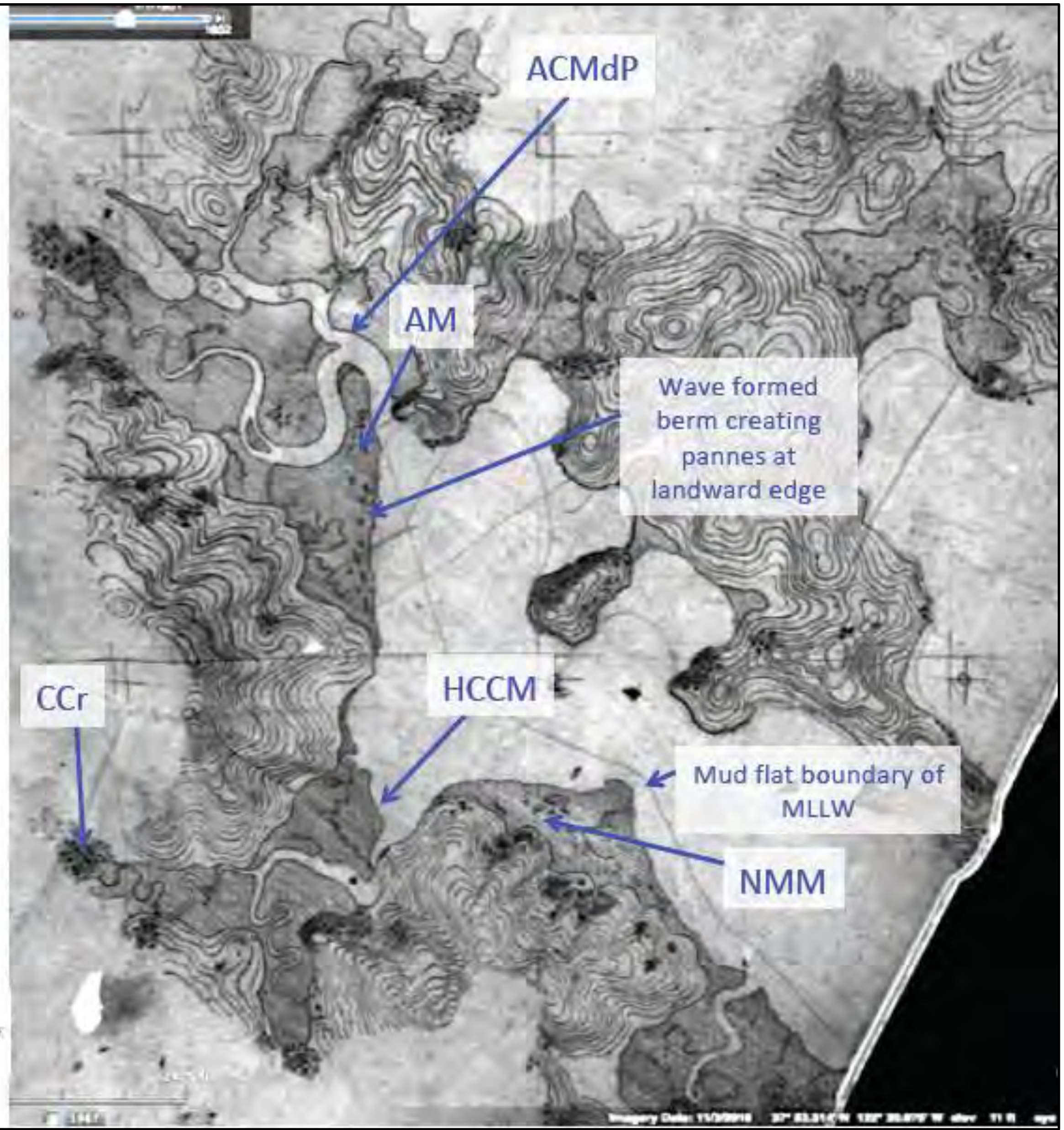

1851, US Coast Survey by AD Bache, AF Rodgers Topographer
Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html
Tidal channel of Coyote Creek
Tidal channel of Tennessee Creek
Almonte Marsh (AM)
Arroyo Corte Madera Del Presidio Creek (ACMdP)
Historical Coyote Creek Marsh (HCCM)
North Manzanita Marsh (NMM)
U.S.Coast Survey
SAN FRANCISCO BAY
No3
Ref 6

1851, US Coast Survey by AD Bache, T-00334

Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html

This map has the earliest depiction of the boundary line of Mean Lower Low Water (MLLW) in the head of Richardson Bay. It is possible that Richardson Bay was already exhibiting some level of shallowing and narrowing of the MLLW boundary by the time the map was made because of the land use activities in the upland watersheds that already included significant disturbances from grazing, logging, and conversion from native perennial grasslands to annual.

Ref 7



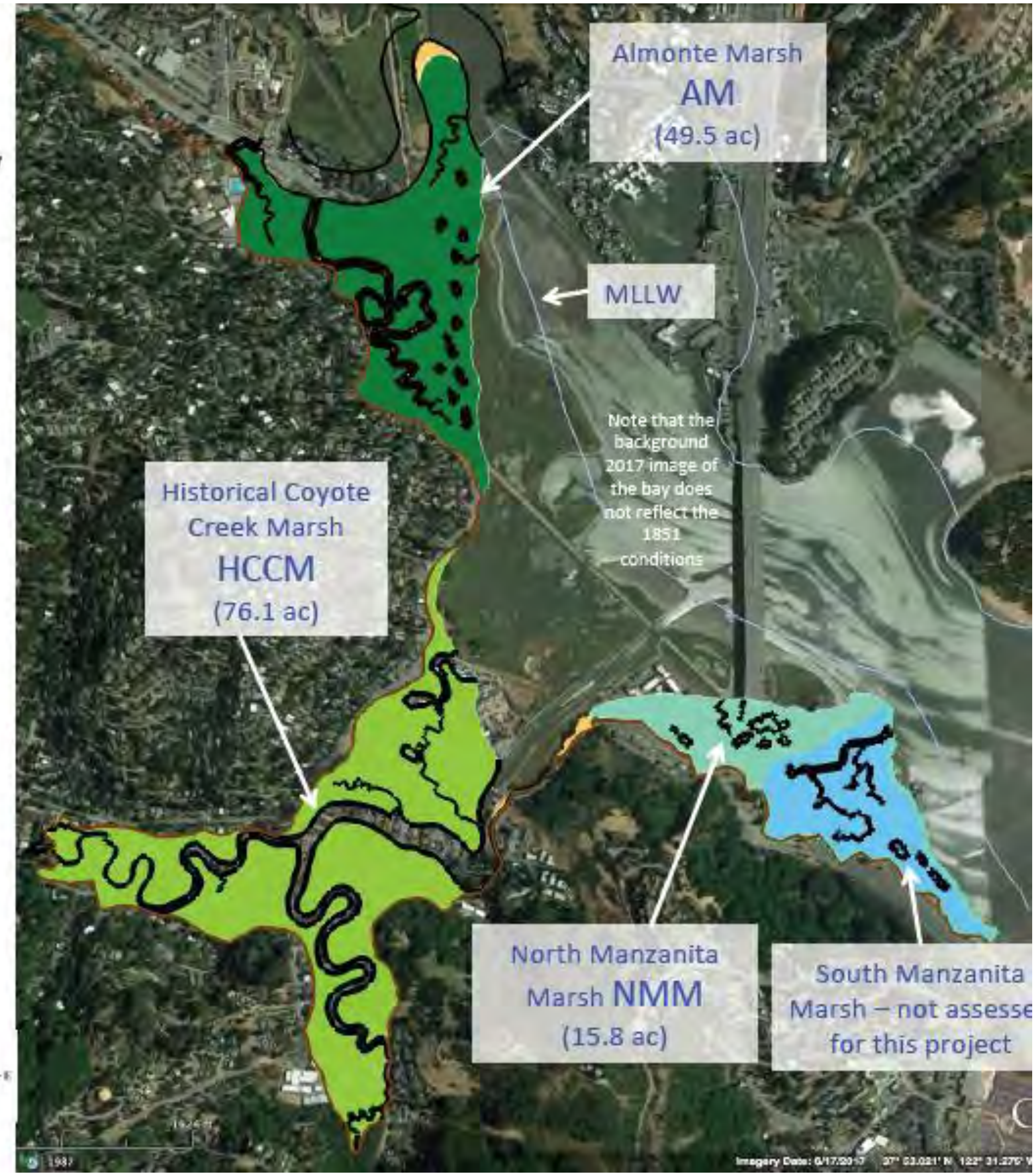
1851, Drainage Area of US Coast Survey by AD Bache, T-00334 Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html

The dramatic reduction in drainage area to SBM was caused by diversion of Coyote Creek and construction of the CCC for flood control. Modern SBM has been robbed of upland fluvial sediment supply.

Ref 8

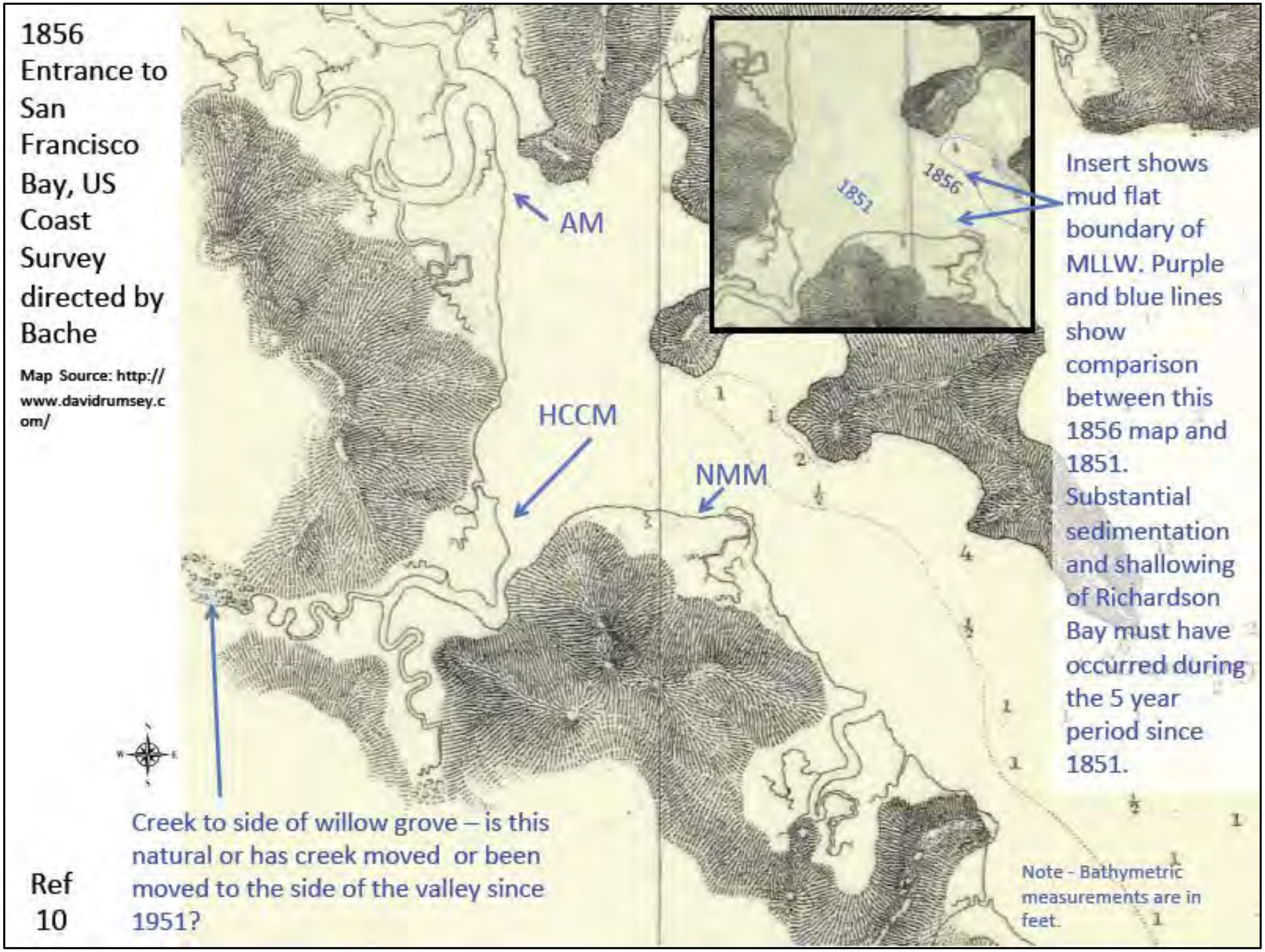
1851, US Coast Survey by AD Bache, T-00334 overlaid onto Google Earth Imagery 6/2017.

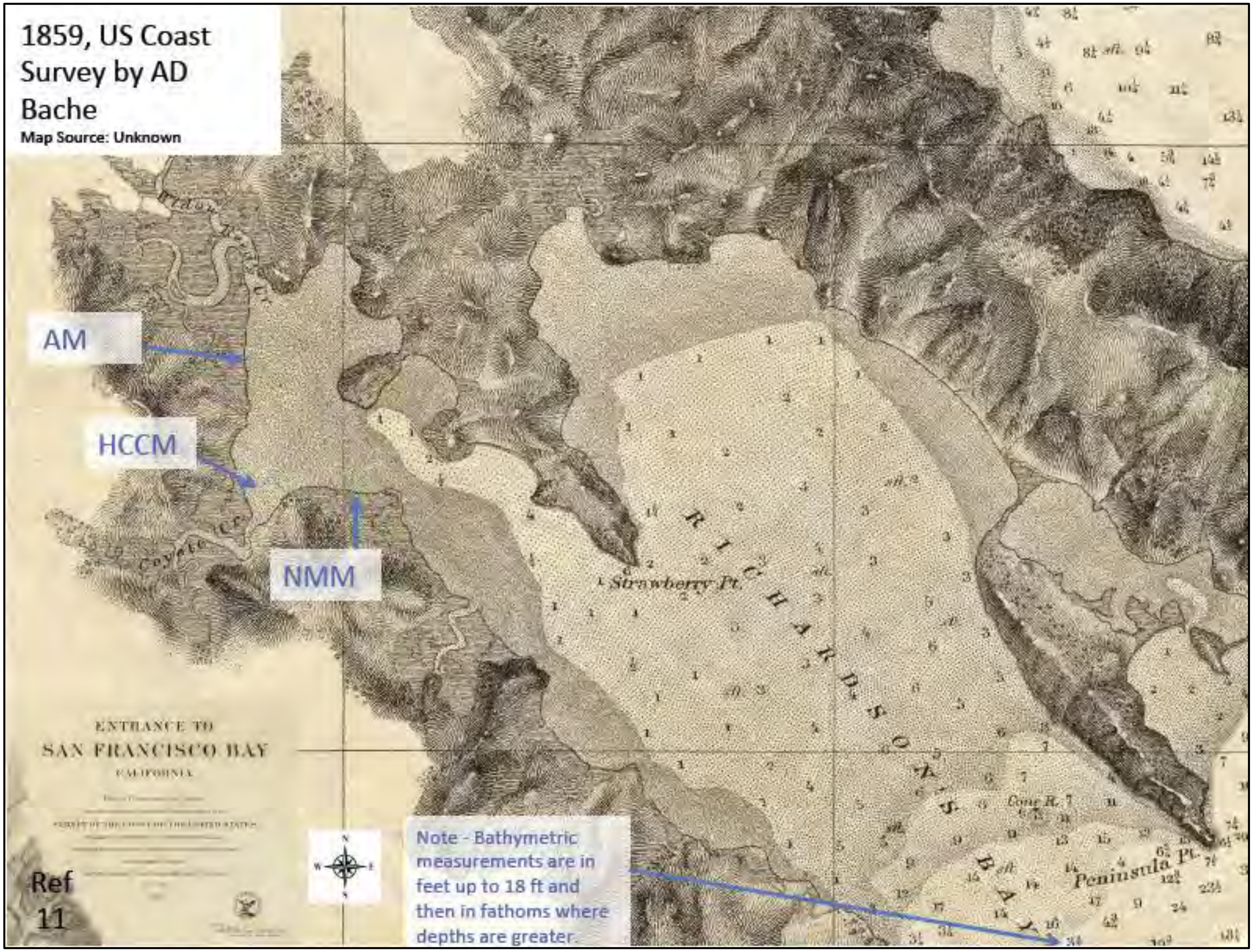
Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html



Relative to the modern landscape, historical 1851 marshes have been highlighted. Green and blue polygons show historical high elevation pickleweed-dominated marshes. Buff colored polygons show low elevation cordgrass-dominated marshes. Black lines show historical tidal channels and ponds. The lavender line shows MLLW.

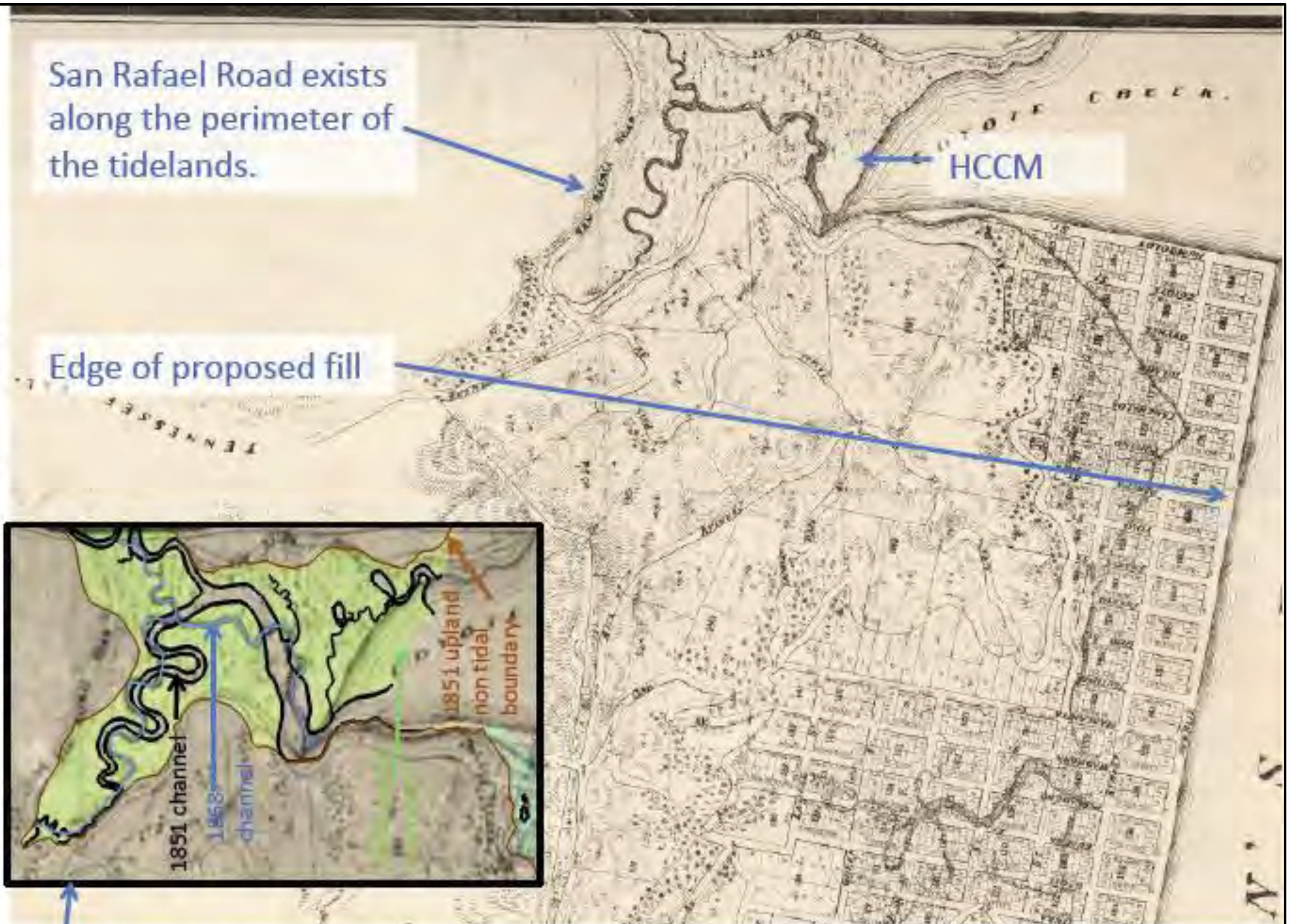
Ref 9


1856 Entrance to San Francisco Bay, US Coast Survey directed by Bache
Map Source: http://www.davidrumsey.com/
AM
HCCM
NMM
1851
1856
Insert shows mud flat boundary of MLLW. Purple and blue lines show comparison between this 1856 map and 1851. Substantial sedimentation and shallowing of Richardson Bay must have occurred during the 5 year period since 1851.
Creek to side of willow grove – is this natural or has creek moved or been moved to the side of the valley since 1951?
Note - Bathymetric measurements are in feet.
Ref 10


1859, US Coast Survey by AD Bache
Map Source: Unknown
AM
HCCM
NMM
Strawberry Pt.
RICHARDSON'S BAY
Peninsula Pt.
ENTRANCE TO
SAN FRANCISCO BAY
CALIFORNIA
Note - Bathymetric measurements are in feet up to 18 ft and then in fathoms where depths are greater.
Ref 11

1868 Detail of Sausalito Land and Ferry Company

Map Source: https://www.google.com/search?q=sausalito+land+and+ferry+company+map&tbm=isch&imgil=g254e1IEcnnaaM%253A%253BkWqyDVbWR_QzRM%253Bhttp%25253A%25252F%25252Fwww.frederickbee.com%252525Fsausalitomap.html&source=iu&pf=m&fir=g254e1IEcnnaaM%253A%252CkWqyDVbWR_QzRM%252C_&usg=__TdENRKEyB87VEOzHgl-MbZL9B8A%3D&biw=1620&bih=1319&ved=0ahUKEwj2wMGcwKzTAhUCsFQKHdkeDbcQyjcITA&ei=kzz1WLarGYLg0gLZvbS4Cw#imgdii=vCtljqNZmaHiXM:&imgrc=g254e1IEcnnaaM:



Detail showing comparison of 1868 channel position and sinuosity to 1851. Note the 1868 map appears to be a conceptualized channel and shoreline. A better survey was done in 1870 of the marsh shoreline. The 1851 marsh boundary is shown in green with the brown line representing the upland non-tidal boundary.

Ref 12

1870, Map No. 7 of Salt Marsh and Tidelands Sales map

Map Source: Marin County Recorder's Office

Proposed Coyote Canal was not constructed in the historical marsh but the lower part of this proposed canal closely aligns with the 1965 CCC that was cut through the modern SBM.

Downstream of these points channel mapping seems to follow the 1851 alignment

Ref 13

May 1870, No. 7 Salt Marsh and Tidelands Sales Map,

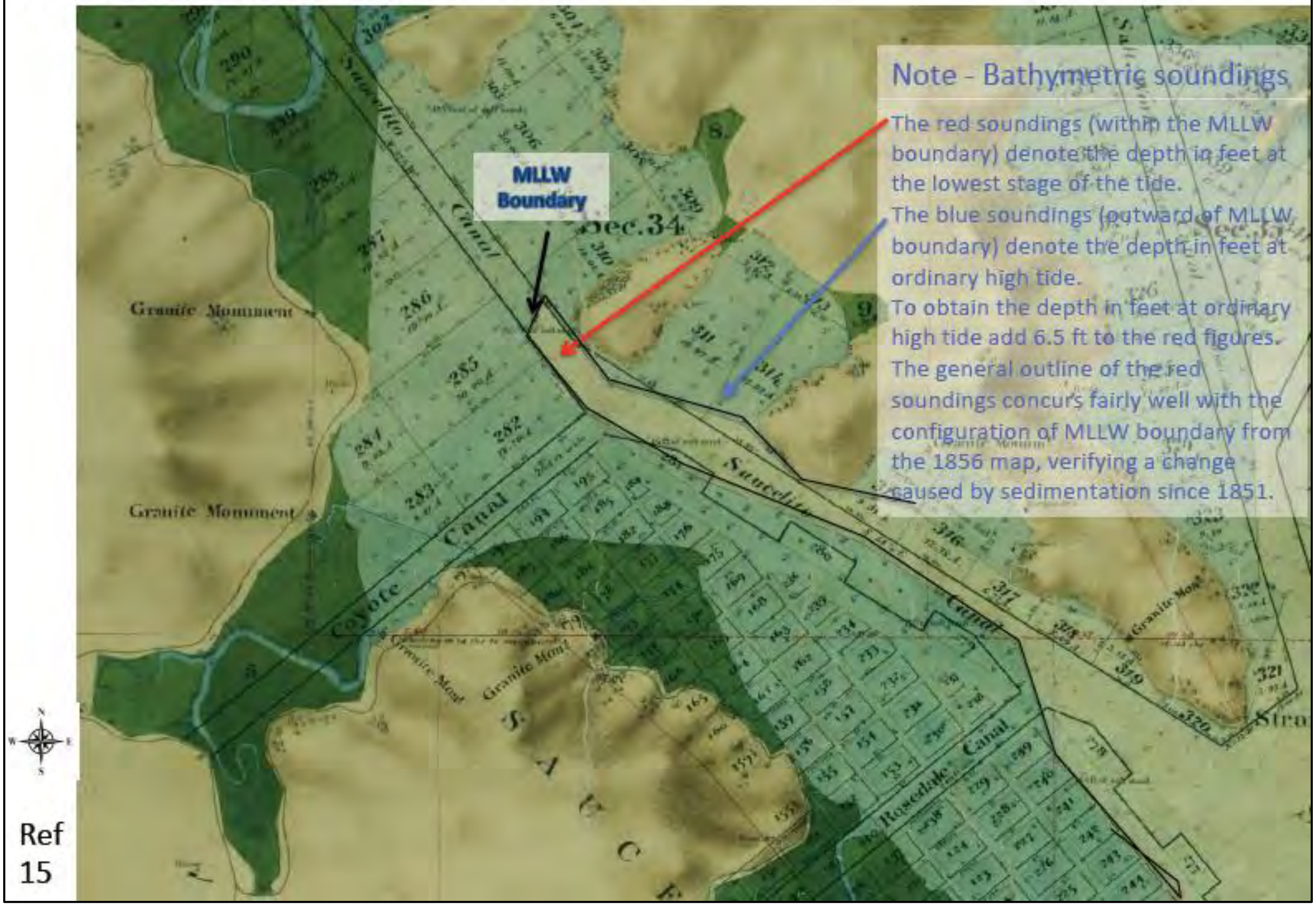
Map Source: Mill Valley Library History Room

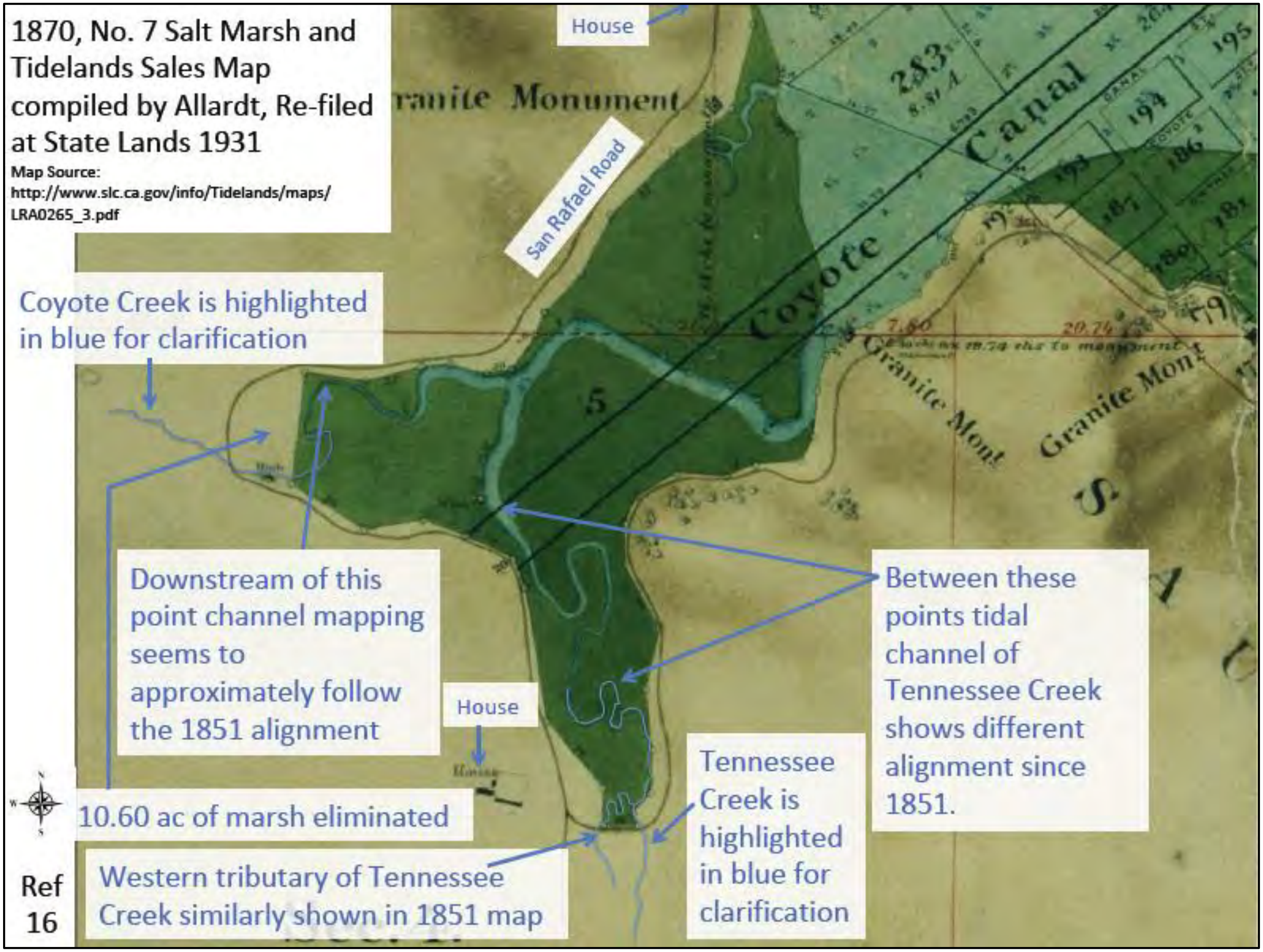
The head of the north fork of the historical marsh has been cut off.

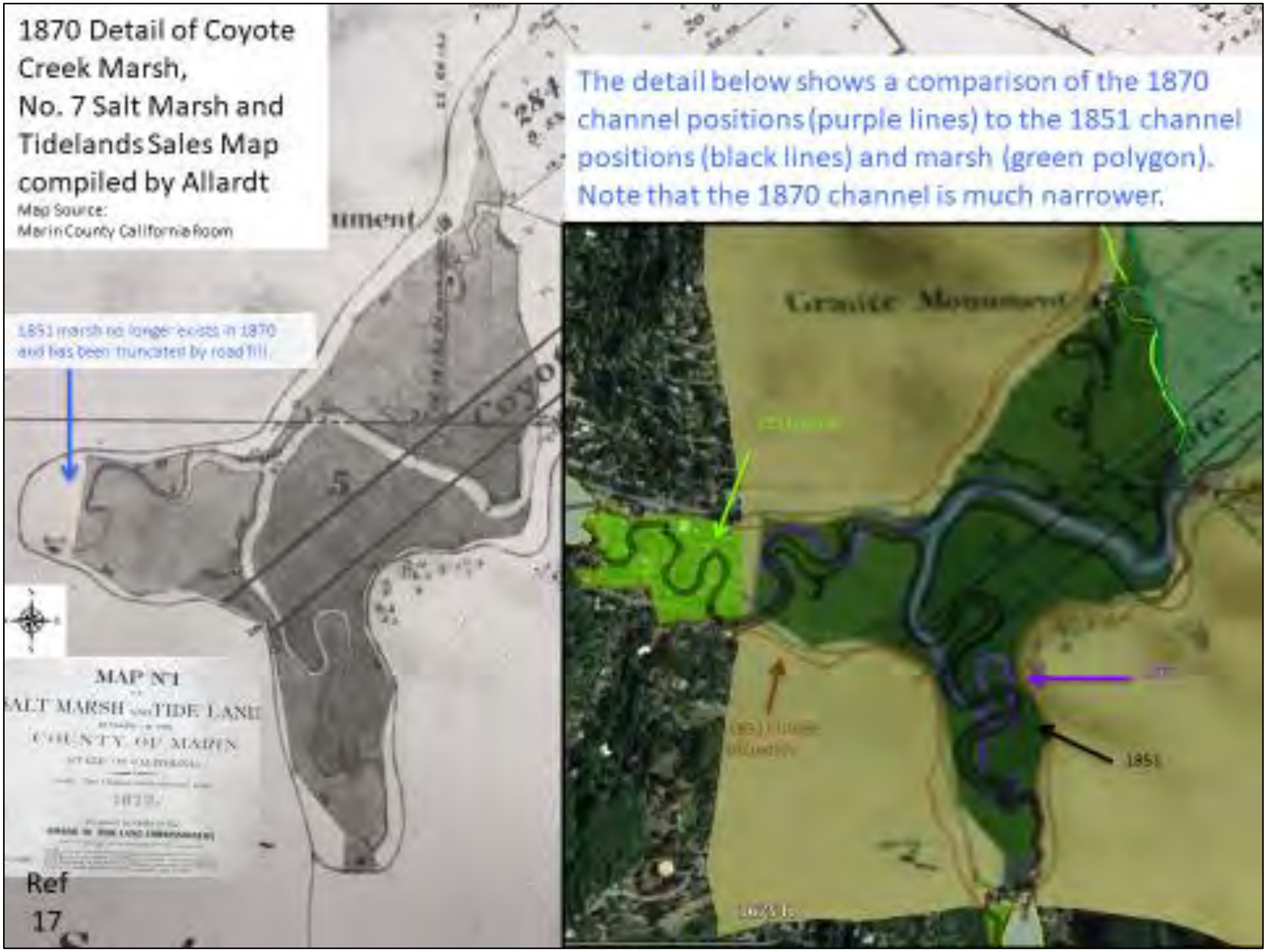
The San Rafael Road otherwise follows the perimeter of the marsh. About 10.6 ac marsh eliminated. Greater creek detail is mapped in other 1870 maps (Image Ref #14, #15 & #16).

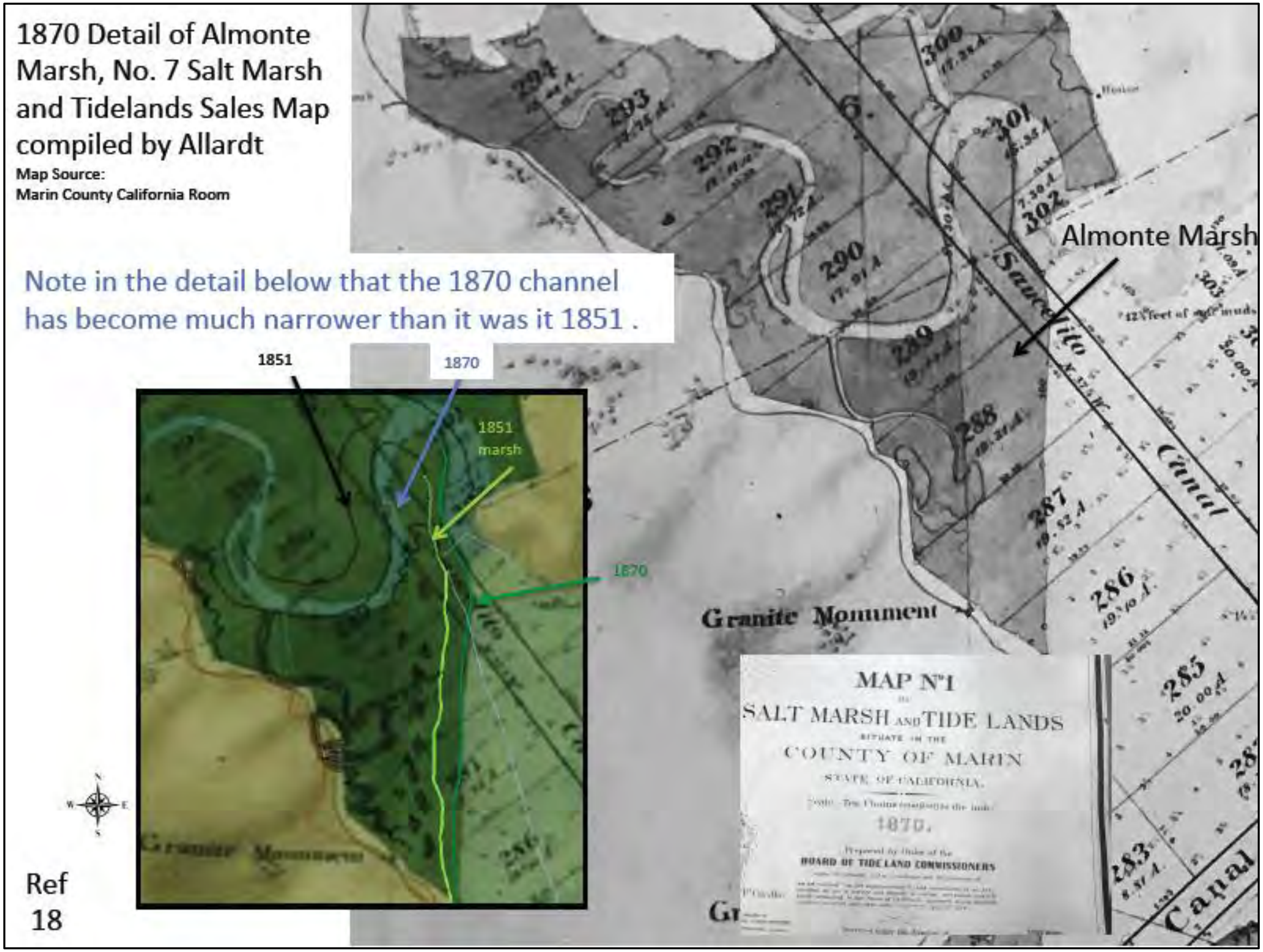
Ref 14

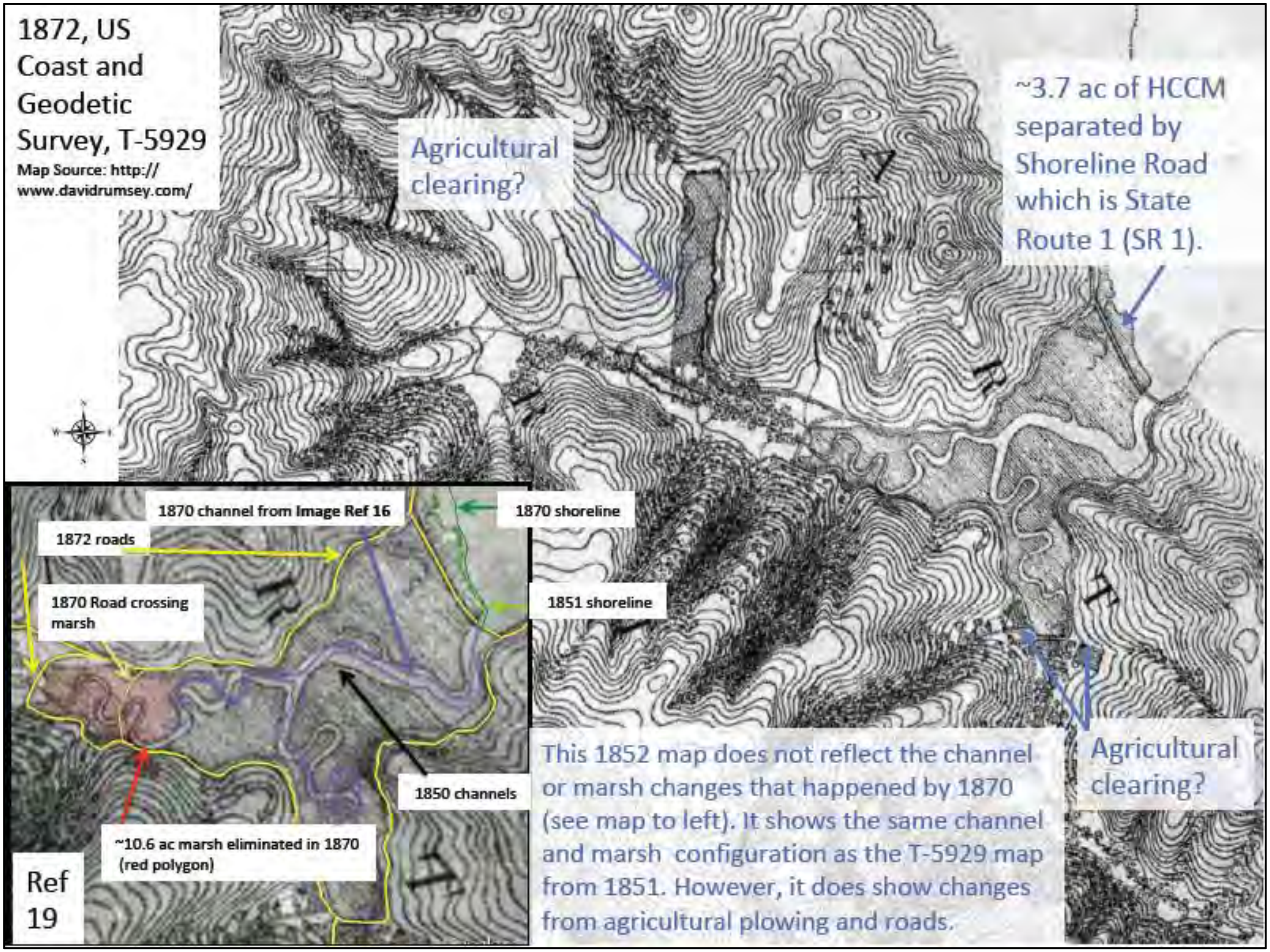
1870, No. 7 Salt Marsh and Tidelands Sales Map compiled by Allardt, Re-filed at State Lands 1931 Map Source:http://www.slc.ca.gov/info/Tidelands/maps/LRA0265_3.pdf

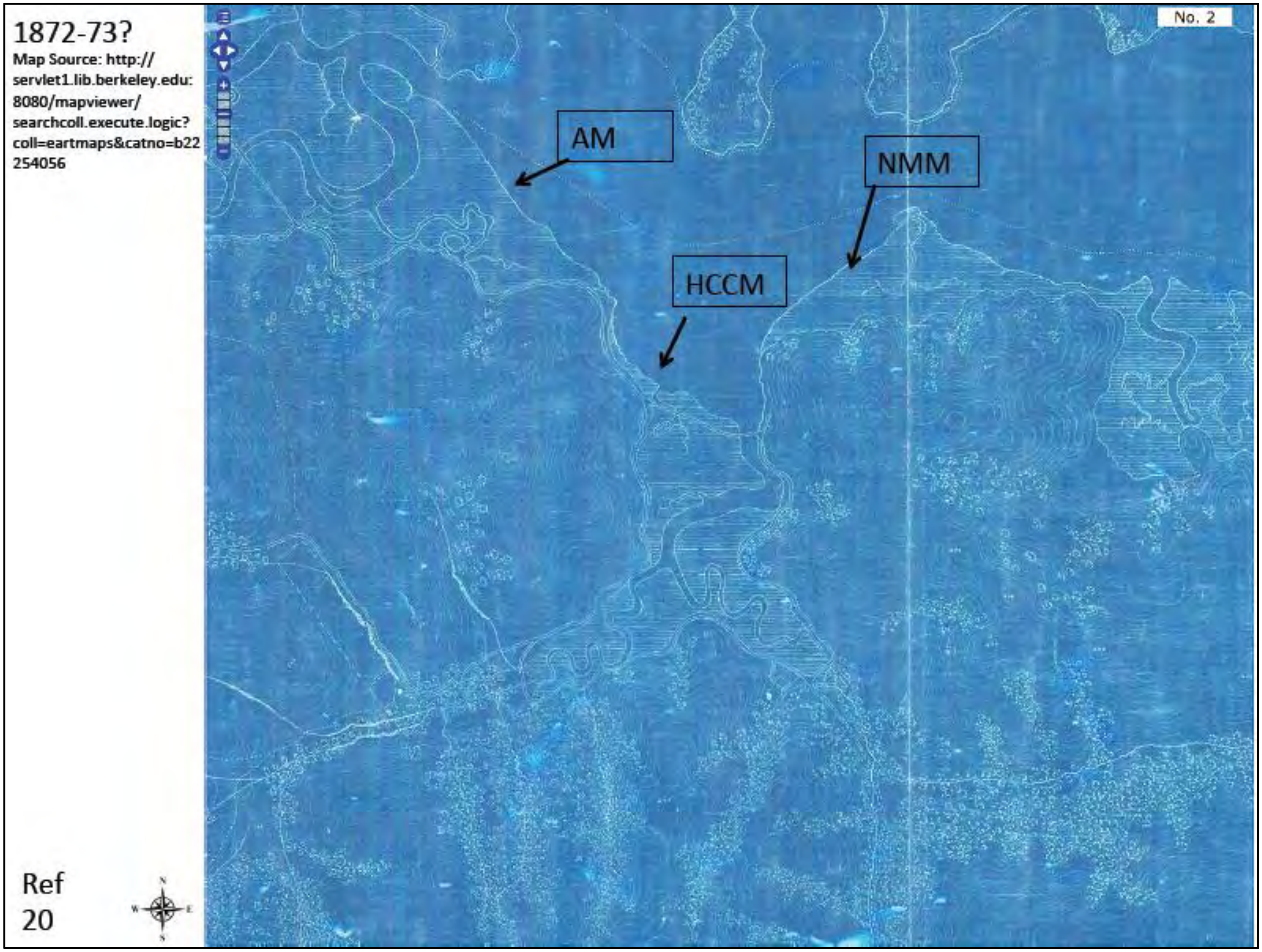


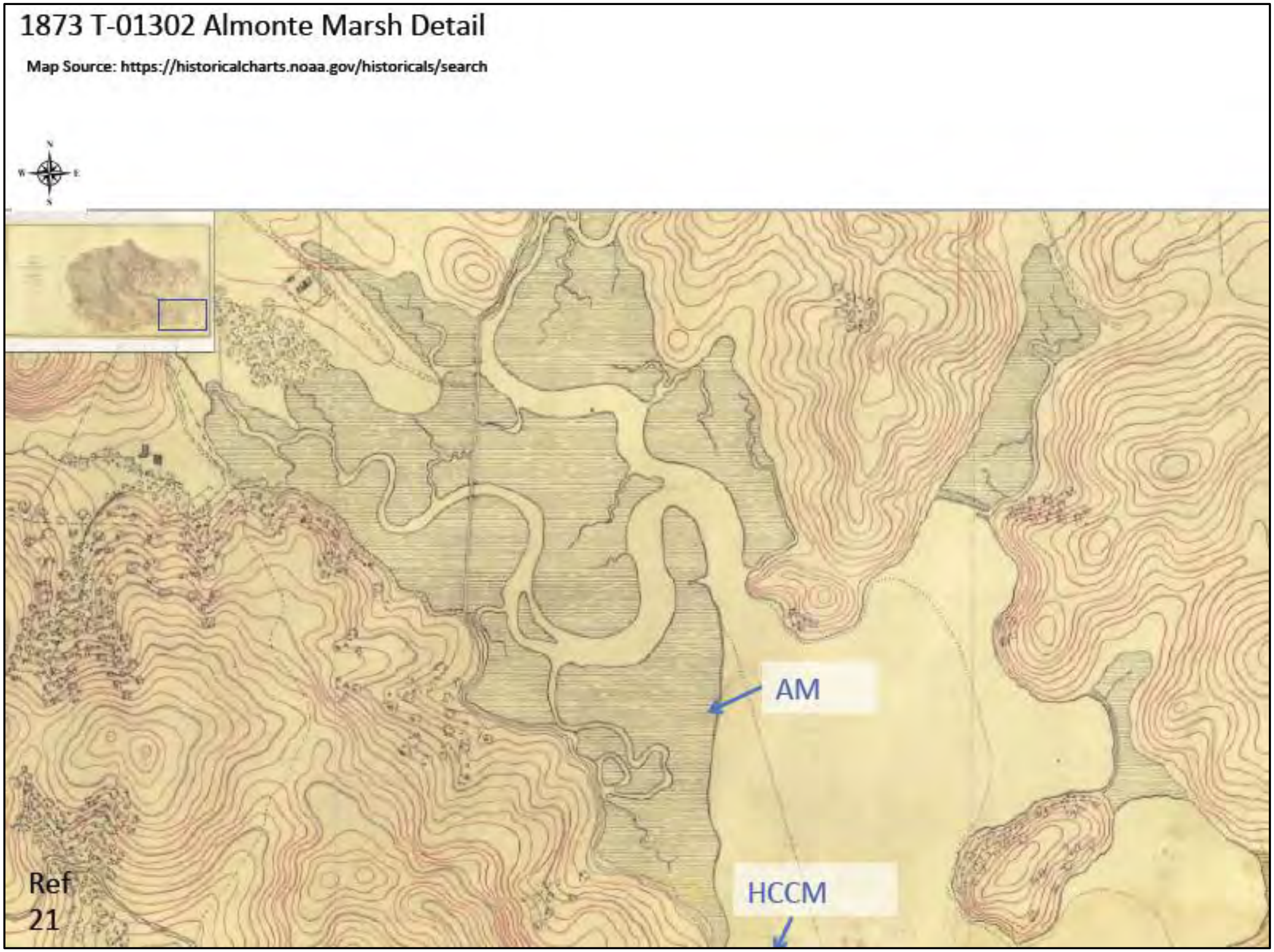

1870, No. 7 Salt Marsh and Tidelands Sales Map compiled by Allardt, Re-filed at State Lands 1931
Map Source: http://www.slc.ca.gov/info/Tidelands/maps/LRA0265_3.pdf
House
Granite Monument
San Rafael Road
Coyote Canal
Coyote Creek is highlighted in blue for clarification
Downstream of this point channel mapping seems to approximately follow the 1851 alignment
House
10.60 ac of marsh eliminated
Western tributary of Tennessee Creek similarly shown in 1851 map
Tennessee Creek is highlighted in blue for clarification
Between these points tidal channel of Tennessee Creek shows different alignment since 1851.
Granite Mont
Granite Mon
Ref 16


1870 Detail of Coyote Creek Marsh, No. 7 Salt Marsh and Tidelands Sales Map compiled by Allardt
Map Source:
Marin County California Room
1851 marsh no longer exists in 1870 and has been truncated by road fill.
MAP No 1
SALT MARSH AND TIDE LAND
COUNTY OF MARIN
Ref 17
The detail below shows a comparison of the 1870 channel positions (purple lines) to the 1851 channel positions (black lines) and marsh (green polygon). Note that the 1870 channel is much narrower.
Granite Monument
1851


1870 Detail of Almonte Marsh, No. 7 Salt Marsh and Tidelands Sales Map compiled by Allardt
Map Source:
Marin County California Room
Note in the detail below that the 1870 channel has become much narrower than it was it 1851 .
1851
1870
1851 marsh
1870
Almonte Marsh
Saucelito
Canal
Granite Monument
MAP No. 1
SALT MARSH AND TIDE LANDS
SITUATE IN THE
COUNTY OF MARIN
STATE OF CALIFORNIA.
1870.
BOARD OF TIDE LAND COMMISSIONERS
Ref 18


1872, US Coast and Geodetic Survey, T-5929
Map Source: http://www.davidrumsey.com/
Agricultural clearing?
~3.7 ac of HCCM separated by Shoreline Road which is State Route 1 (SR 1).
1870 channel from Image Ref 16
1870 shoreline
1872 roads
1870 Road crossing marsh
1851 shoreline
1850 channels
~10.6 ac marsh eliminated in 1870 (red polygon)
Ref 19
This 1852 map does not reflect the channel or marsh changes that happened by 1870 (see map to left). It shows the same channel and marsh configuration as the T-5929 map from 1851. However, it does show changes from agricultural plowing and roads.
Agricultural clearing?


1872-73?
Map Source: http://servlet1.lib.berkeley.edu:8080/mapviewer/searchcoll.execute.logic?coll=eartmaps&catno=b22254056
No. 2
AM
NMM
HCCM
Ref 20


1873 T-01302 Almonte Marsh Detail
Map Source: https://historicalcharts.noaa.gov/historicals/search
AM
HCCM
Ref
21

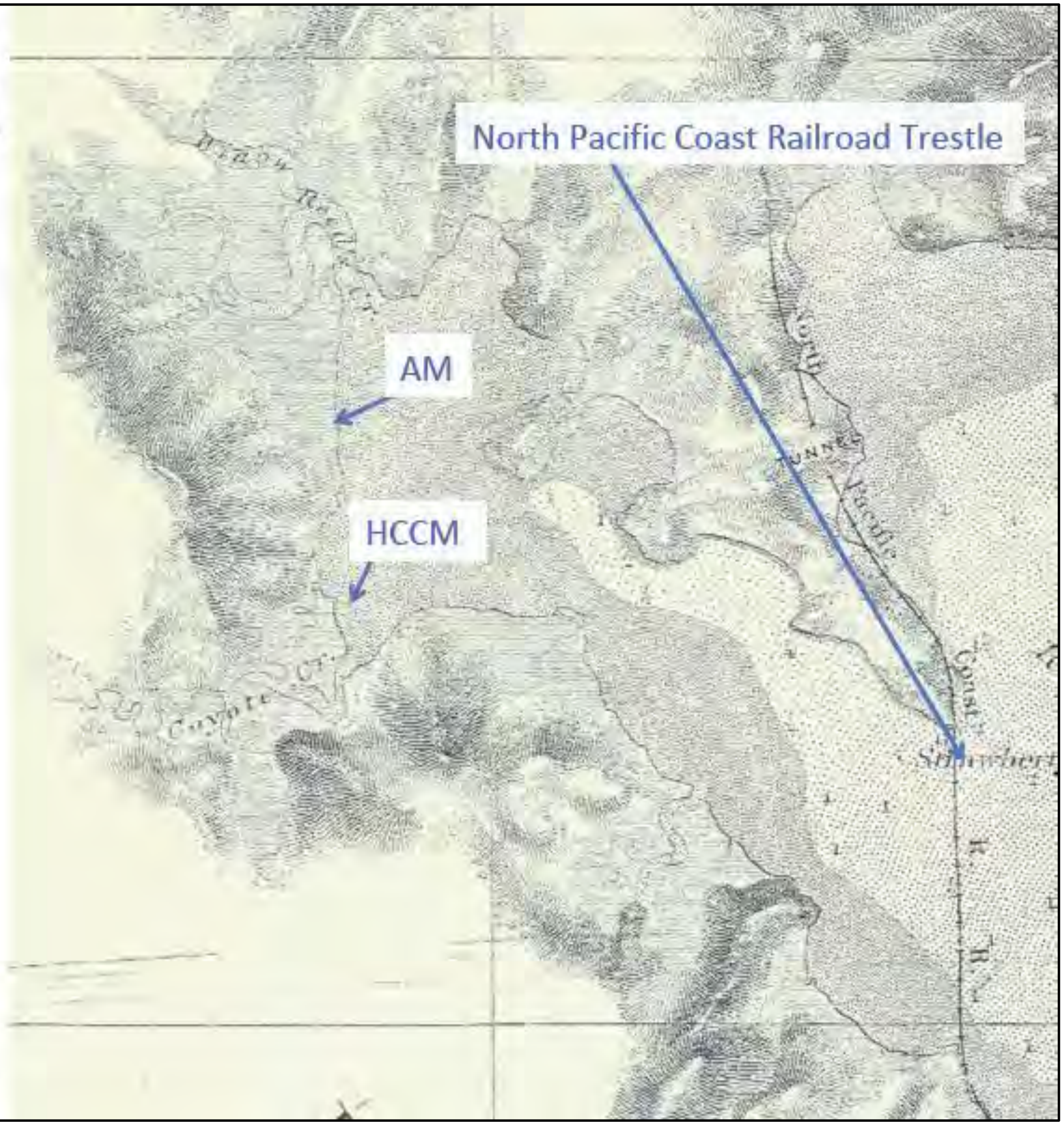
1873 Detail of Map of Marin County Compiled by Austin, drawn by Whitney

Map Source: Marin History Museum

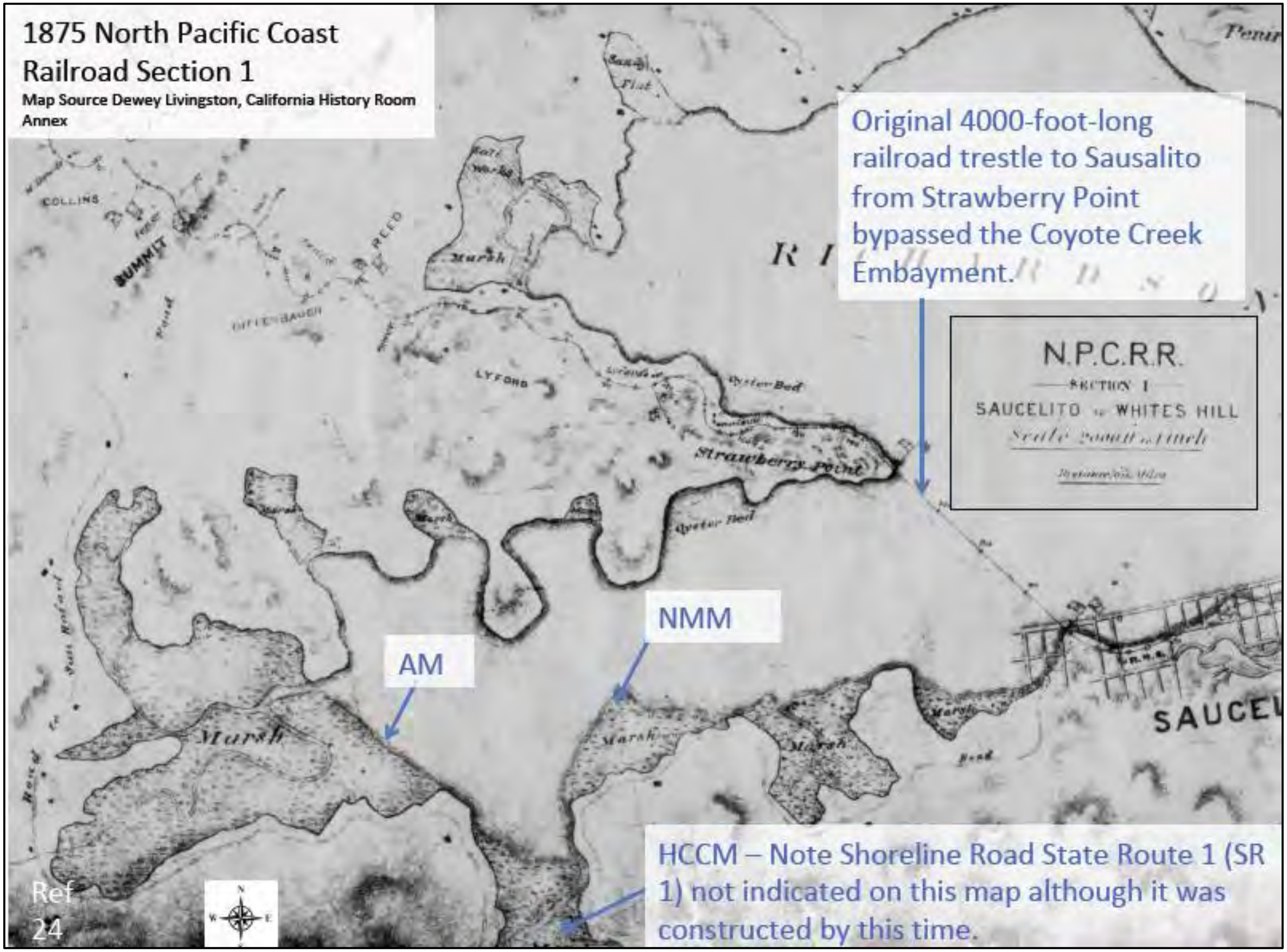
Ref 22

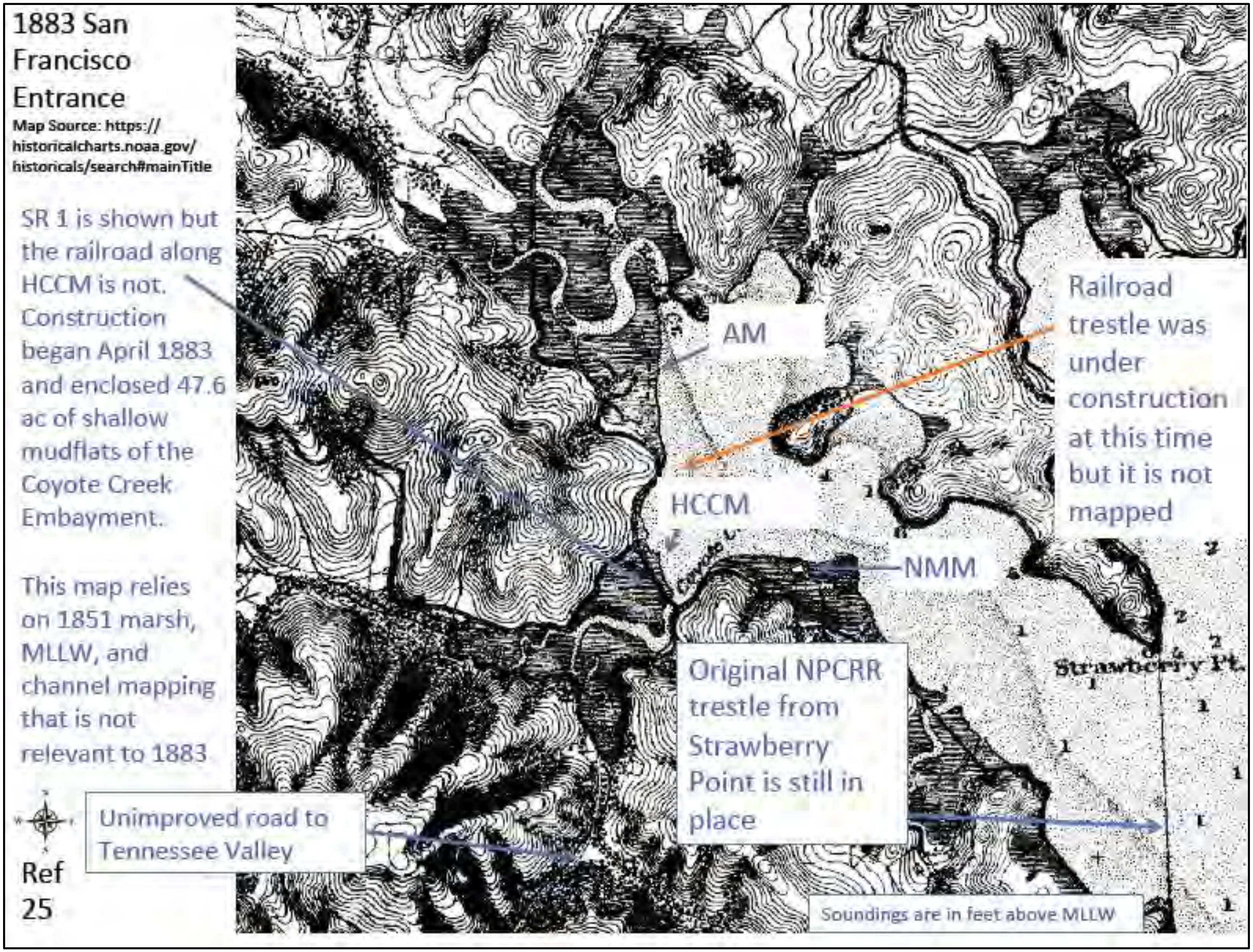
1873 (??) showing earliest North Pacific RR trestle to Sausalito on an earlier map of 1859 Entrance to San Francisco Bay Map by US Coast Survey directed by Bache

Map Source: http://www.davidrumsey.com/



Ref 23


1875 North Pacific Coast Railroad Section 1
Map Source Dewey Livingston, California History Room Annex
Original 4000-foot-long railroad trestle to Sausalito from Strawberry Point bypassed the Coyote Creek Embayment.
N.P.C.R.R.
SECTION 1
SAUCELITO to WHITES HILL
Strawberry Point
Oyster Bed
Marsh
SUMMIT
COLLINS
LYFORD
NMM
AM
SAUCEL
HCCM – Note Shoreline Road State Route 1 (SR 1) not indicated on this map although it was constructed by this time.
Ref 24

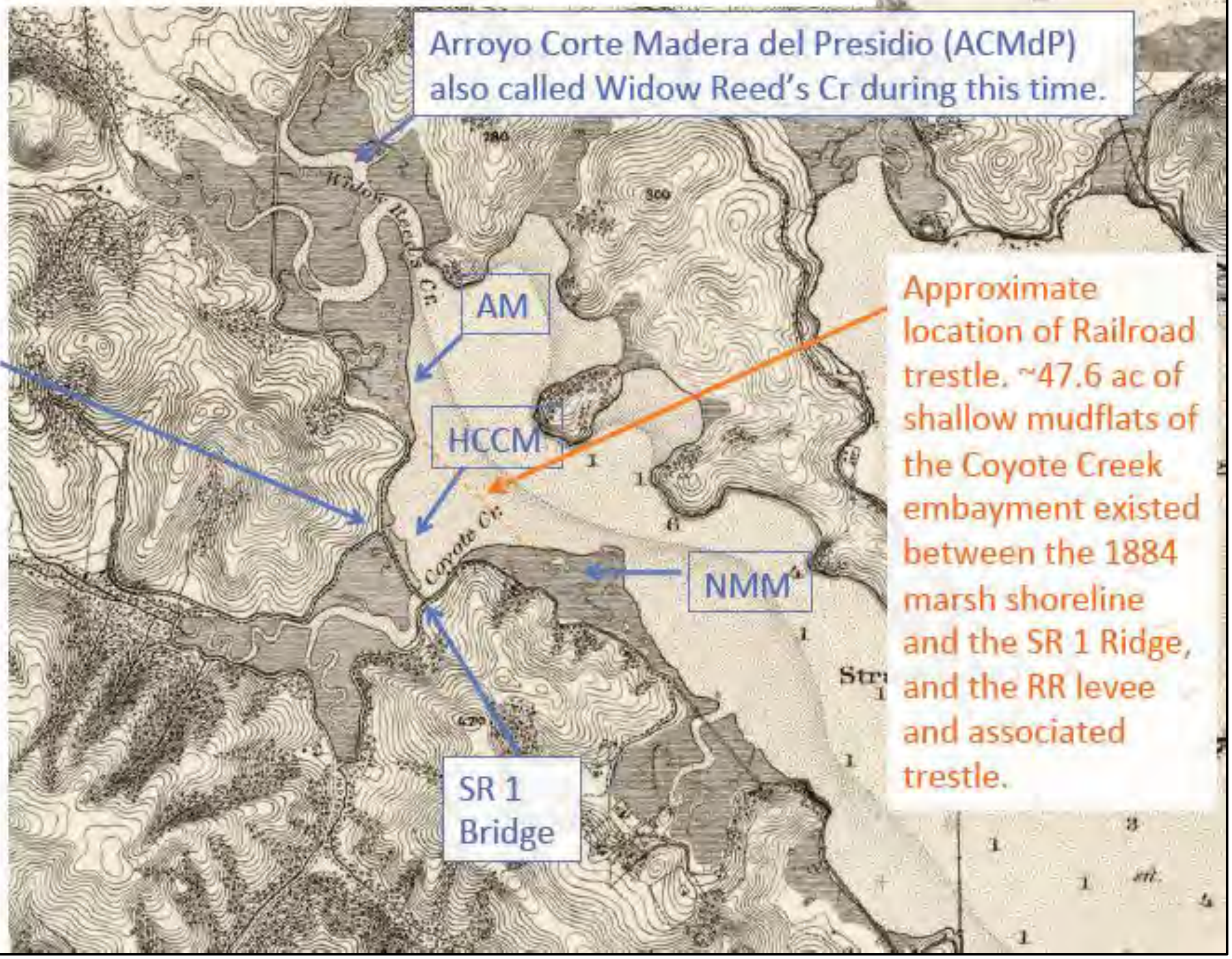

1883 San Francisco Entrance
Map Source: https://historicalcharts.noaa.gov/historicals/search#mainTitle
SR 1 is shown but the railroad along HCCM is not. Construction began April 1883 and enclosed 47.6 ac of shallow mudflats of the Coyote Creek Embayment.
This map relies on 1851 marsh, MLLW, and channel mapping that is not relevant to 1883
Ref 25
Unimproved road to Tennessee Valley
AM
HCCM
NMM
Railroad trestle was under construction at this time but it is not mapped
Original NPCRR trestle from Strawberry Point is still in place
Strawberry Pt.
Soundings are in feet above MLLW

1884 Detail San Francisco Entrance, U.S. Coast Survey.

Map Source: https://www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~239951~5512086:San-Francisco-entrance,-California-?sort=Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No&qvq=q:COAST%2BSURVEY%2BEntrance%2BSAN%2BFRANCISCO%2BBAY;sort:Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No;lc:RUMSEY~8~1&mi=0&trs=10

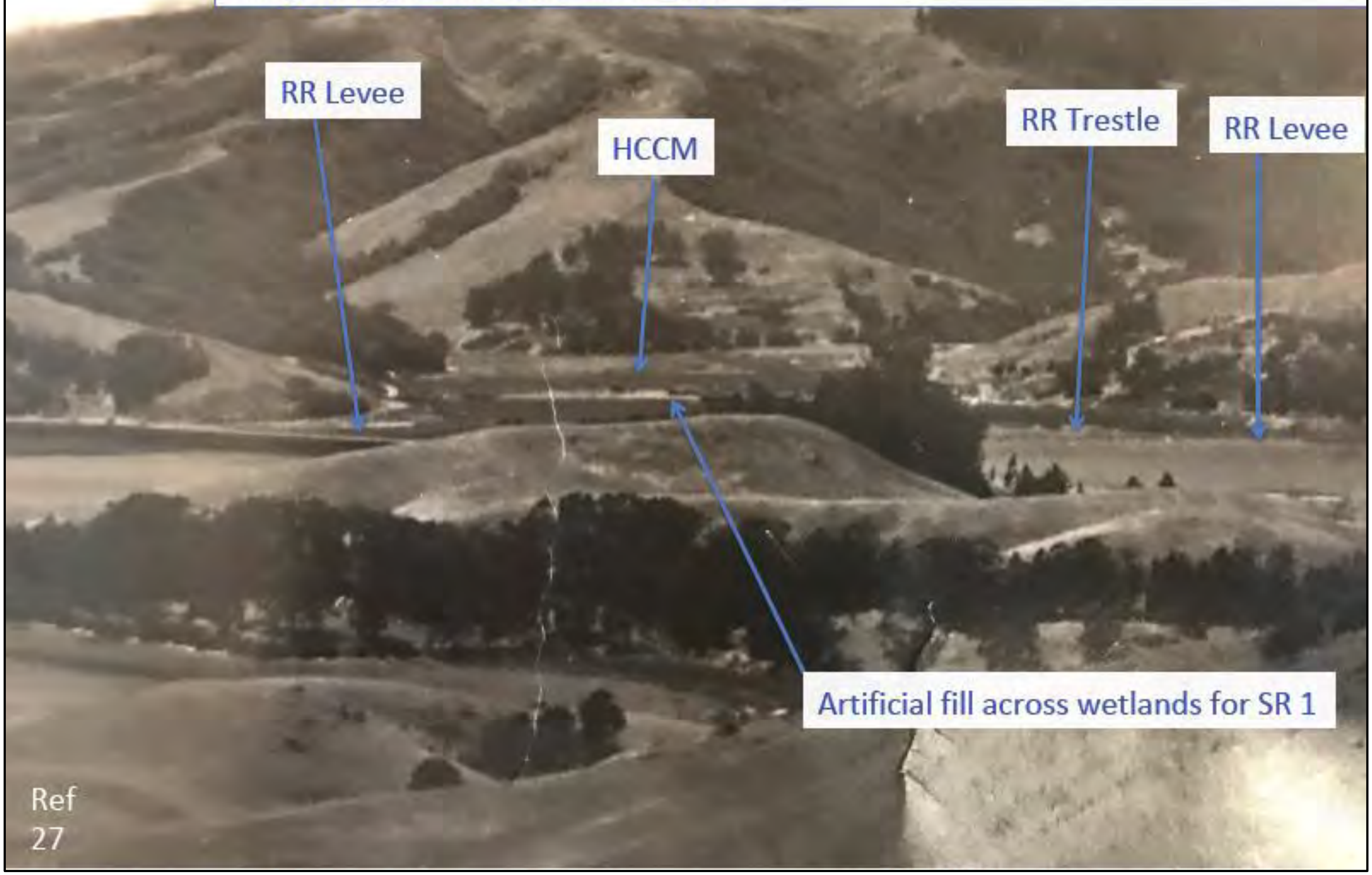
Although the roads appear to be updated, the marsh, channel, and MLLW features appear to rely on the 1851 mapping. The NPCRR across AM and Coyote Creek Embayment was completed by April 1884 but it is not shown on this map.

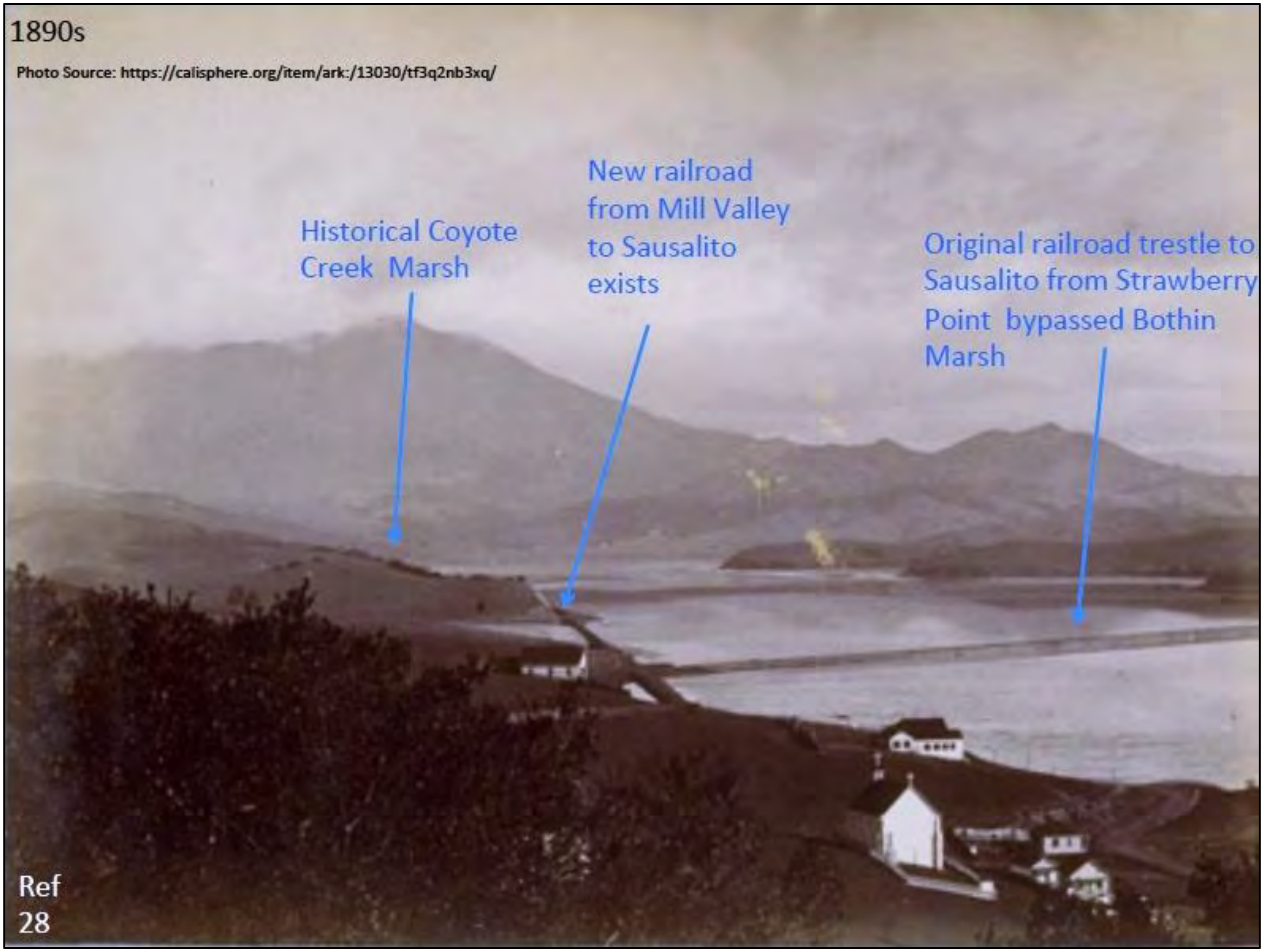
Ref 26



Post 1884?
Photo Source: GIS Dept. Marin County

Looking west toward Historical Coyote Creek Marsh. The railroad trestle can be seen crossing the Coyote Creek Embayment. Construction began on this branch of the NPCRR in April 1983. Service began in April 1984. Extensive wetlands still exist west up the tributary valleys of Coyote and Tennessee Creeks.



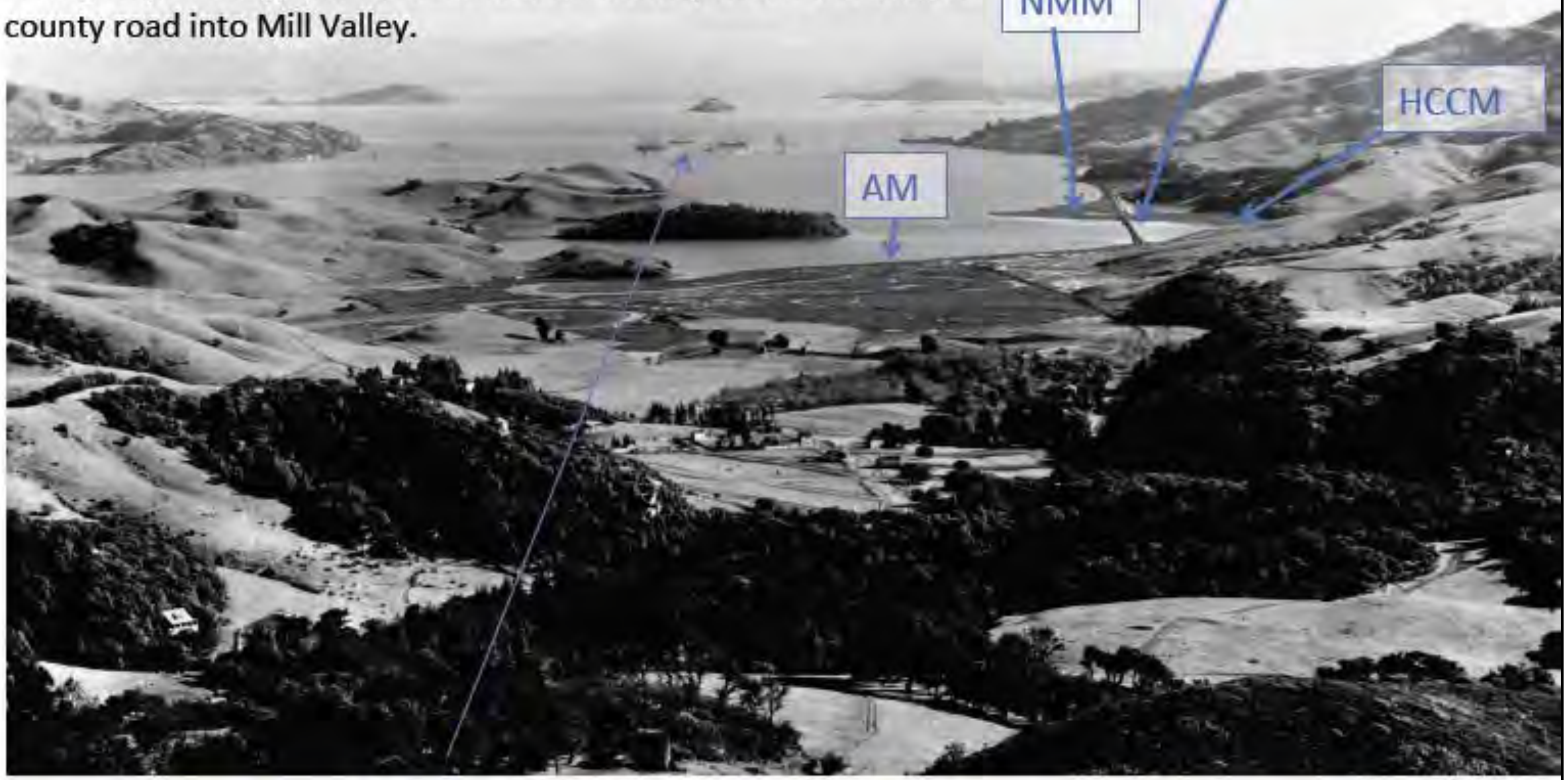

1890s
Photo Source: https://calisphere.org/item/ark:/13030/tf3q2nb3xq/
Historical Coyote Creek Marsh
New railroad from Mill Valley to Sausalito exists
Original railroad trestle to Sausalito from Strawberry Point bypassed Bothin Marsh
Ref 28

Early 1890

Photo Source: Ref #MVN1146v1, History Room, Mill Valley Public Library

Looking down from Summit Avenue in 1890, ten years before the city was incorporated. In this year the first lots were sold at auction by Tamalpais Land and Water Co. Photo shows train trestle from Sausalito and tracks into town, marshes extending far into town, sailing ships in Bay, and East Blithedale Avenue, which was the old county road into Mill Valley.

Note - The 1300 foot-long railroad trestle can still be seen across the Coyote Creek Embayment.

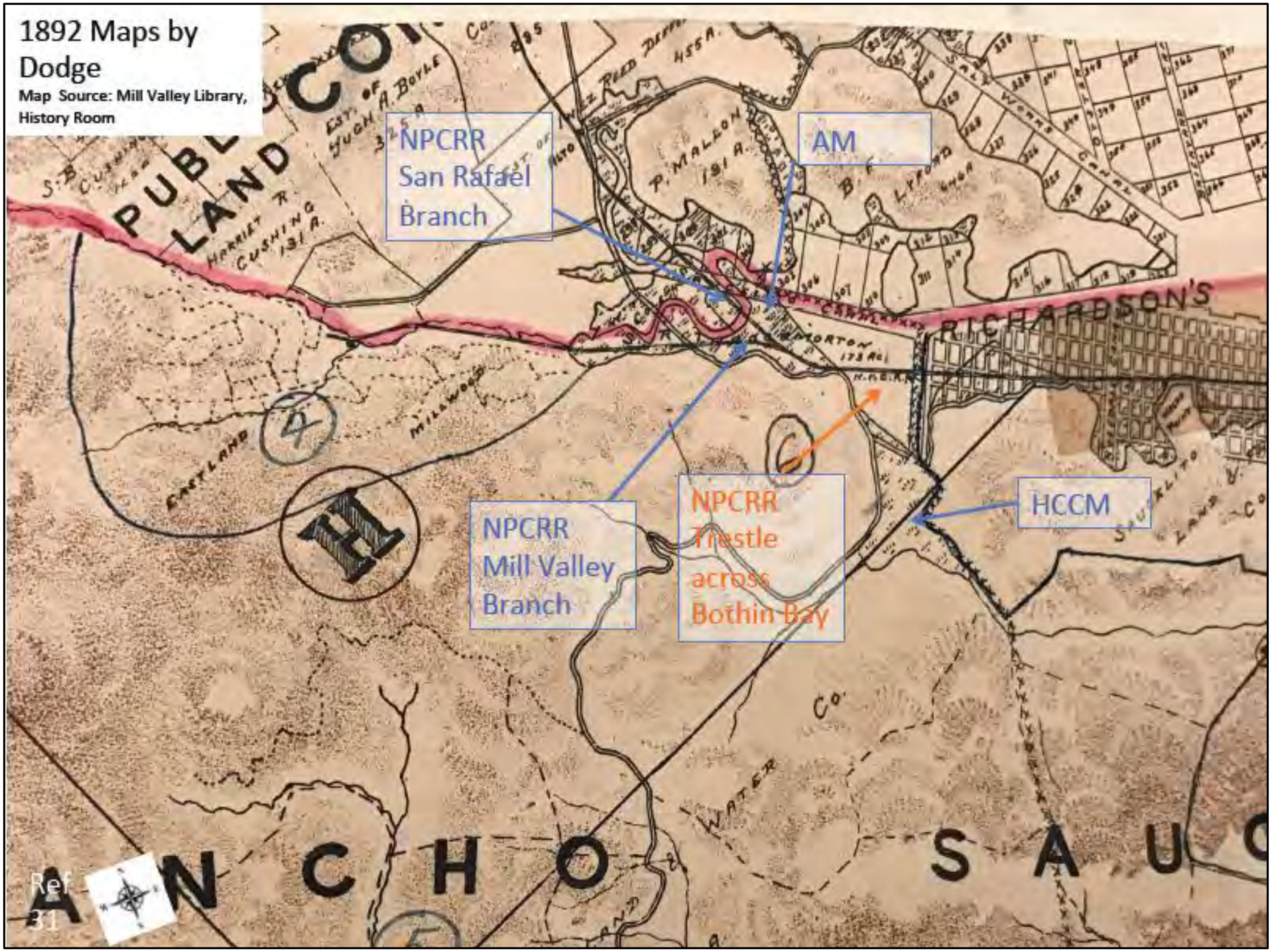


Ref 29 Schooners anchored at the entrance to Richardson Bay rather than within it, possibly because it was too shallow by this time.

Early 1890, Color Enhanced Postcard (same as Image Ref 29)

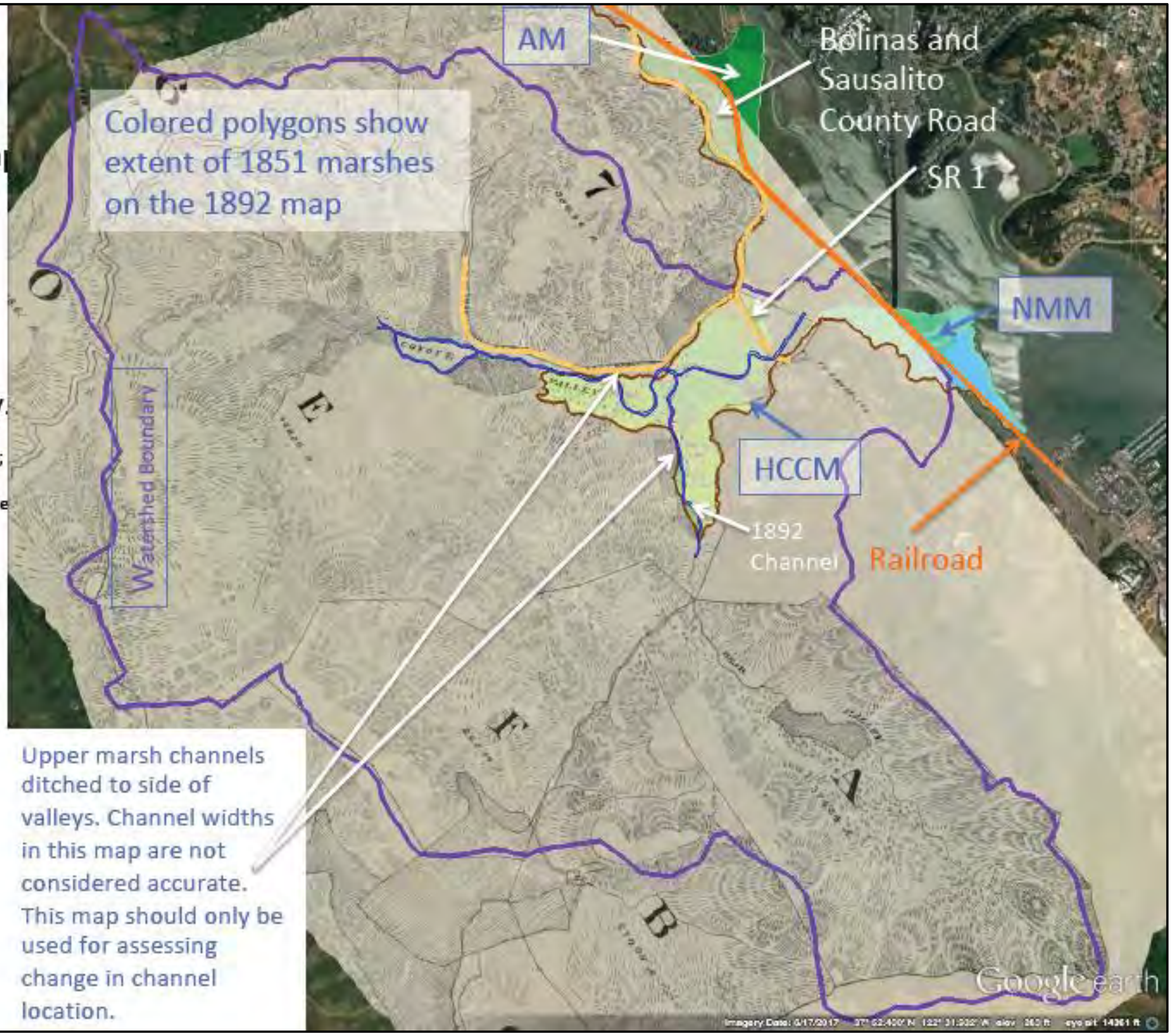
Photo Source: Anne T. Kent California Room, Marin County Free Library

Ref
30

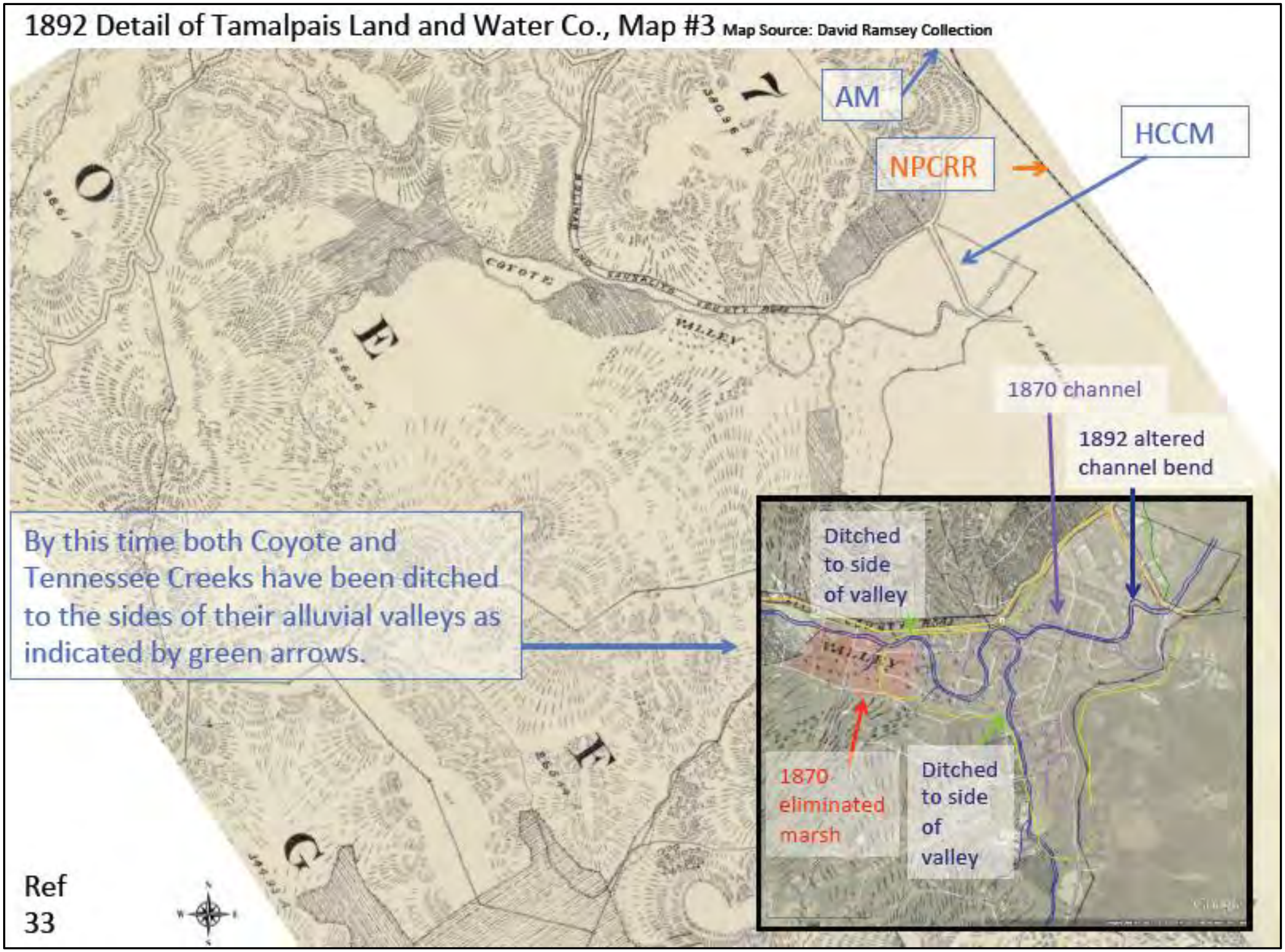

1892 Maps by Dodge
Map Source: Mill Valley Library, History Room
NPCRR San Rafael Branch
AM
NPCRR Mill Valley Branch
NPCRR Trestle across Bothin Bay
HCCM
PUBLIC LAND
RICHARDSON'S
RANCHO
SAUC
Ref 31

1892 Tamalpais Land and Water Co. Map #3 with 1851 tideland polygons projected on 2017 Google Earth Imagery.

Source: 1892 map from David Ramsey Collection; 1851 mapping from US Coast Survey by AD Bache T-00334



Ref 32

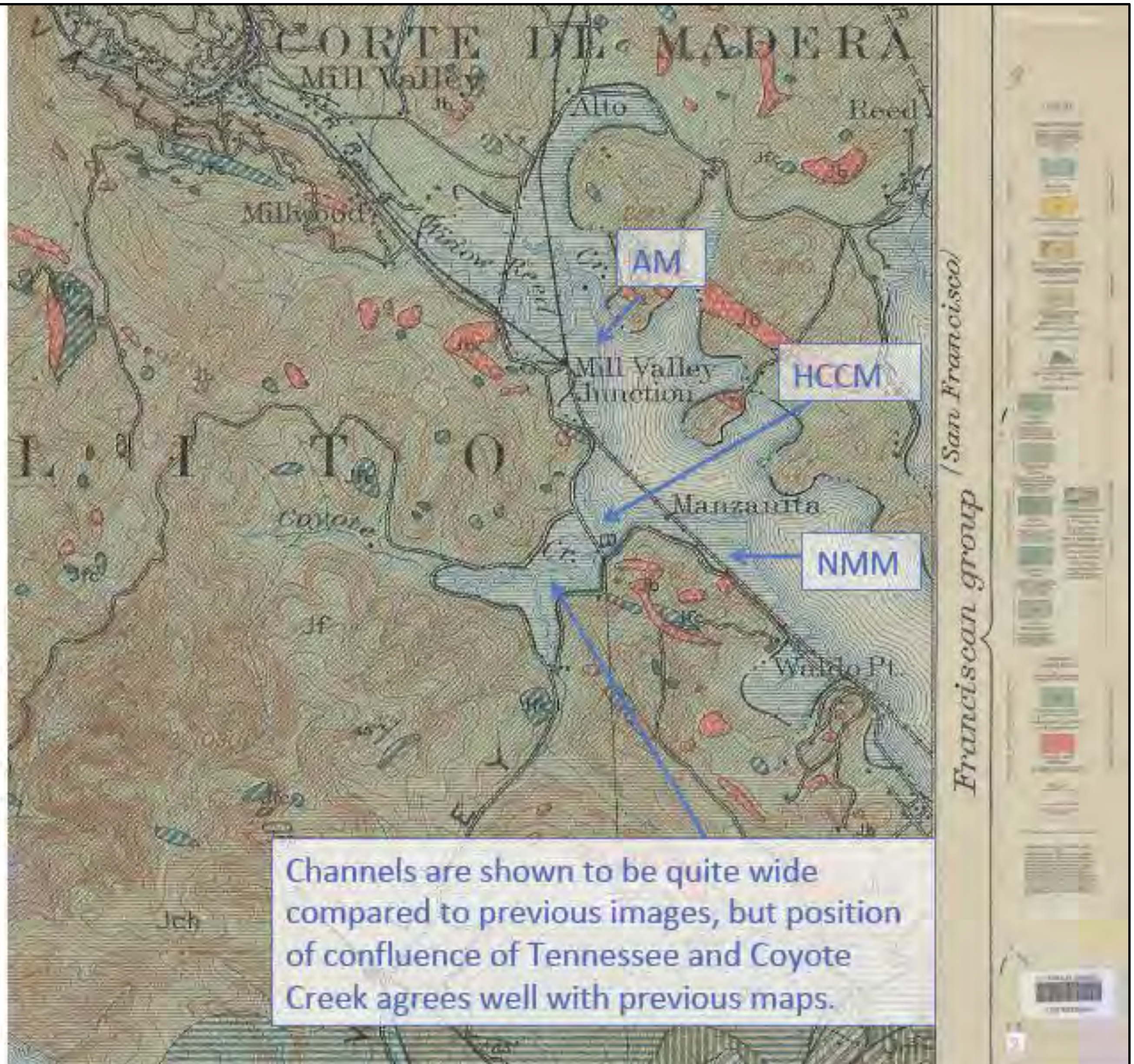

1892 Detail of Tamalpais Land and Water Co., Map #3 Map Source: David Ramsey Collection
AM
NPCRR
HCCM
COYOTE
VALLEY
1870 channel
1892 altered channel bend
By this time both Coyote and Tennessee Creeks have been ditched to the sides of their alluvial valleys as indicated by green arrows.
Ditched to side of valley
1870 eliminated marsh
Ditched to side of valley
Ref 33

1894-1895 US Coast Survey mapping used on a 1913 Areal Geology Map by Andrew Lawson, detail shown

Map Source:
UC Berkeley Library
C039230698

This map does not show changes in marsh or tidal channels relative to the 1908 date since the topographic information is from R.B. Marshall from 1894-1895.

Ref
34



Undated photographs "1 and 2" from Garcia and Associates Letter of 12 December 2016 that misidentifies this area as Coyote Marsh. Source: Garcia Assoc., Memo of 12/16/16

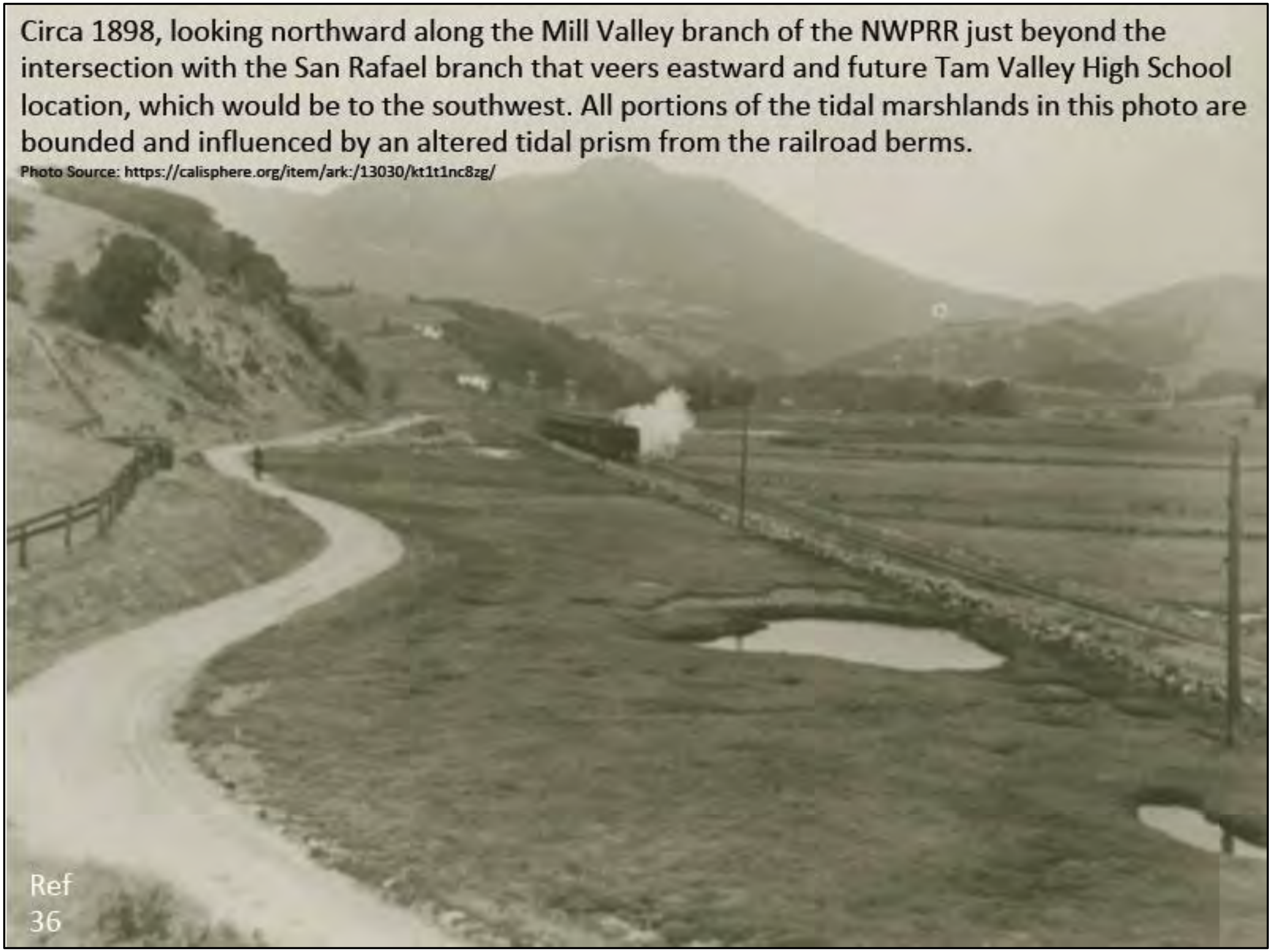
Upper photo is looking northward from Sausalito at a RR levee along Sausalito south of Bothin Marsh. It looks like the drawbridge of the Redwood Bridge of Hwy 1 can be seen in the distant background. Note how high the RR levee is with new fill for the double track. By 2017 in Bothin Marsh sediment has filled substantially to a greater height along both sides of the RR The red arrow is presumed to be pointing at an outlet beneath the tracks.

Picture 1

Picture 2

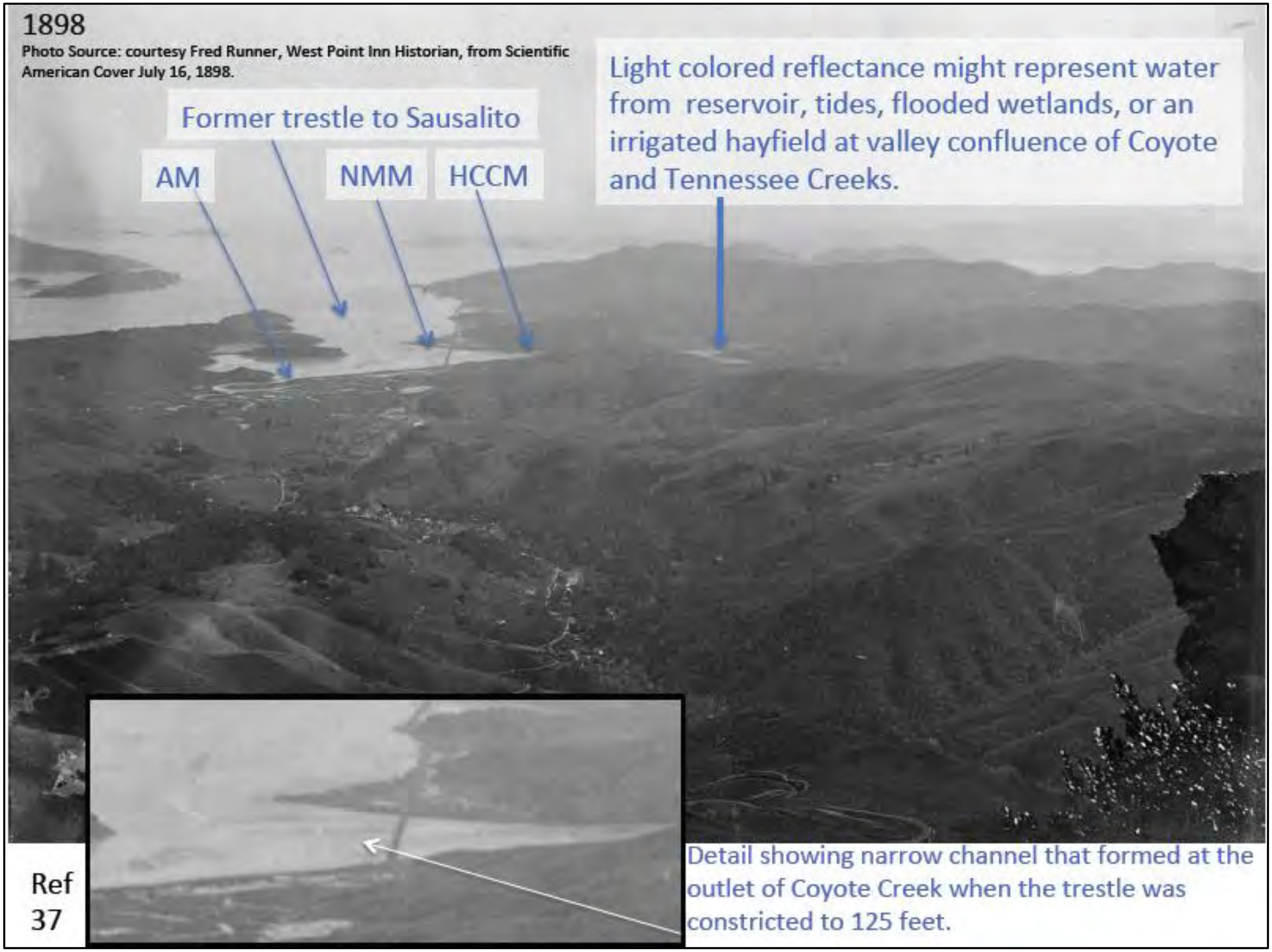
The lower photo shows Almonte Marsh to either side of the tracks while looking northward where the Mill Valley branch splits from the San Rafael Branch

Ref 35



Circa 1898, looking northward along the Mill Valley branch of the NWPRR just beyond the intersection with the San Rafael branch that veers eastward and future Tam Valley High School location, which would be to the southwest. All portions of the tidal marshlands in this photo are bounded and influenced by an altered tidal prism from the railroad berms.

Photo Source: https://calisphere.org/item/ark:/13030/kt1t1nc8zg/


1898
Photo Source: courtesy Fred Runner, West Point Inn Historian, from Scientific American Cover July 16, 1898.
Former trestle to Sausalito
AM
NMM
HCCM
Light colored reflectance might represent water from reservoir, tides, flooded wetlands, or an irrigated hayfield at valley confluence of Coyote and Tennessee Creeks.
Ref 37
Detail showing narrow channel that formed at the outlet of Coyote Creek when the trestle was constricted to 125 feet.

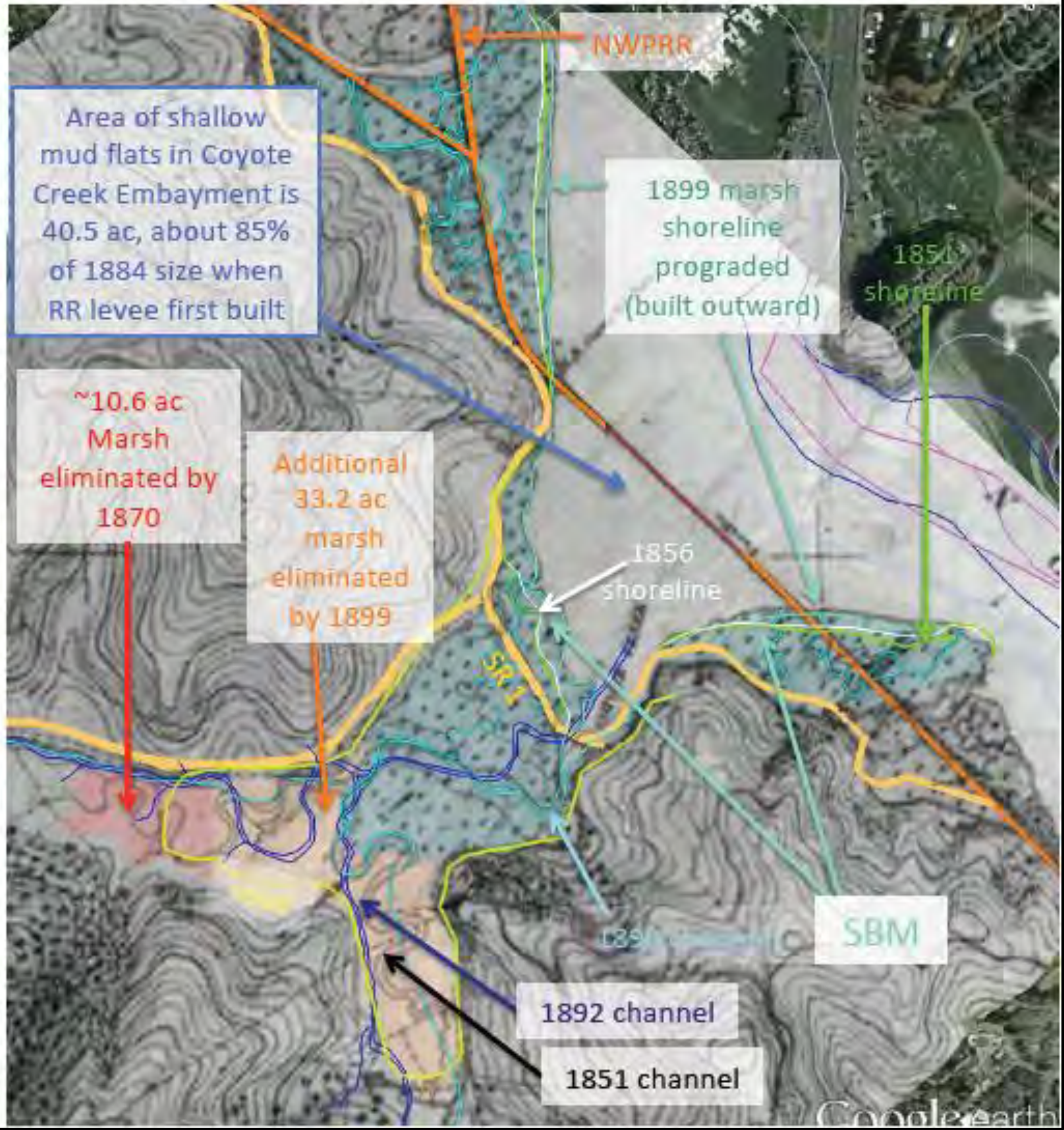
1899, Detail of T-sheet 2485 USCGS, San Francisco Bay, California, City Pt. to Pt. San Quentin and Head of Richardson Bay. Image on left is overlaid onto 2017 Google earth Imagery.

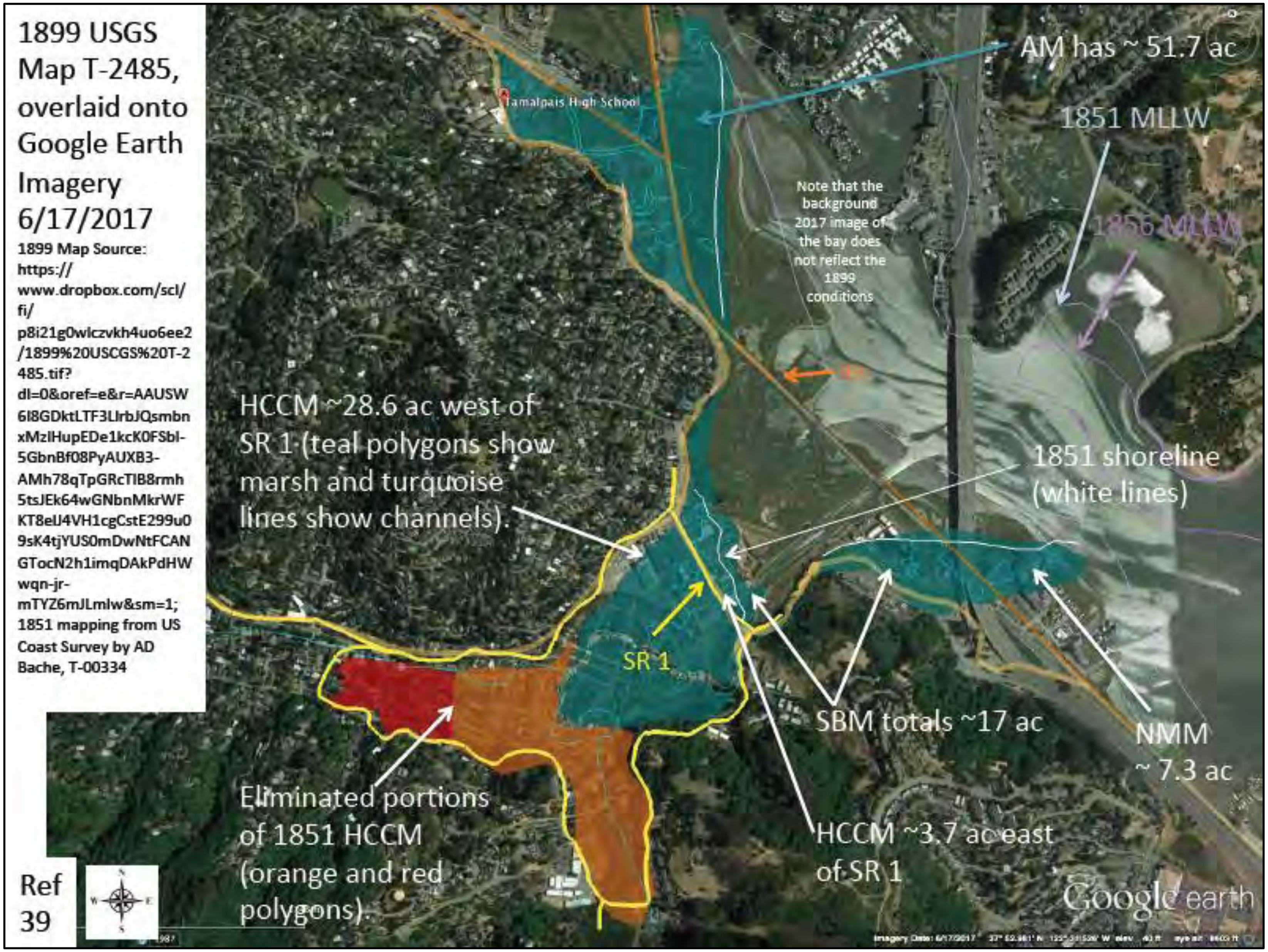
Map Source:
https://www.dropbox.com/scl/fi/p8i21g0wlczvkh4uo6ee2/1899%20USCGS%20T-2485.tifl=0&oref=e&r=AAUSW6I8GDktLTF3LlrbJQsmbnxMzlHupEDe1kcK0FSbl-5GbnBf08PyAUXB3-AMh78qTpGRcTlB8rmh5tsJEk64wGNbnMkrWFKT8eIJ4VH1cgCstE299u09sK4tjYUS0mDwNtFCANGTocN2h1imqDAkPdHWwqn-jr-mTYZ6mJLmlw&sm=1

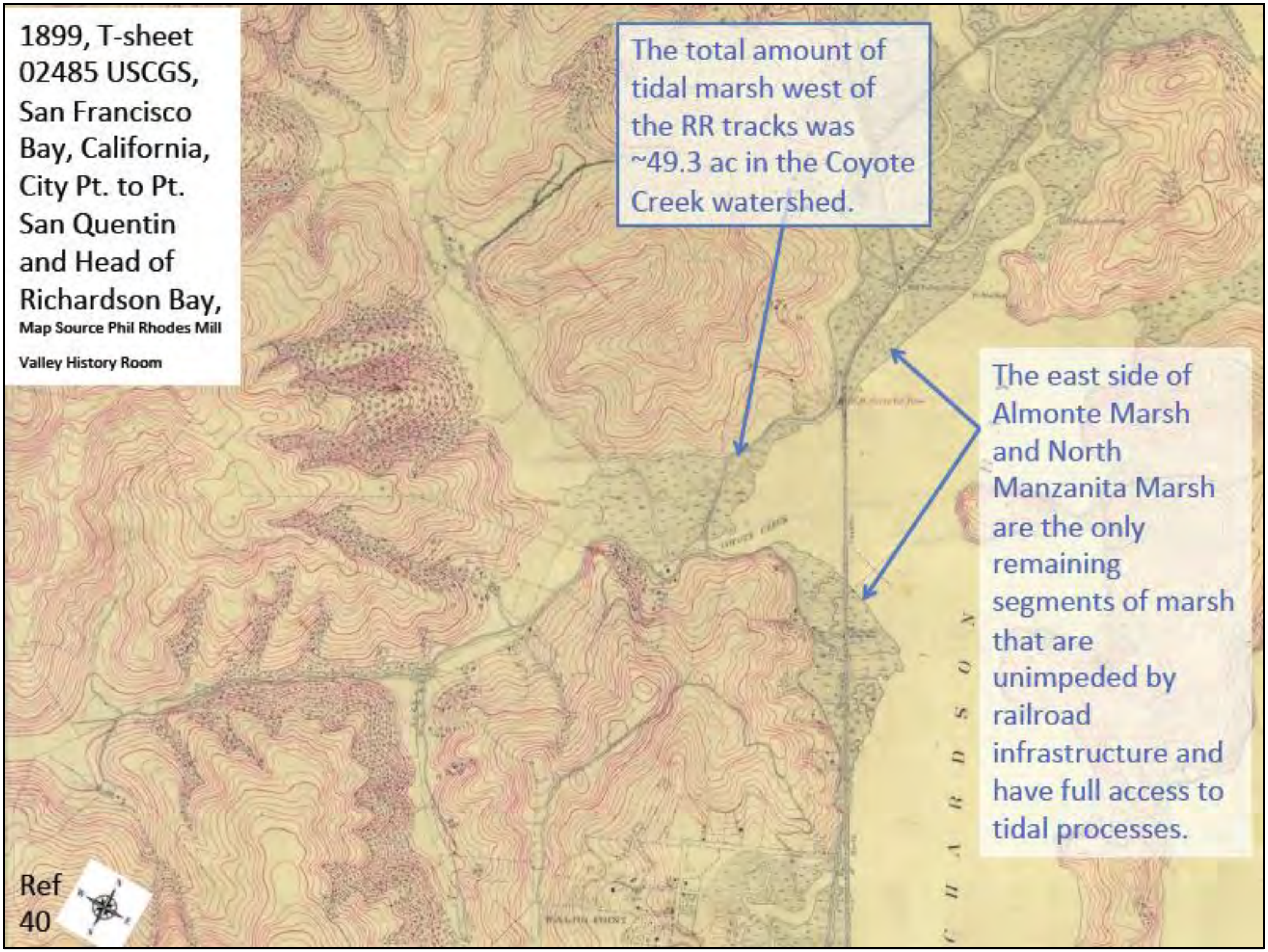
Note that as of 1899, following RR levee construction, new marsh that prograded into the Coyote Creek Embayment beyond the 1851 shoreline is here referred to as South Bothin Marsh (SBM), which has built ~6.6 ac of new marsh against the 1851 shoreline. An additional ~10.4 ac of NMM was isolated by tracks and it is here counted as part of SBM, causing it to have a combined total of 17 ac.

The total remaining HCCM east and west of SR 1 was 32.3 ac.

Ref
38



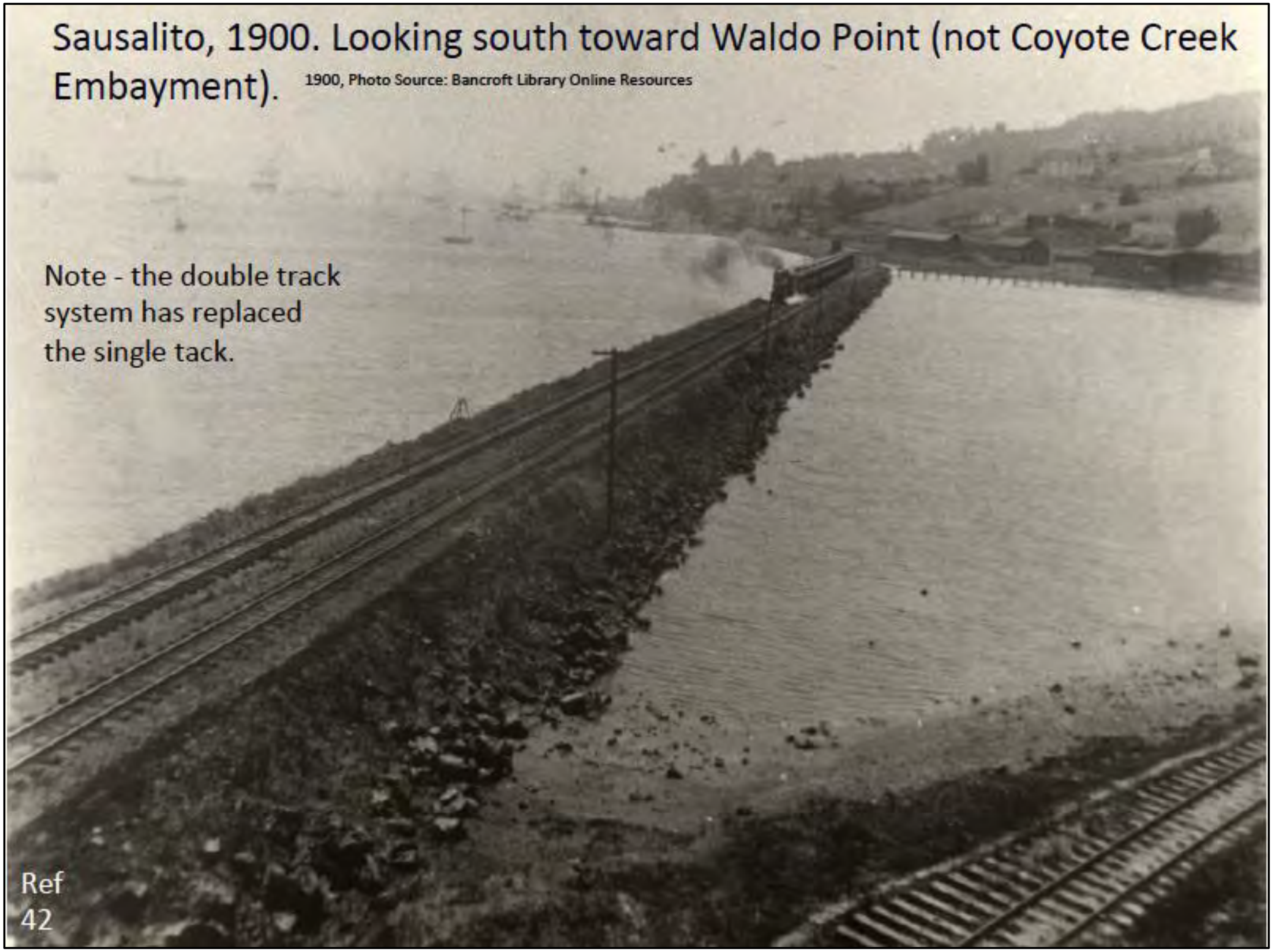

1899 USGS Map T-2485, overlaid onto Google Earth Imagery 6/17/2017
1899 Map Source: https://www.dropbox.com/scl/fi/p8i21g0wlczvkh4uo6ee2/1899%20USCGS%20T-2485.tif?dl=0&oref=e&r=AAUSW6l8GDktLTF3LlrbJQsmbnxMzlHupEDe1kcK0FSbl-5GbnBf08PyAUXB3-AMh78qTpGRcTIB8rmh5tsJEk64wGNbnMkrWFKT8eU4VH1cgCstE299u09sK4tjYUS0mDwNtFCANGTocN2h1imqDAkPdHWwqn-jr-mTYZ6mJLmlw&sm=1; 1851 mapping from US Coast Survey by AD Bache, T-00334
AM has ~ 51.7 ac
Tamalpais High School
1851 MLLW
1856 MLLW
Note that the background 2017 image of the bay does not reflect the 1899 conditions
HCCM ~28.6 ac west of SR 1 (teal polygons show marsh and turquoise lines show channels).
1851 shoreline (white lines)
SR 1
SBM totals ~17 ac
NMM ~ 7.3 ac
Eliminated portions of 1851 HCCM (orange and red polygons).
HCCM ~3.7 ac east of SR 1
Ref 39
Google earth


1899, T-sheet 02485 USCGS, San Francisco Bay, California, City Pt. to Pt. San Quentin and Head of Richardson Bay,
Map Source Phil Rhodes Mill Valley History Room
The total amount of tidal marsh west of the RR tracks was ~49.3 ac in the Coyote Creek watershed.
The east side of Almonte Marsh and North Manzanita Marsh are the only remaining segments of marsh that are unimpeded by railroad infrastructure and have full access to tidal processes.
Ref 40

1899, Detail of T-sheet 02485 USCGS, San Francisco Bay, California, City Point to Point San Quentin and Head of Richardson Bay, Map Source Phil Rhodes Mill Valley History Room

Railroad trestle is here depicted in detail. Outside hatch marks typically denote fill. Bridge abutments are denoted with curving outside lines that bend away from the span. These are clearly evident on this map. While there is no certainty this 1899 map is entirely correct in its depiction of the rail line here, Rhodes (Mill Valley Library History Room) considers it unlikely that the surveyor and drafter of this map would have gotten such key details on a waterway wrong. Source: 1899 T-sheet from P. Rhodes, email 4/25/2017. Historians from the NWPRR Society state that the trestle was replaced with a berm in 1894 (verbal communication to L. Collins). This seems consistent with information developed for this report. The length of the original trestle over the Coyote Creek Embayment appears to have been about 1310 feet long while the total amount of berm extending across the bay from the 1899 shoreline to the trestle was about 850 feet.

Ref 41

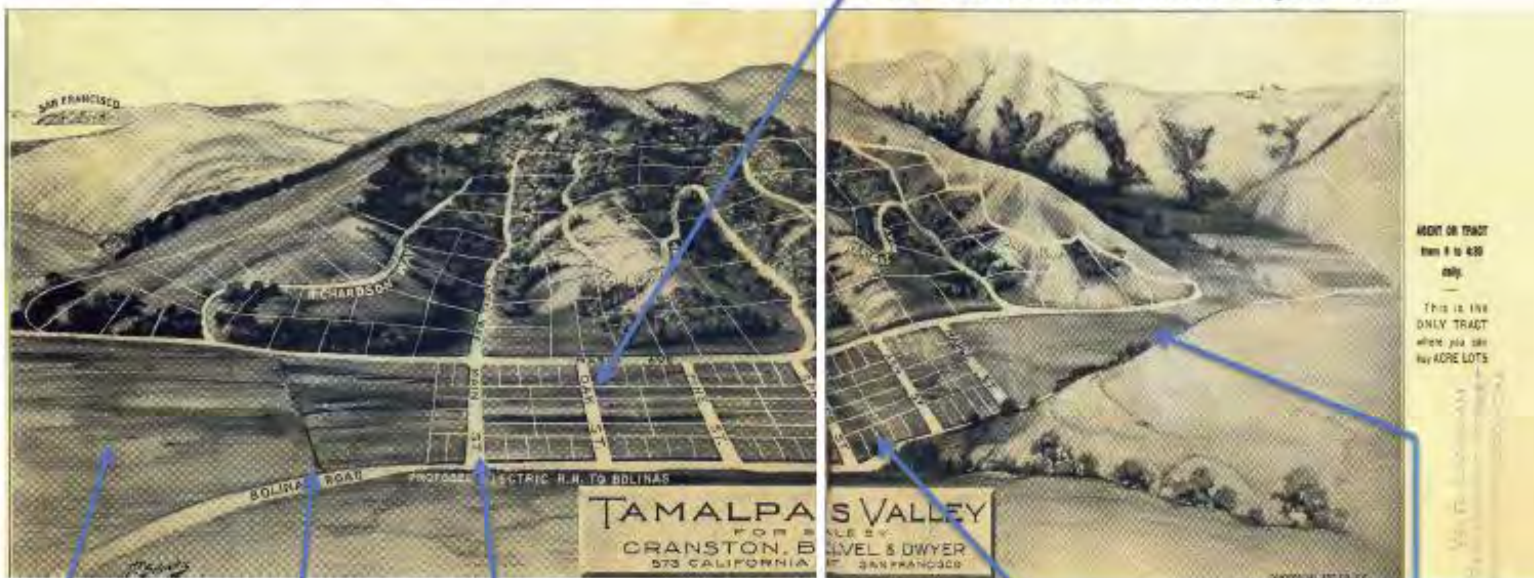


Sausalito, 1900. Looking south toward Waldo Point (not Coyote Creek Embayment). 1900, Photo Source: Bancroft Library Online Resources

1900 Tam Valley for Sale, looking south at former head of tide at Coyote Creek

Map Source: Anne T. Kent California Room, Marin County Free Library

Oak Street now called Poplar St.



Tidal wetlands

Possible levee that might coincide with one that was constructed by 1870 and eliminated 10.6 acres of tidal marsh?

Main Street now called Laurel Way

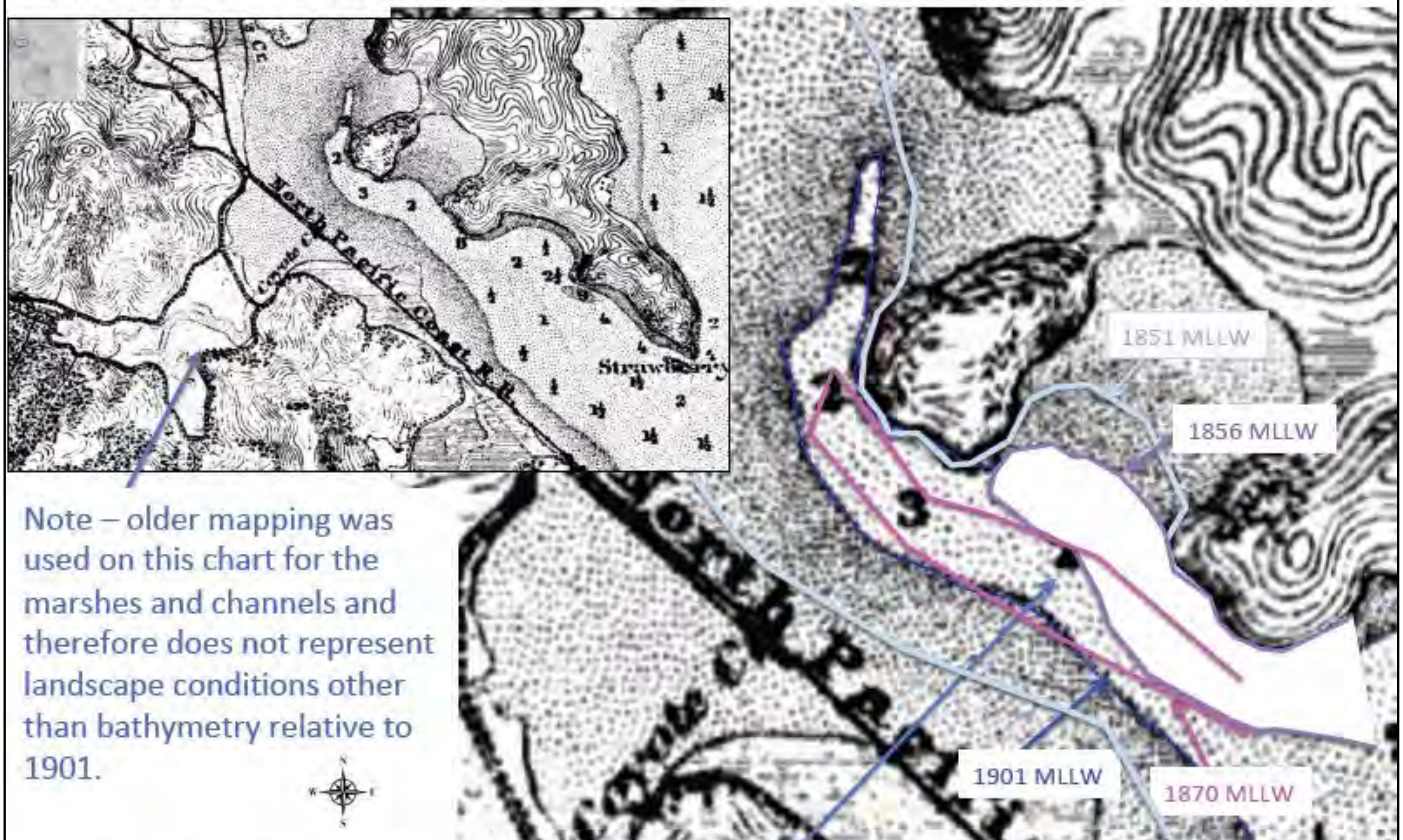
Alluvial valley of Coyote Creek

Historical tidal marsh existed down valley of Spruce Street but it is interesting to see this distinct change in slope in the transition from alluvial stream to tidelands in this rendering

Ref 43

1901, Nautical Chart, Detail of San Francisco Entrance US Coast and Geodetic Survey

Map Source: https://historicalcharts.noaa.gov/historicals/search#mainTitle

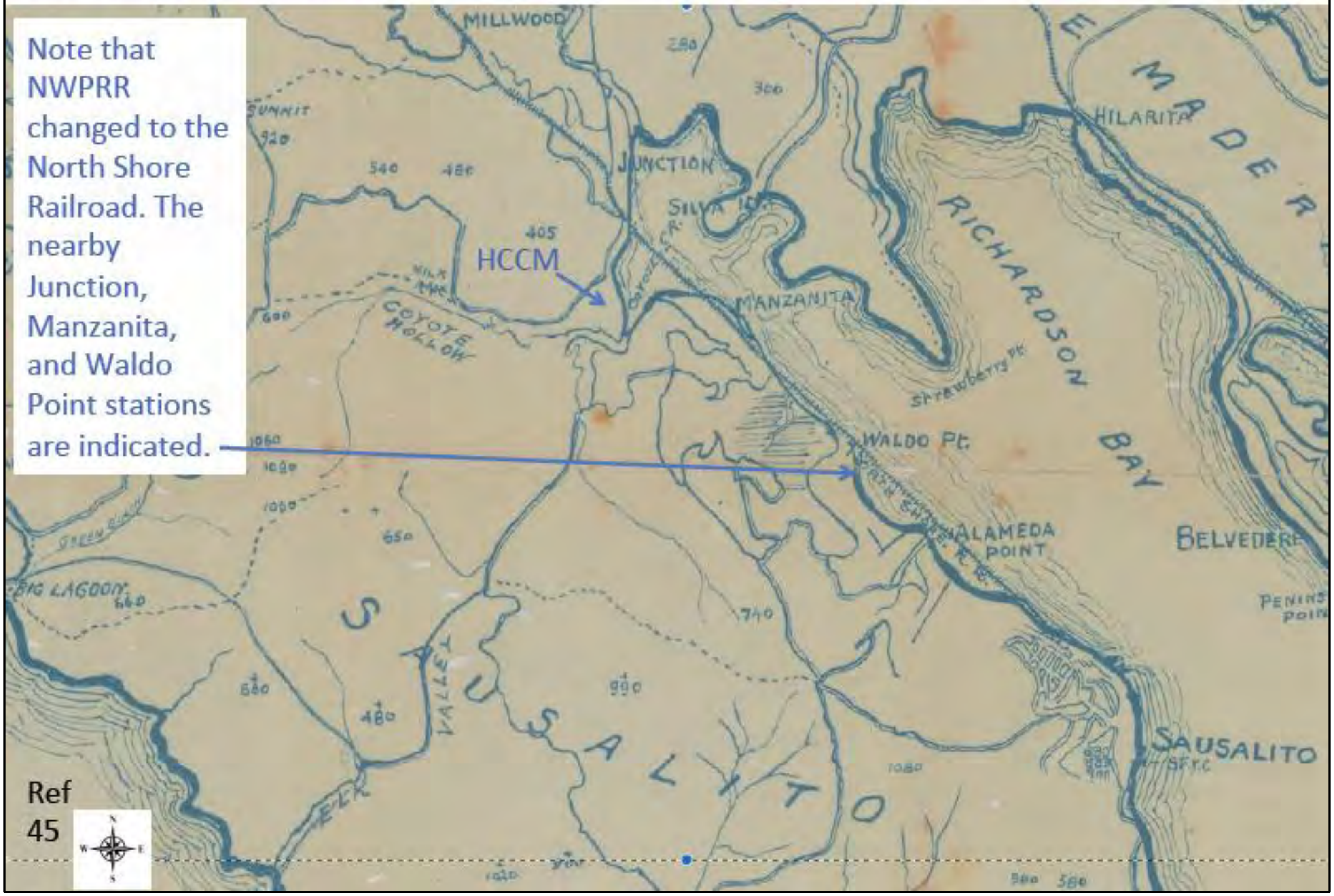


Ref 44

Note - Soundings are in feet above MLLW. Shallow mudflats continue to be more extensive than they were in 1851 (light blue line), but following the extensive sedimentation in 1856 (purple line), the MLLW boundary has been progressively expanding and deepening landward since 1870 (pink line).

1903 Road Map of Marin

Map Source: http://servlet1.lib.berkeley.edu:8080/mapviewer/searchcoll.execute.logic?coll=eartmaps&catno=b22254341



1905 San Francisco Entrance, U.S. Coast Survey Chart 5532

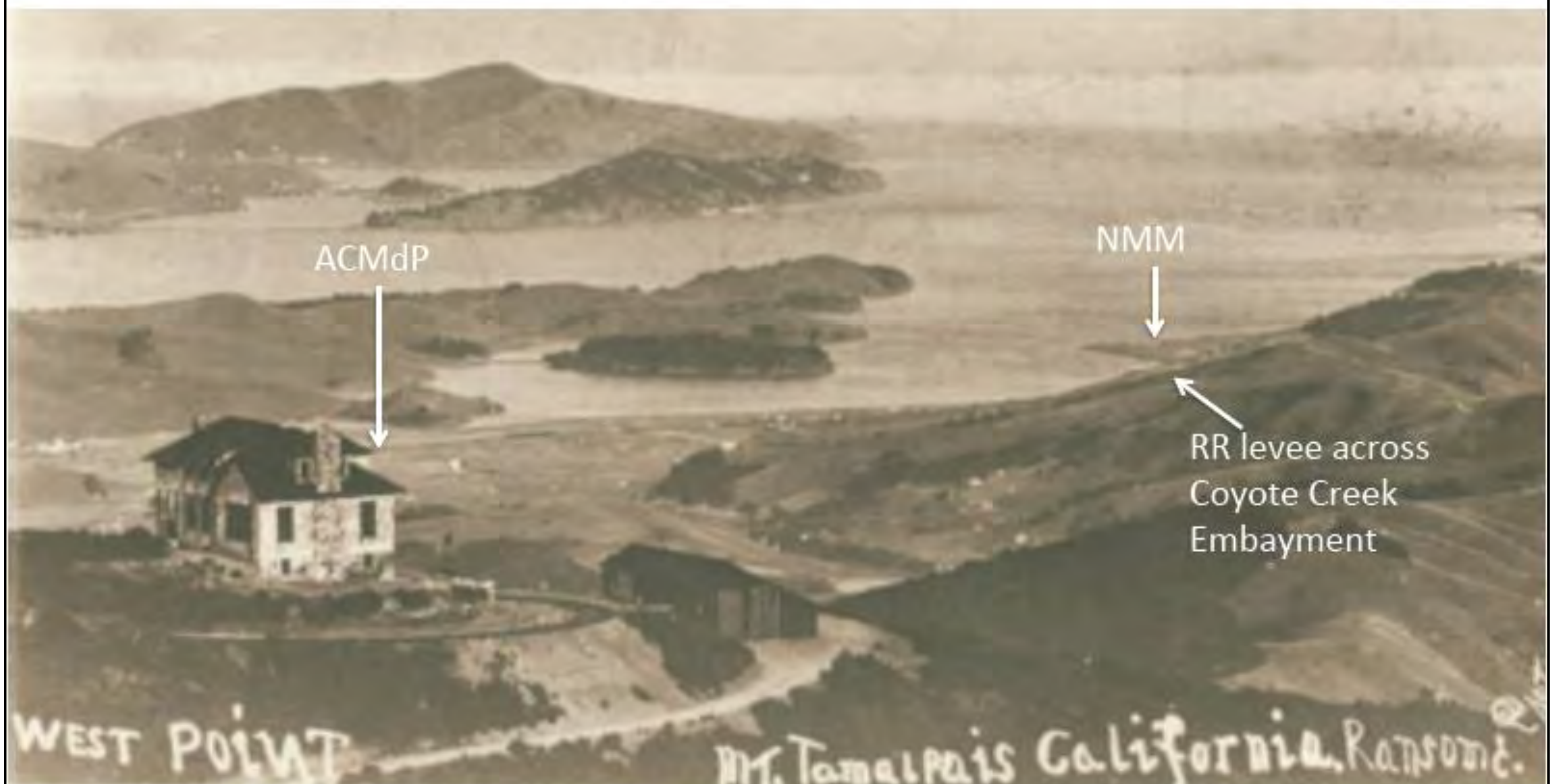
Map Sourcehttps://www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~4227~360039:San-Francisco-entrance,-California-?sort=Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No&qvq=q:1905%2BCOAST%2BSURVEY%2BSAN%2BFRANCISCO%2BBAY;sort:Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No;lc:RUMSEY~8~1&mi=1&trs=3

This map used the HCCM channel mapping from 1899 T-02485 and therefore is only used for assessing bathymetric change.

Ref 46

1906 Arroyo Corte Madera del Presidio Marsh,

Photo Source: https://calisphere.org/item/ark:/13030/kt358024j5/



Ref
47

1908

Photo Source: https://mvhistory.org/wp-content/uploads/2014/08/TamTrainStop.jpg

Students waiting for commuter train at the new train stop on the Mill Valley line fronting the high school. November 1908

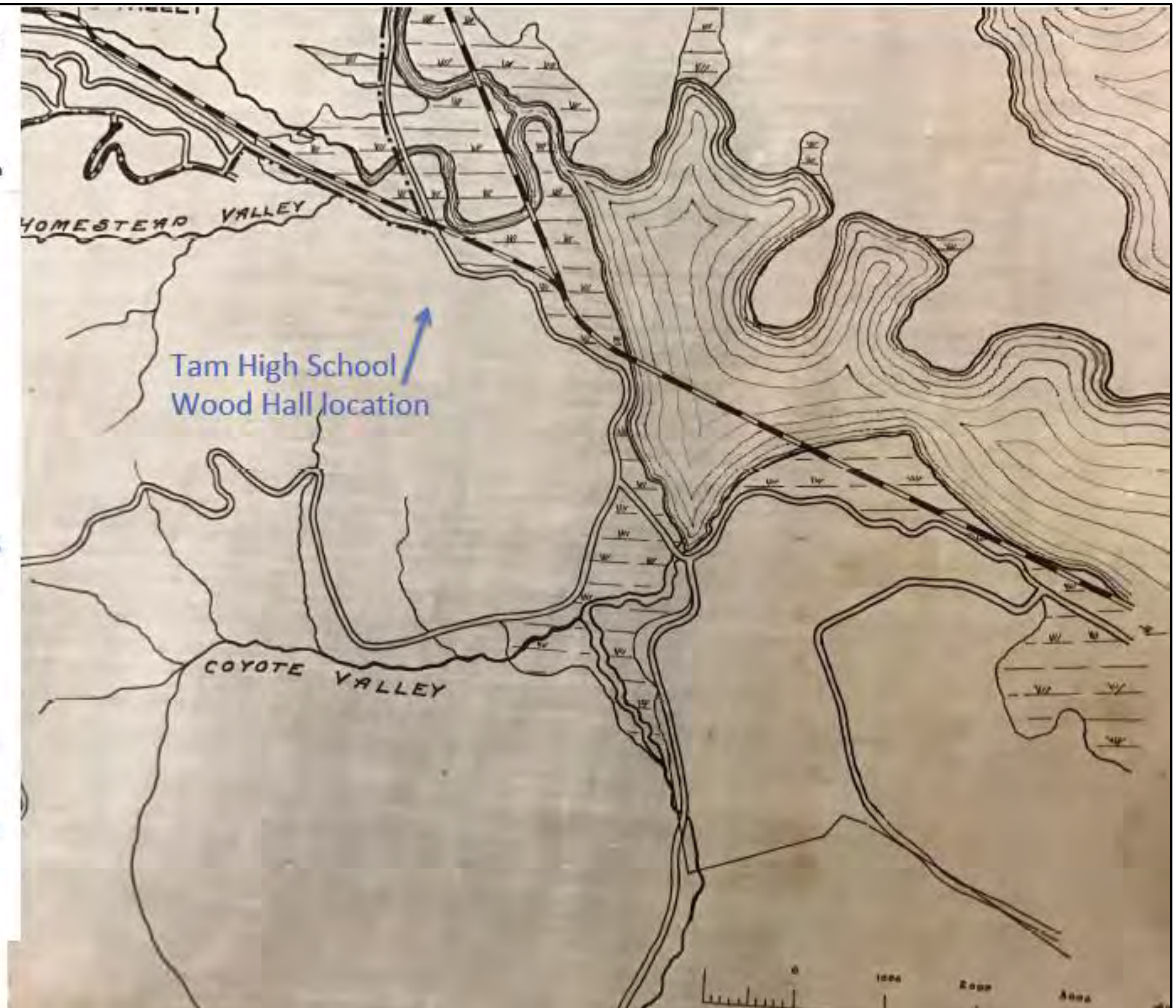
Ref
48

1908 Marin Water Co, Map

Source: Mill Valley Library History Room

This map does not show the changes in marsh or tidal channels relative to actual 1908 conditions. It does reflect the 1870 eliminated ~10.6 acre of marsh in the Coyote Drainage.

Ref 49



Post 1908-09 (?)

Photo Source: https://s-media-cache-ak0.pinimg.com/originals/e8/c0/2e/e8c02e2b816187bf75603fd820c5db41.jpg

Wood Hall, building with tower on right, was built first in 1908. http://thetamnews.org/lifestyles/tamalpais-high-school-an-architectural-history/

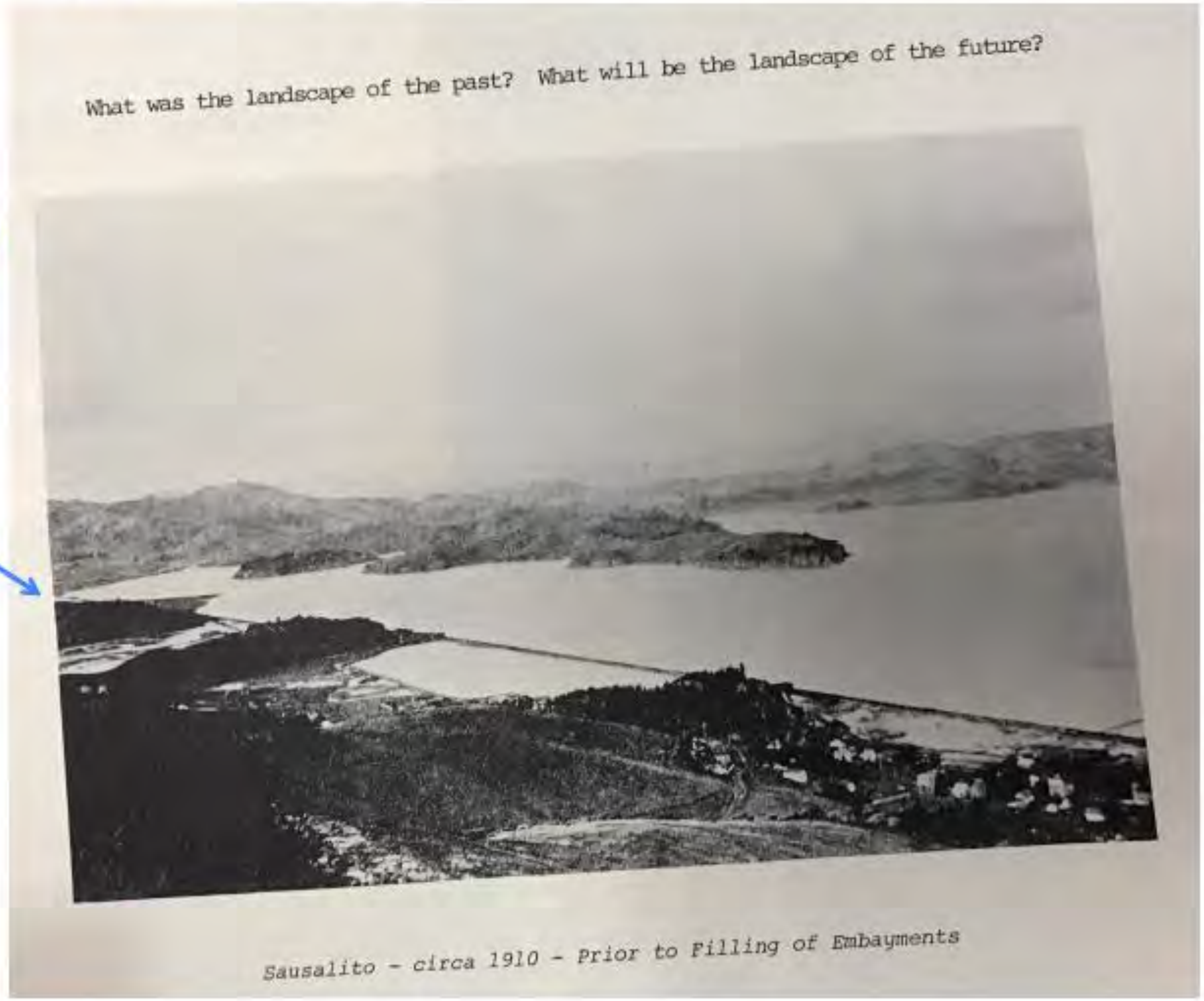
Ref 50

Circa 1910 Richardson Bay in Transition

Photo Source: Anne T. Kent California Room, Marin County Free Library

Note – Embayments in Sausalito are not yet filled landward from the backshore of of the railroad levees.

HCCM



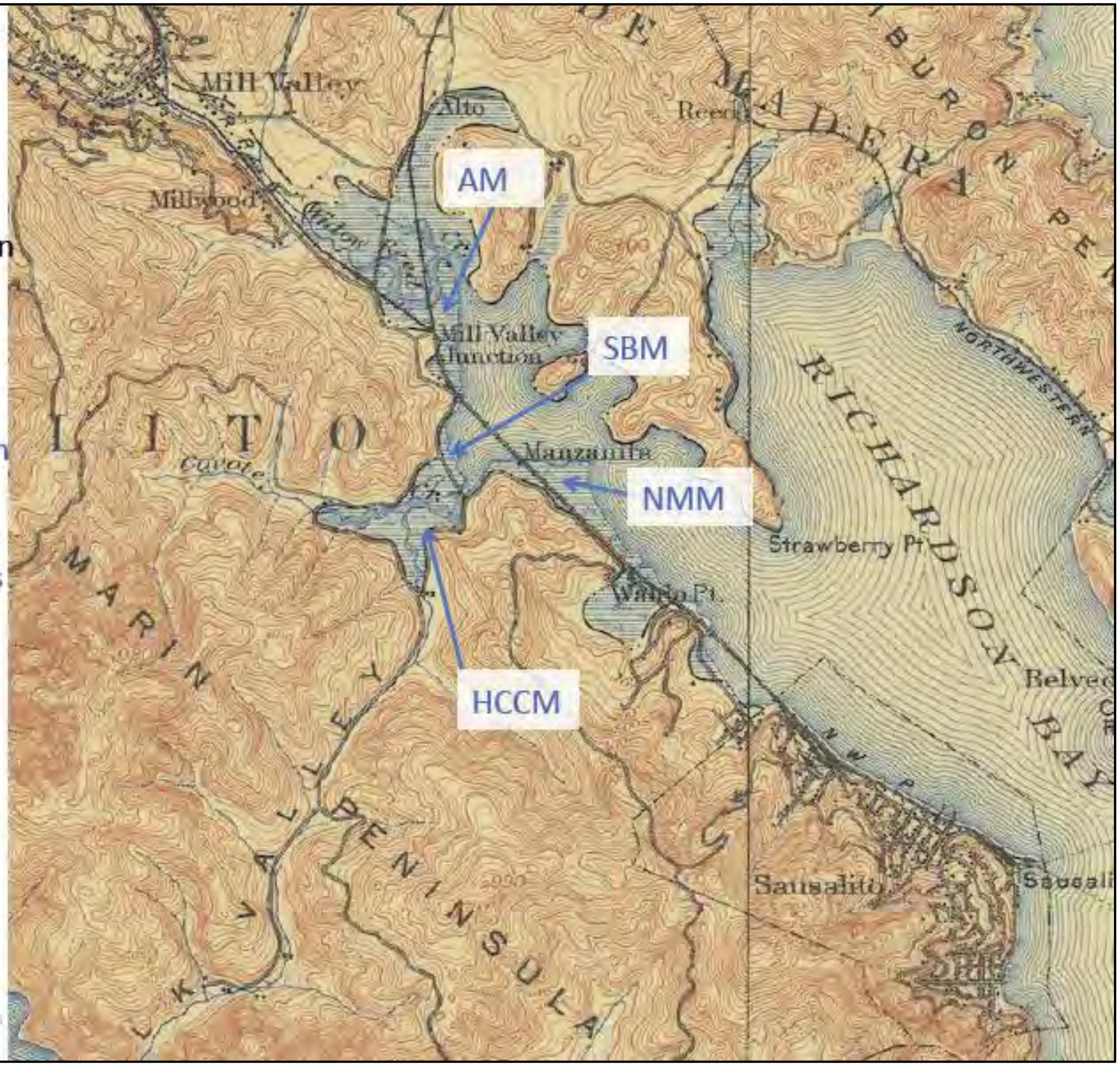
Ref 51

1915 San Francisco and Vicinity Map, Surveyed 1894-1913, 25-ft contour intervals, (detail of Richardson Bay)

Source: USGS

This map does not show the changes in marsh or tidal channels relative to the 1908 conditions and since it has a range of years for survey dates, it cannot be used to asses channel or marsh change for the Coyote Creek Marsh.

Ref 52



1915, Just South of Tamalpais High School

Photo Source: https://calisphere.org/item/ark:/13030/kt5p3025pm/

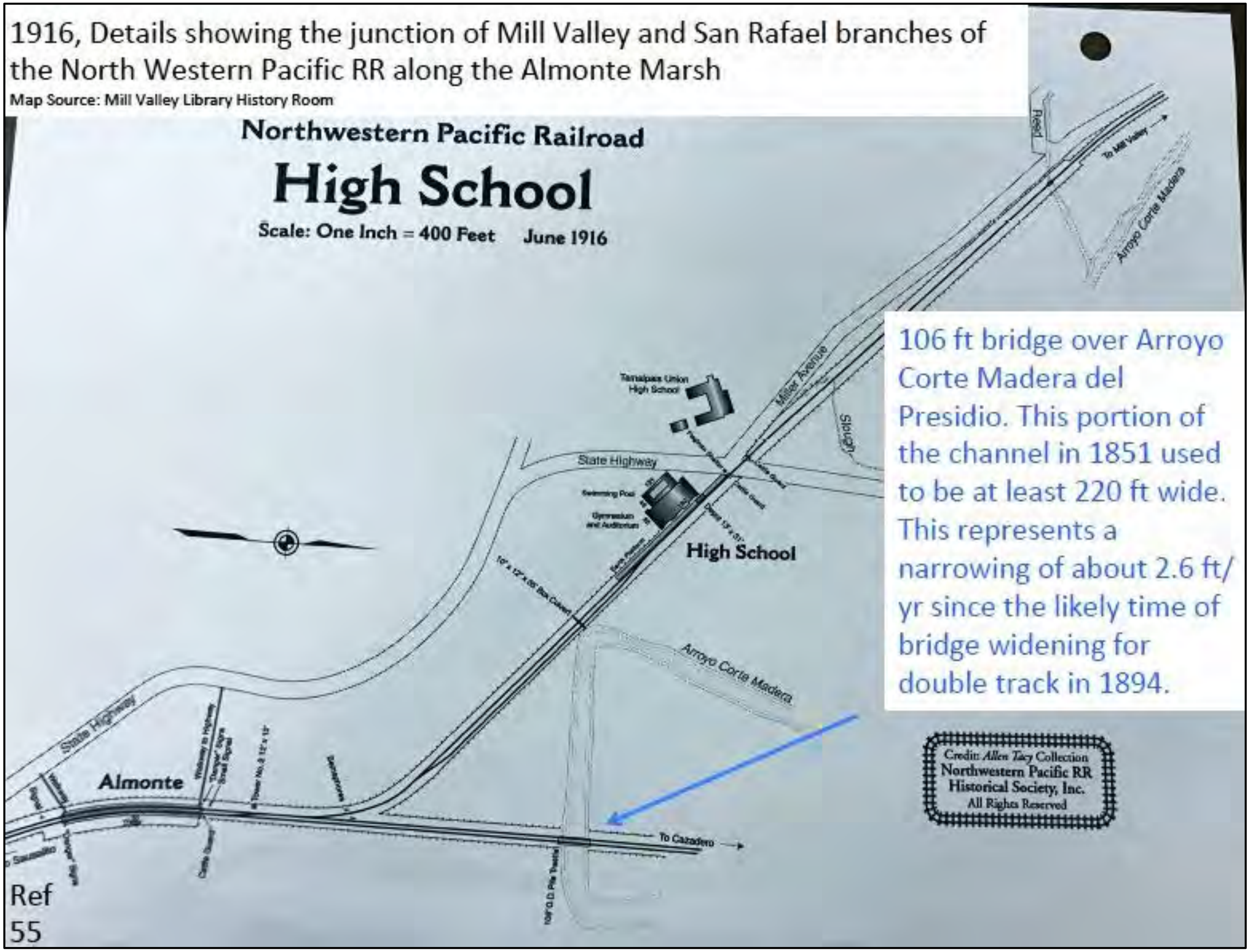
Ref 53 This remnant 1851 channel bend of a tidal tributary to Arroyo Corte Madera del Presidio used to be at least 40 ft wide.

1915, San Francisco Entrance

Map source: https://historicalcharts.noaa.gov/historicals/search

This map shows the marsh and tidal channels relative to the 1899 and bathymetry relative to 1905, therefore it cannot be used to assess channel or marsh change during 1915 for the Coyote Creek Marsh.

Ref 54

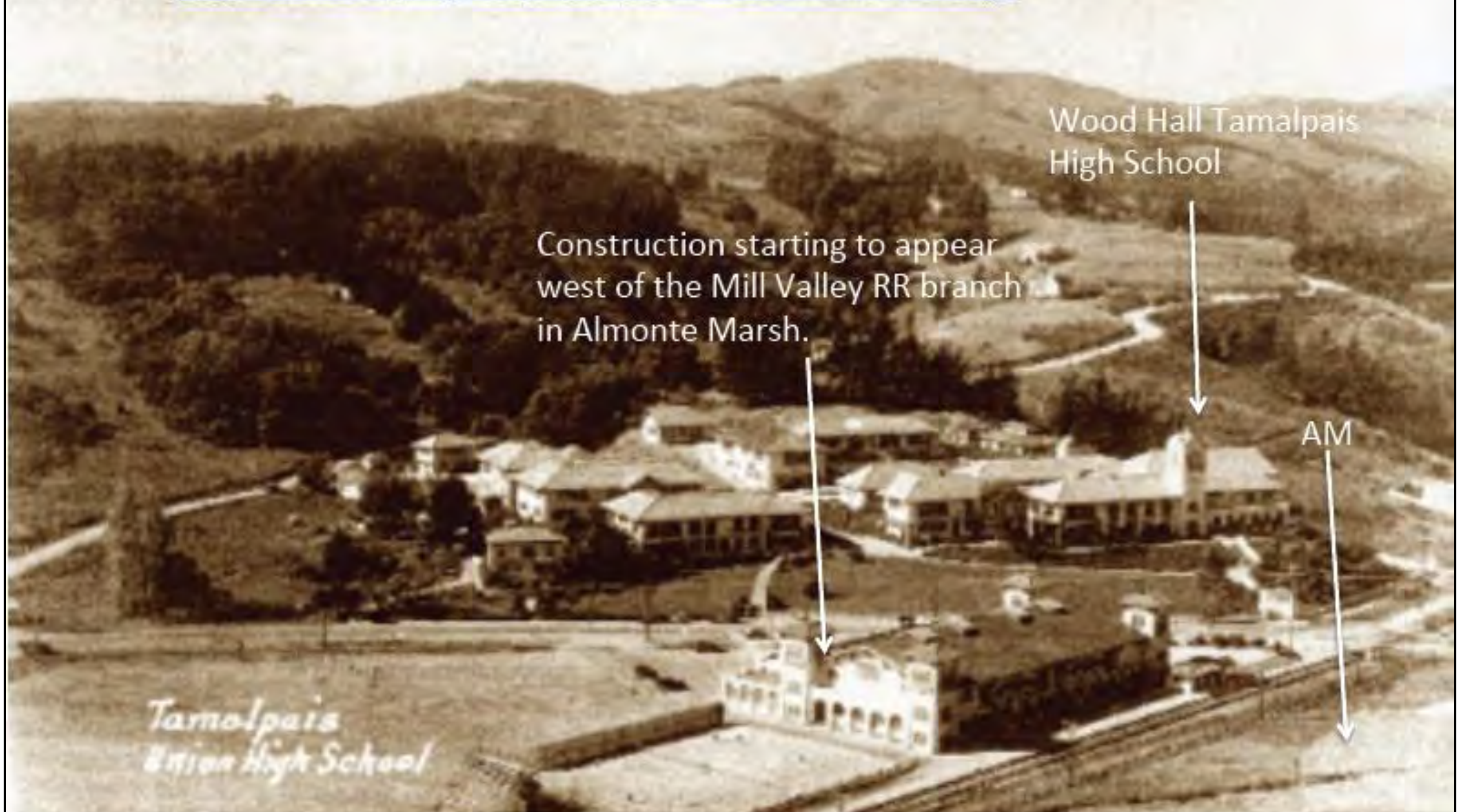


1916, Details showing the junction of Mill Valley and San Rafael branches of the North Western Pacific RR along the Almonte Marsh

Map Source: Mill Valley Library History Room

Post 1920s, Tamalpais High School

Photo Source: https://s-media-cache-ak0.pinimg.com/originals/e3/d1/18/e3d118b13d382772e408c8a0c1e81cd9.jpg



This picture must follow the 1920's because Keyser Hall and Gus Gym were constructed by the 1920s. http://thetamnews.org/lifestyles/tamalpais-high-school-an-architectural-history/

Ref 56

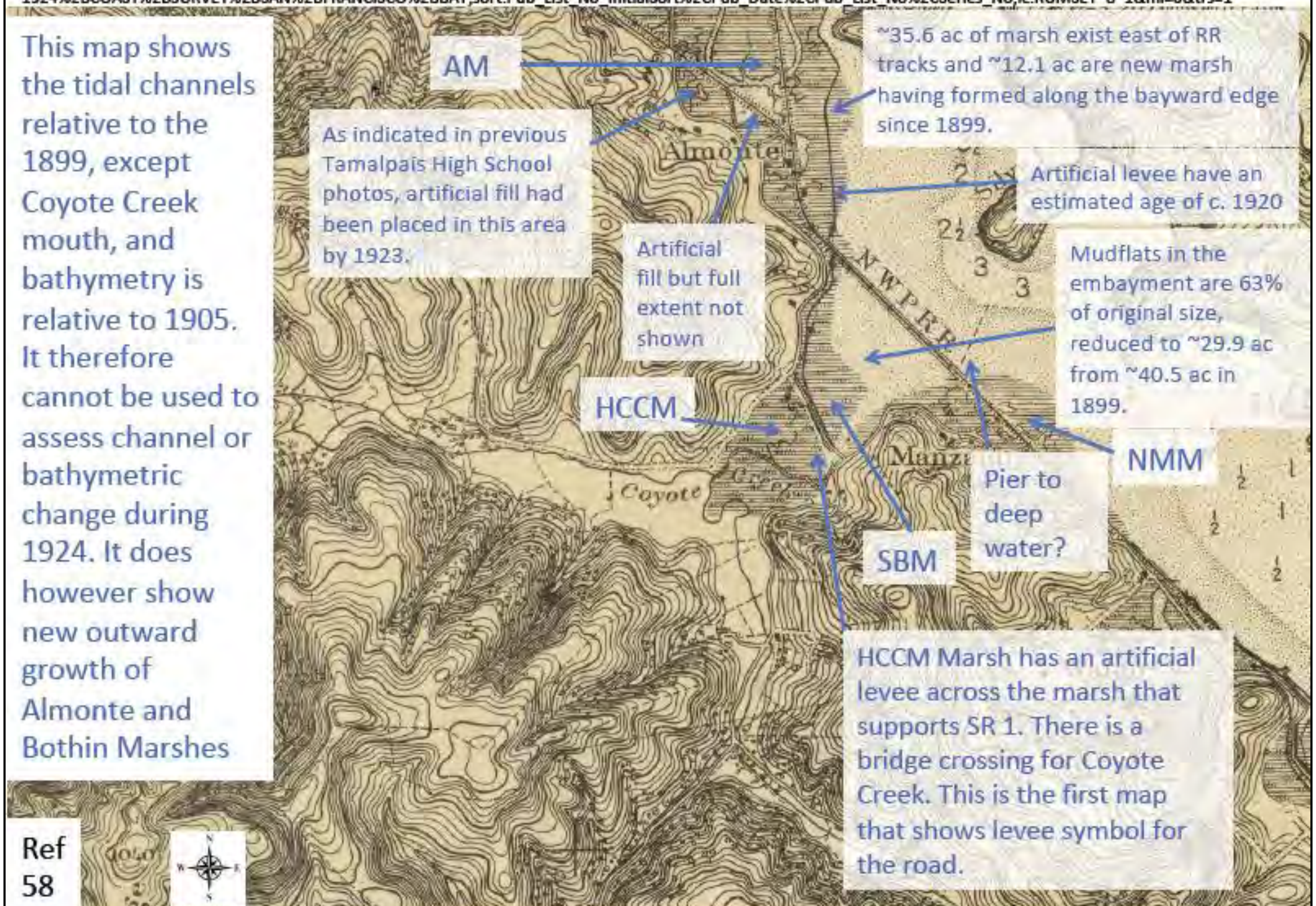
1923, Tamalpais High School. Photo Source: https://mvhistory.org/wp-content/uploads/2014/08/TamHigh1923.jpg

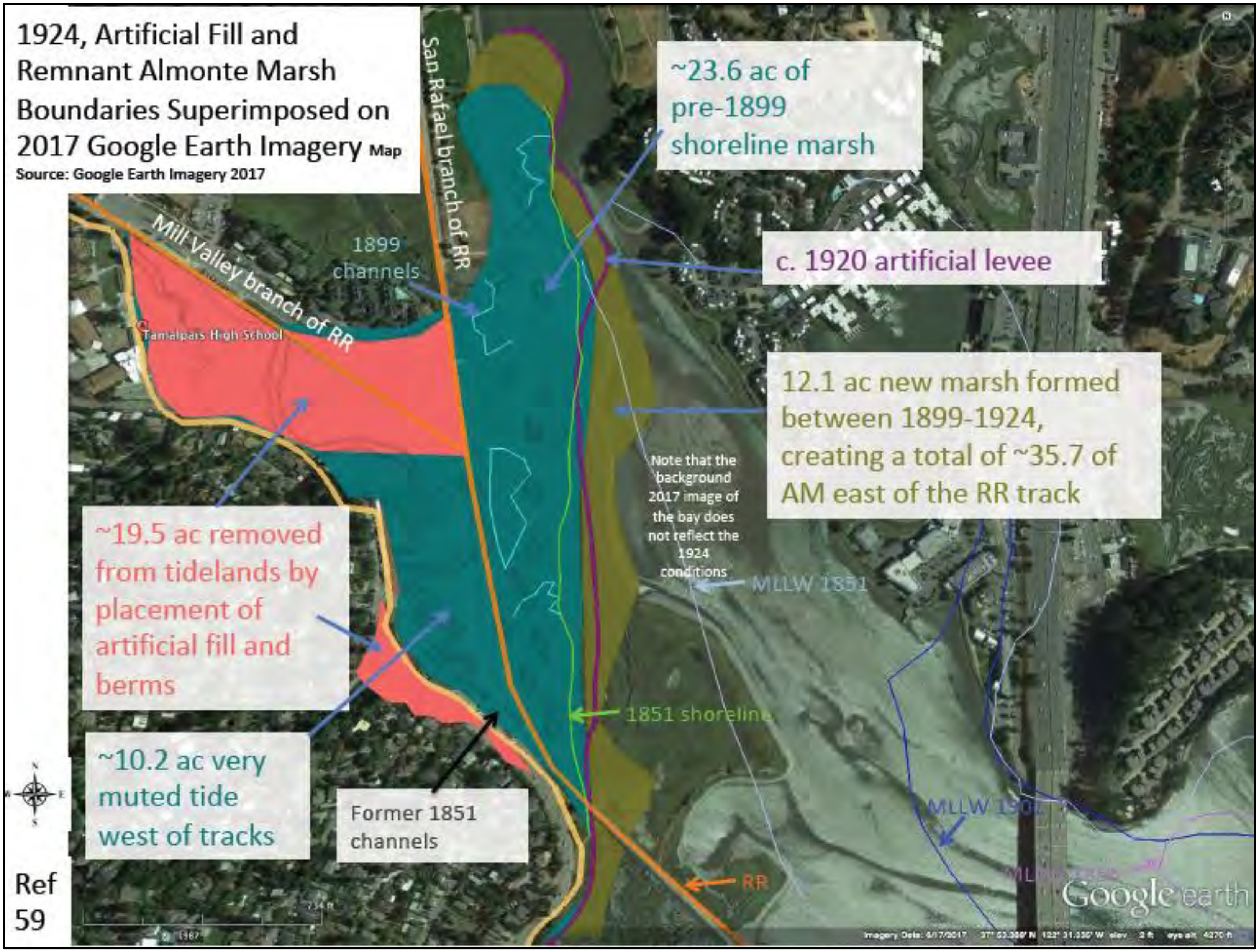
This early 1923 sports field track is the site of the 2017 parking lot. About 5.8 ac of marsh were eliminated at this location and another ~2.0 ac were probably eliminated along the western upland edge of the San Rafael Road, now called Homestead Blvd.

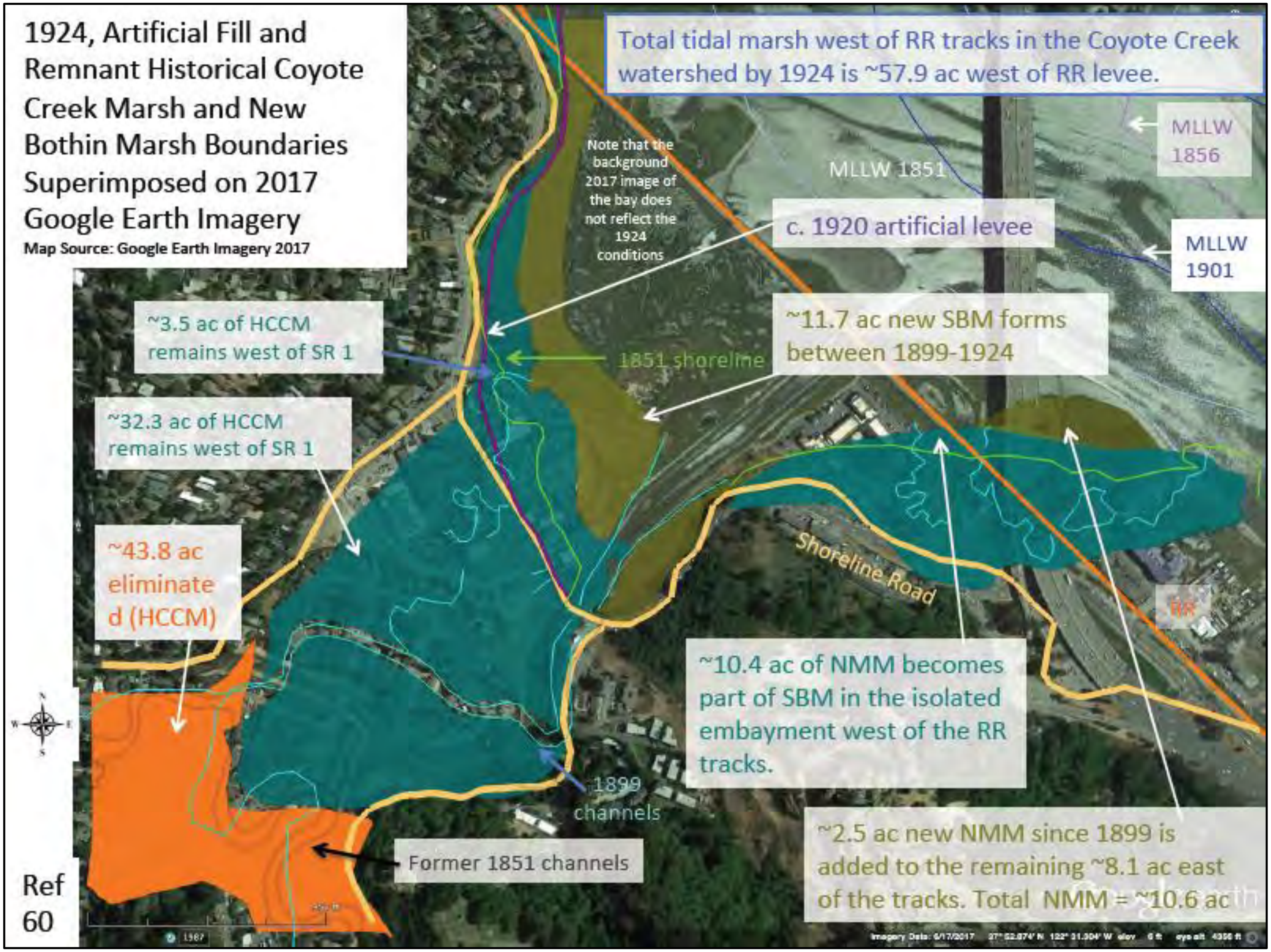
Aerial photo showing the lower portion of Keyser completed and the upper Keyser being built. Note the "Canteen" at Almonte and Camino Alto Ave far left side.

Ref 57

1924, San Francisco Entrance U.S. Coast Survey Chart 5532 Source: https://www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~265460~5524567:United-States--West-coast,-san-Fran?sort=Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No&qvq=q:1924%2BCOAST%2BSURVEY%2BSAN%2BFRANCISCO%2BBAY;sort:Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No;lc:RUMSEY~8~1&mi=0&trs=1




1924, Artificial Fill and Remnant Almonte Marsh Boundaries Superimposed on 2017 Google Earth Imagery Map
Source: Google Earth Imagery 2017
San Rafael branch of RR
Mill Valley branch of RR
Tamalpais High School
1899 channels
~23.6 ac of pre-1899 shoreline marsh
c. 1920 artificial levee
12.1 ac new marsh formed between 1899-1924, creating a total of ~35.7 of AM east of the RR track
Note that the background 2017 image of the bay does not reflect the 1924 conditions
MLLW 1851
~19.5 ac removed from tidelands by placement of artificial fill and berms
1851 shoreline
~10.2 ac very muted tide west of tracks
Former 1851 channels
RR
Ref 59
Google earth


1924, Artificial Fill and Remnant Historical Coyote Creek Marsh and New Bothin Marsh Boundaries Superimposed on 2017 Google Earth Imagery
Map Source: Google Earth Imagery 2017
Total tidal marsh west of RR tracks in the Coyote Creek watershed by 1924 is ~57.9 ac west of RR levee.
Note that the background 2017 image of the bay does not reflect the 1924 conditions
MLLW 1851
MLLW 1856
MLLW 1901
c. 1920 artificial levee
~3.5 ac of HCCM remains west of SR 1
1851 shoreline
~11.7 ac new SBM forms between 1899-1924
~32.3 ac of HCCM remains west of SR 1
~43.8 ac eliminated (HCCM)
Shoreline Road
RR
~10.4 ac of NMM becomes part of SBM in the isolated embayment west of the RR tracks.
1899 channels
Former 1851 channels
~2.5 ac new NMM since 1899 is added to the remaining ~8.1 ac east of the tracks. Total NMM = ~10.6 ac
Ref 60

1925 Hiking Map of Marin by NWPRR

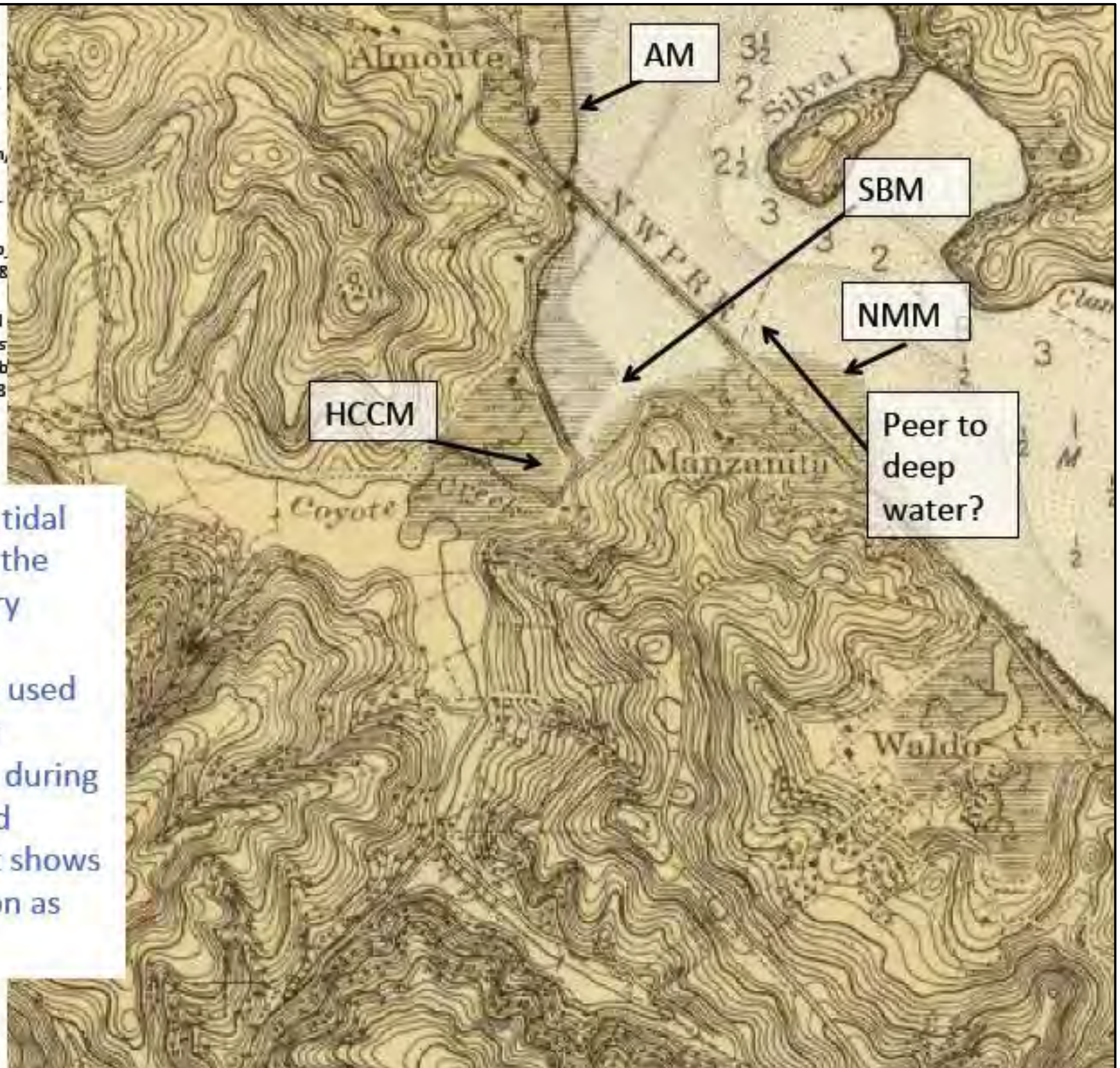
Map Source: California History Room, Library Marin Civic Center

Railroad station names are indicated on this map.

Ref 61

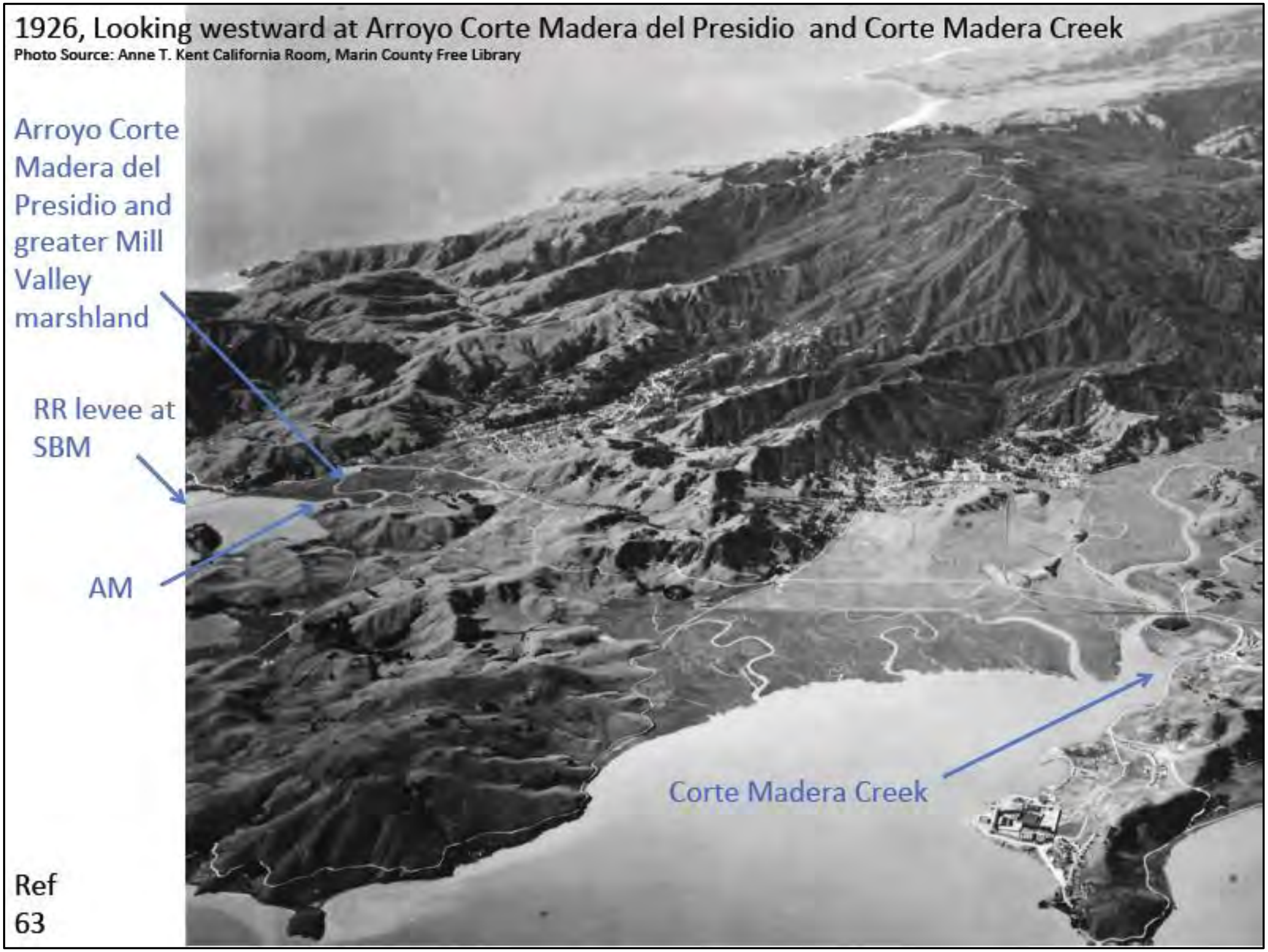
1926 San Francisco Entrance, U.S. Coast Survey Chart 5532

Map Source: www.davidrumsey.com/ luna/servlet/detail/ RUMSEY~8~1~4228~360040:United- States---West-Coast--San-Fra? sort=Pub_List_No_InitialSort%2CPub_ Date%2CPub_List_No%2CSeries_No8 qvq=q: 1926%2BCOAST%2BSURVEY%2BSAN %2BFRANCISCO%2BBAY;sort:Pub_Lis _No_InitialSort%2CPub_Date%2CPub _List_No%2CSeries_No;lc:RUMSEY~8 ~1&mi=0&trs=1



This map shows the tidal channels relative to the 1899 and bathymetry relative to 1905, it therefore cannot be used to assess channel or bathymetric change during 1924. For Bothin and Almonte Marshes, it shows the same information as the 1924 chart.

Ref 62



1926, Looking westward at Arroyo Corte Madera del Presidio and Corte Madera Creek

Photo Source: Anne T. Kent California Room, Marin County Free Library

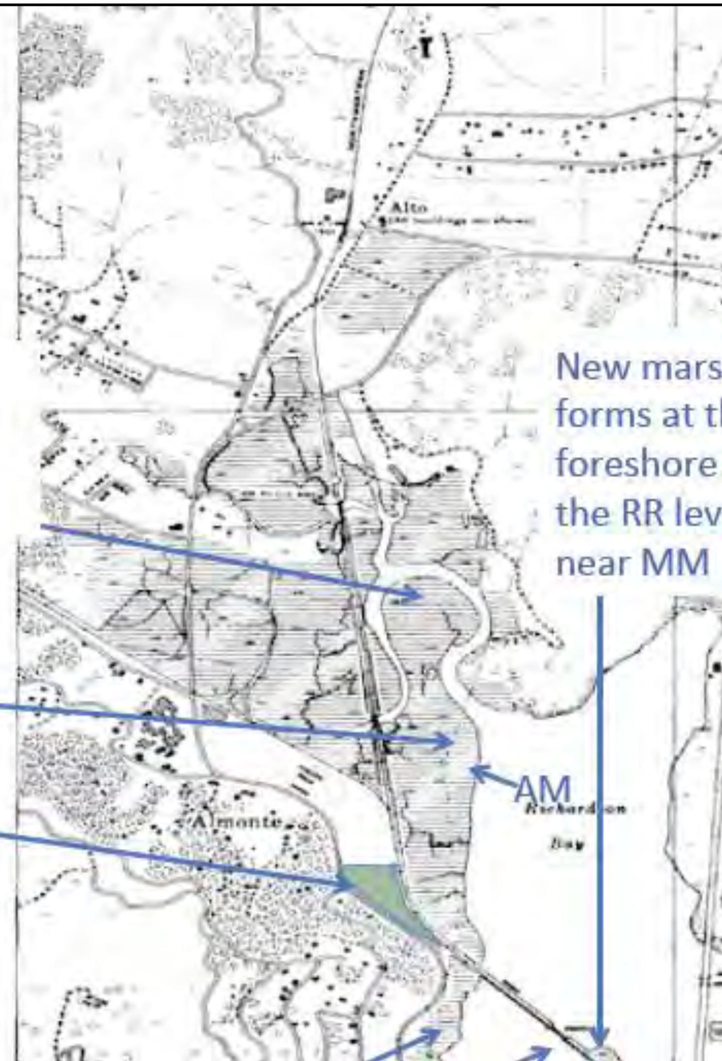
1927, US Coast and Geodetic Survey, Planimetric Map T-sheet 5929 overlaid onto 8/2016 Google Earth Imagery

Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html

Bend along Arroyo Corte Madera, referred to as the "bulb", extended northward creating new marsh and then migrated westward at the last bend before the mouth, thereby eroding parts of AM.

Electrical power line corridor and boardwalk

~3.8 ac of "Tam" marsh, still remained in this section but are not depicted with appropriate symbology on this map. Tam marsh is tallied as part of AM.

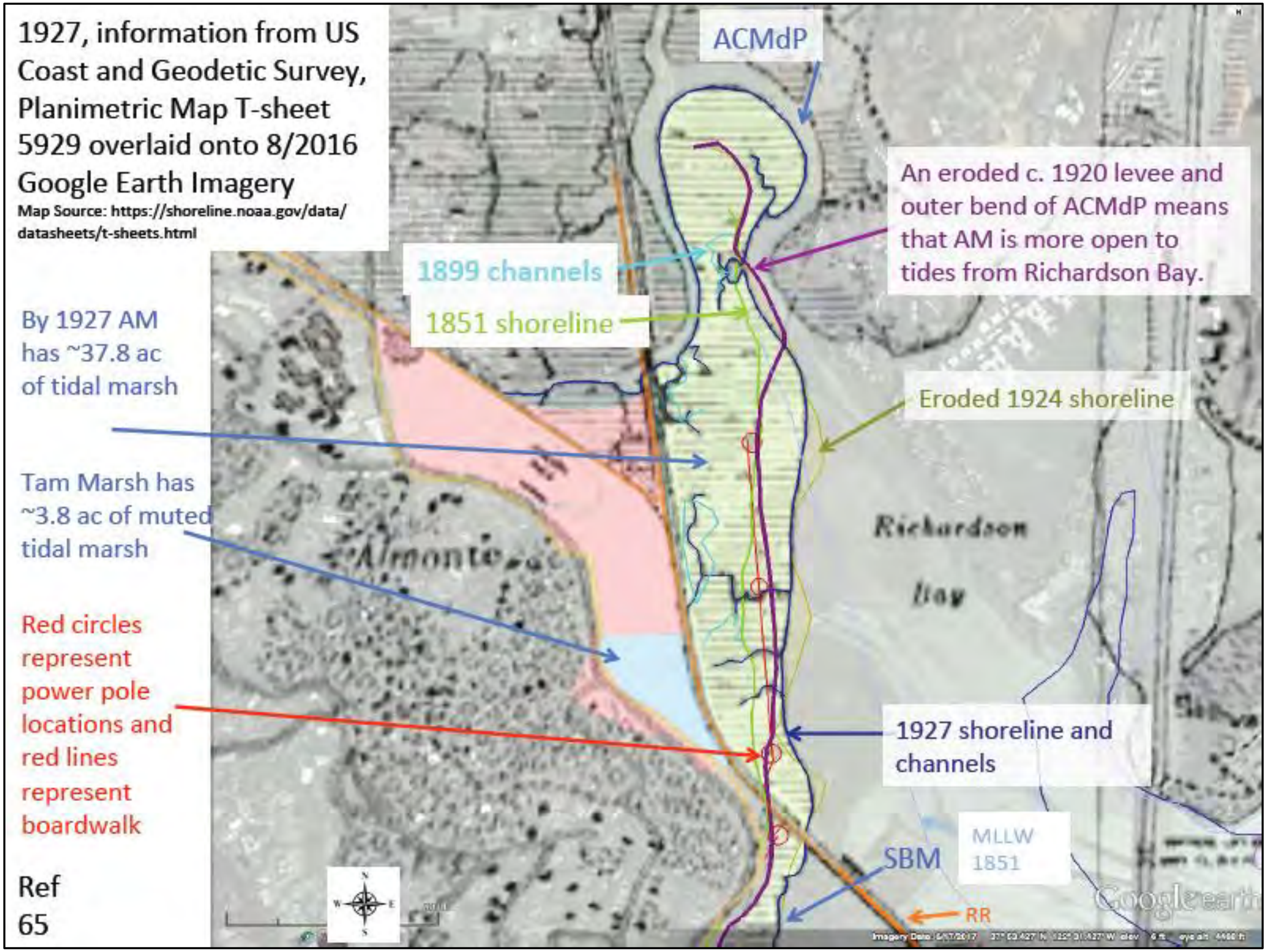


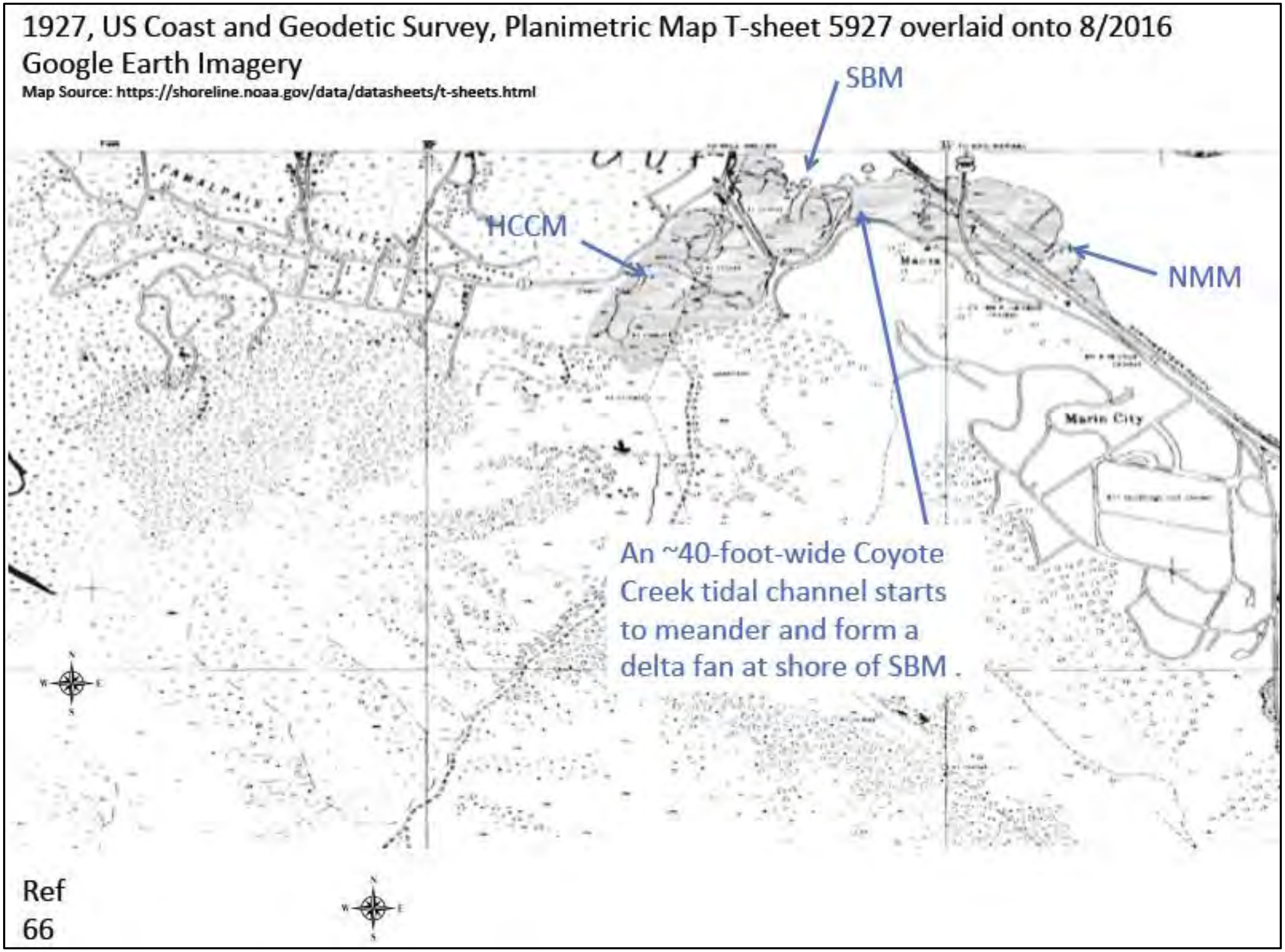
New marsh forms at the foreshore of the RR levee near MM

SBM

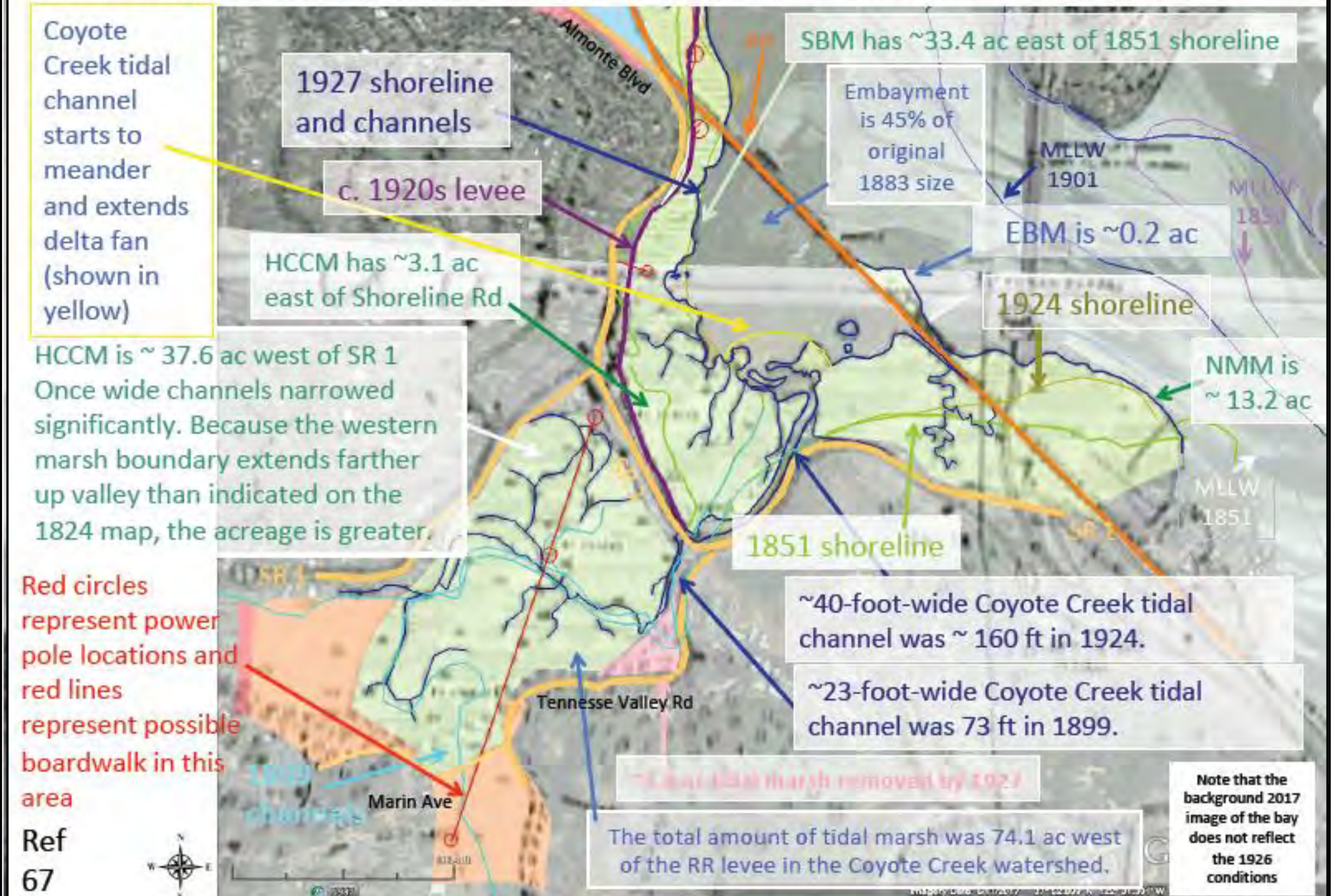
~125 ft-long trestle spans the Coyote Creek embayment

Ref 64


1927, information from US Coast and Geodetic Survey, Planimetric Map T-sheet 5929 overlaid onto 8/2016 Google Earth Imagery
Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html
By 1927 AM has ~37.8 ac of tidal marsh
Tam Marsh has ~3.8 ac of muted tidal marsh
Red circles represent power pole locations and red lines represent boardwalk
Ref 65
ACMdP
An eroded c. 1920 levee and outer bend of ACMdP means that AM is more open to tides from Richardson Bay.
1899 channels
1851 shoreline
Eroded 1924 shoreline
Almonte
Richardson Bay
1927 shoreline and channels
MLLW 1851
SBM
RR
Google earth


1927, US Coast and Geodetic Survey, Planimetric Map T-sheet 5927 overlaid onto 8/2016 Google Earth Imagery
Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html
SBM
HCCM
NMM
Marin City
An ~40-foot-wide Coyote Creek tidal channel starts to meander and form a delta fan at shore of SBM .
Ref 66

1927, US Coast and Geodetic Survey, Planimetric Maps T-sheet 5927 and 5929 overlaid onto 6/2017 Google Earth Imagery Map Source: https://shoreline.noaa.gov/data/datasheets/t-sheets.html



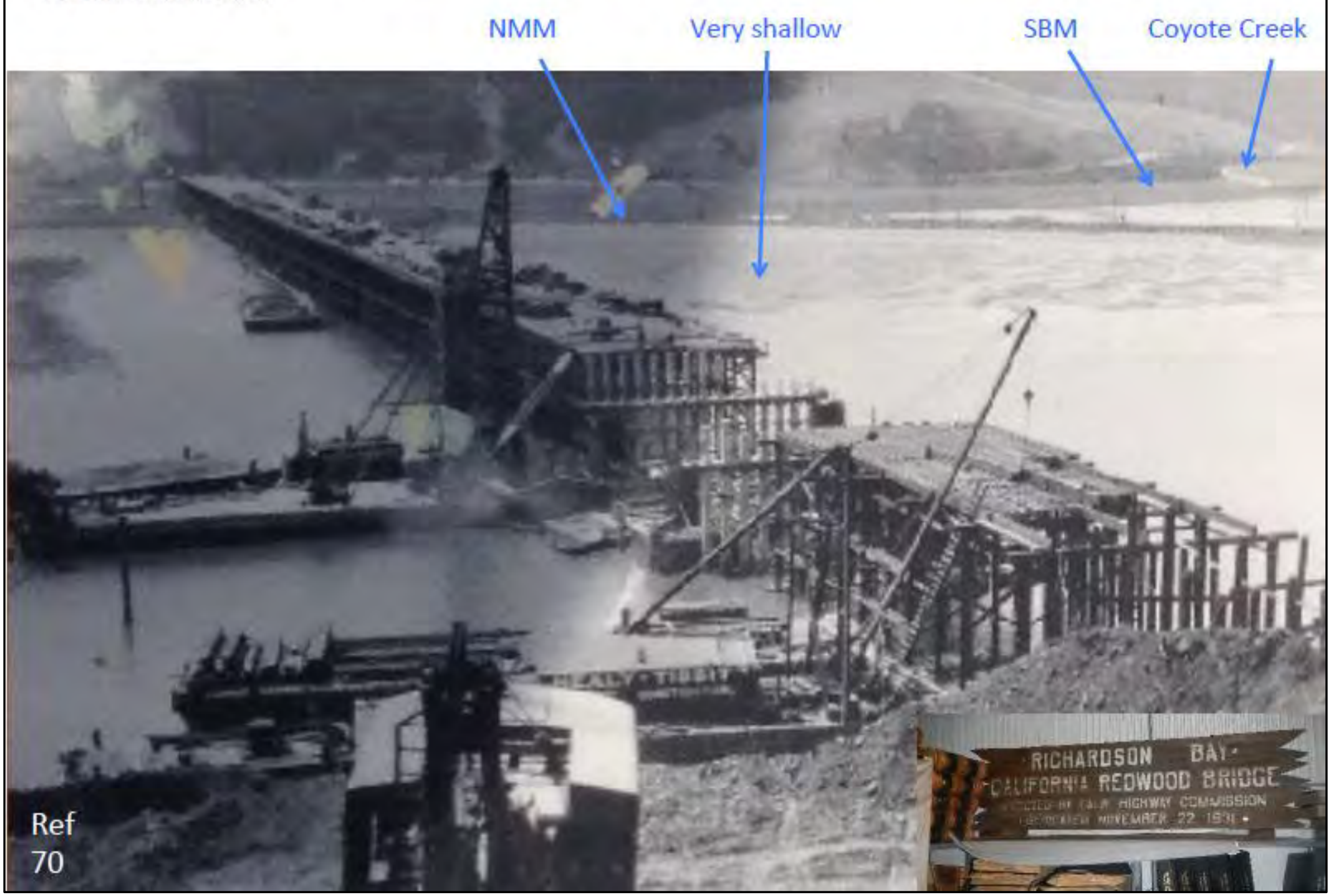
July 1929 Smoke from Mount Tamalpais/Mill Valley Fire

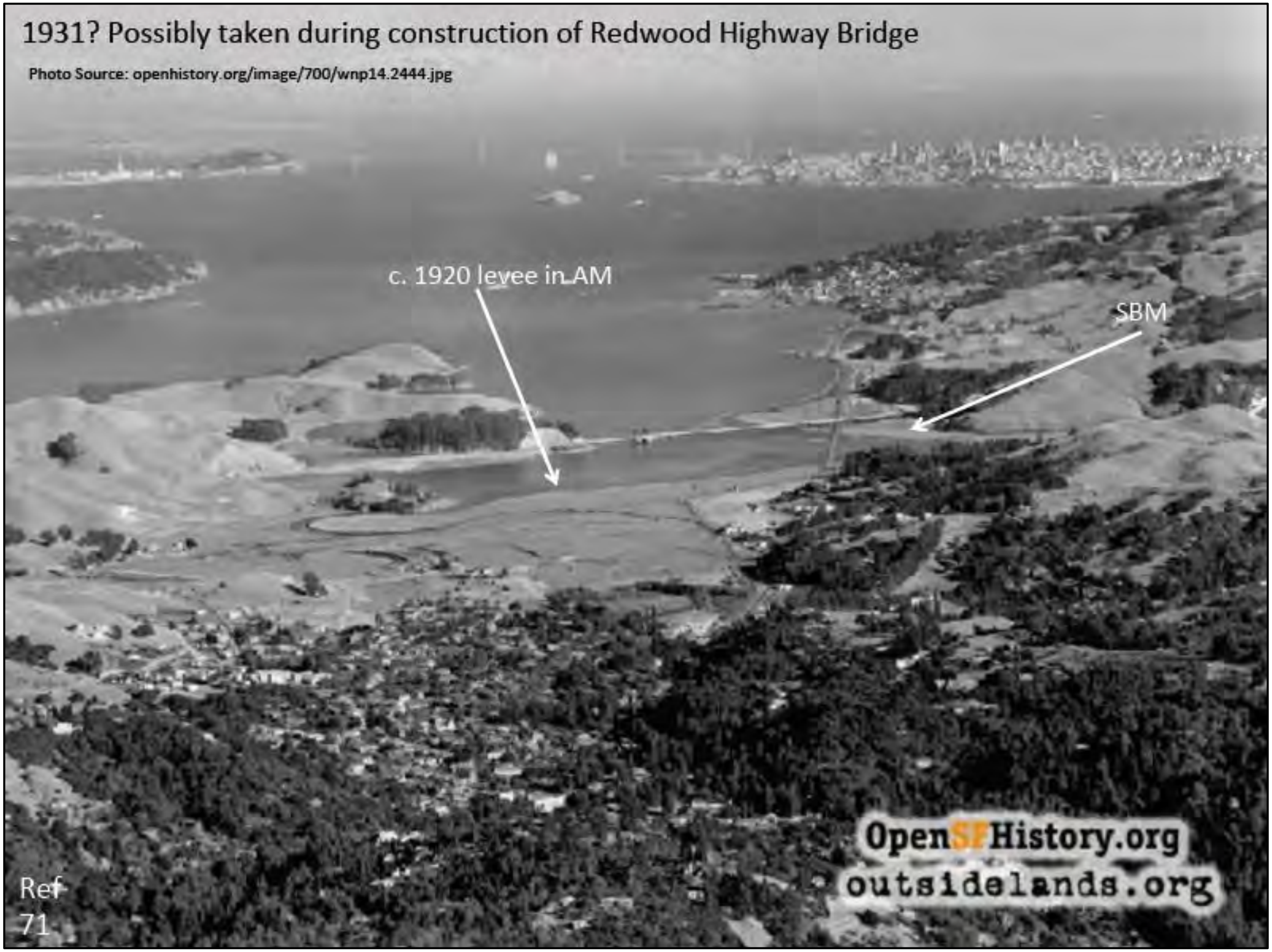
Photo, Source: https://www.marincounty.org/~/media/images/departments/fr/history/1920/1929_fire_5_after_jpg.jpg

1931, Illustrative sign along Bay Trail in Bothin Marsh **Source: Marin County Parks Sign**

1931, Construction of the Redwood Highway Bridge, South Bothin Marsh in background.

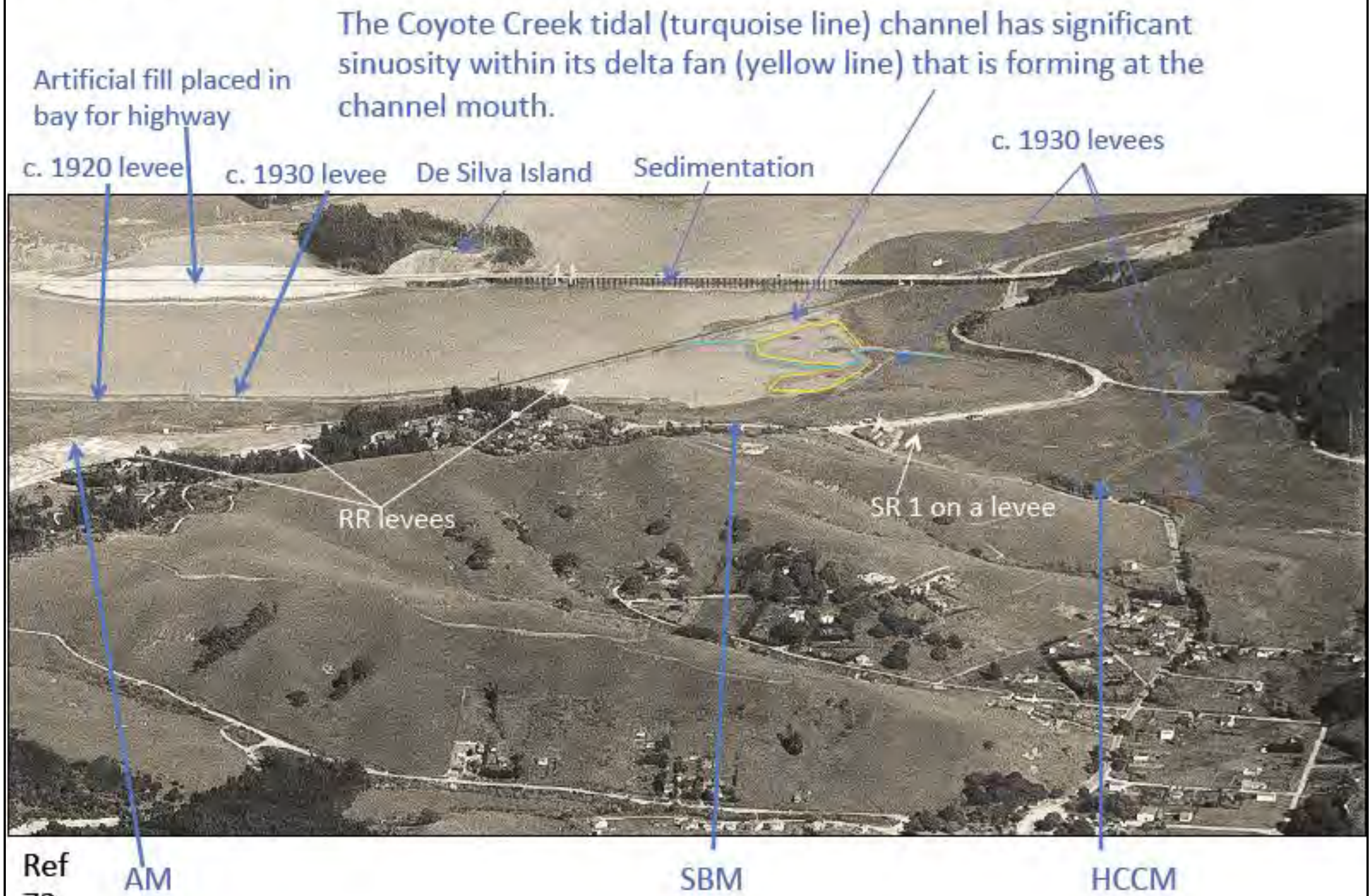
Photo Source: Richard Tourney




1931? Possibly taken during construction of Redwood Highway Bridge
Photo Source: openhistory.org/image/700/wnp14.2444.jpg
c. 1920 levee in AM
SBM
OpenSFHistory.org
outsidelands.org
Ref
71

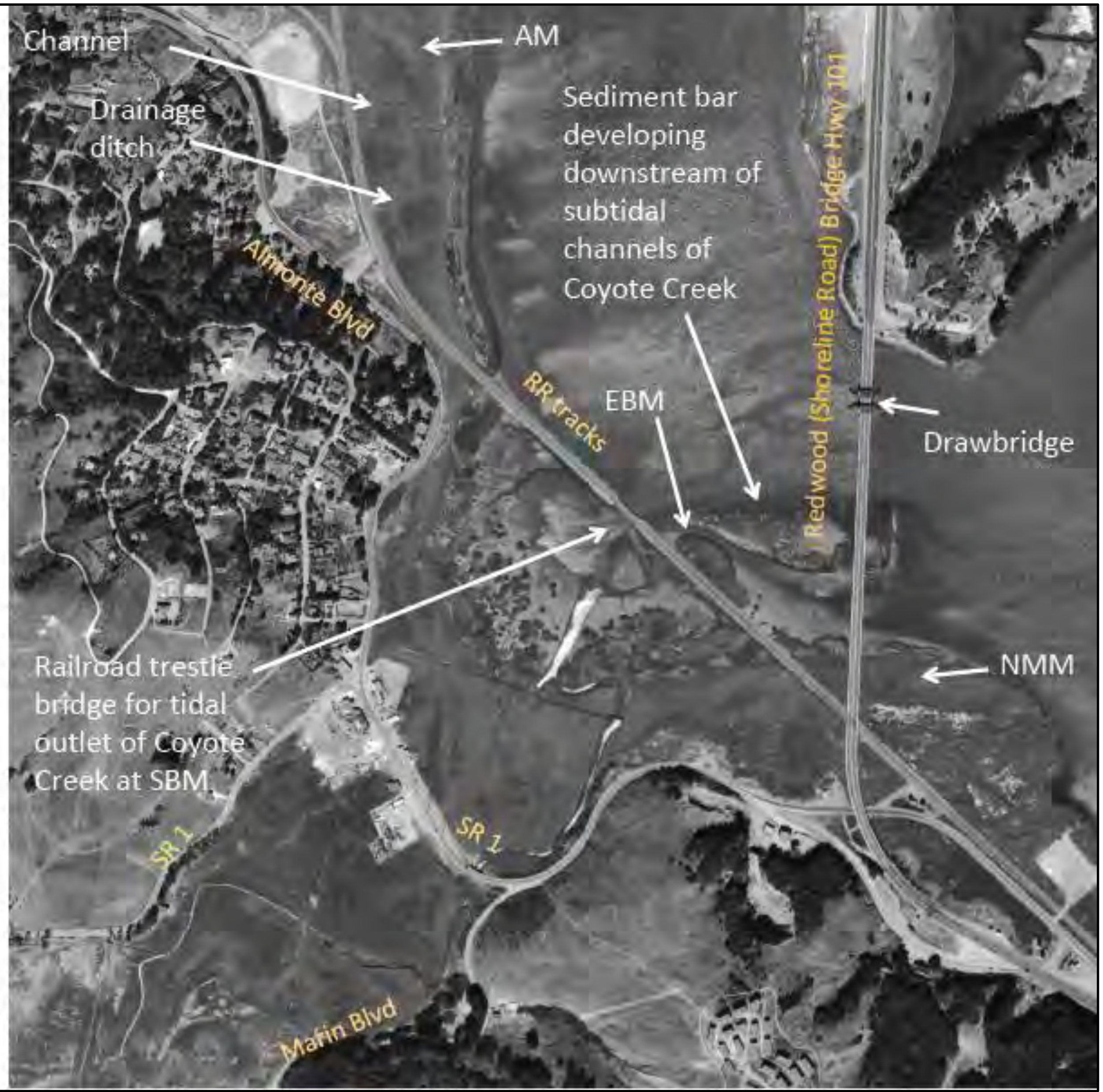
1932?,

Photo Source: https://mvhistory.org/wp-content/uploads/2015/07/Tam-Valley-24.jpg

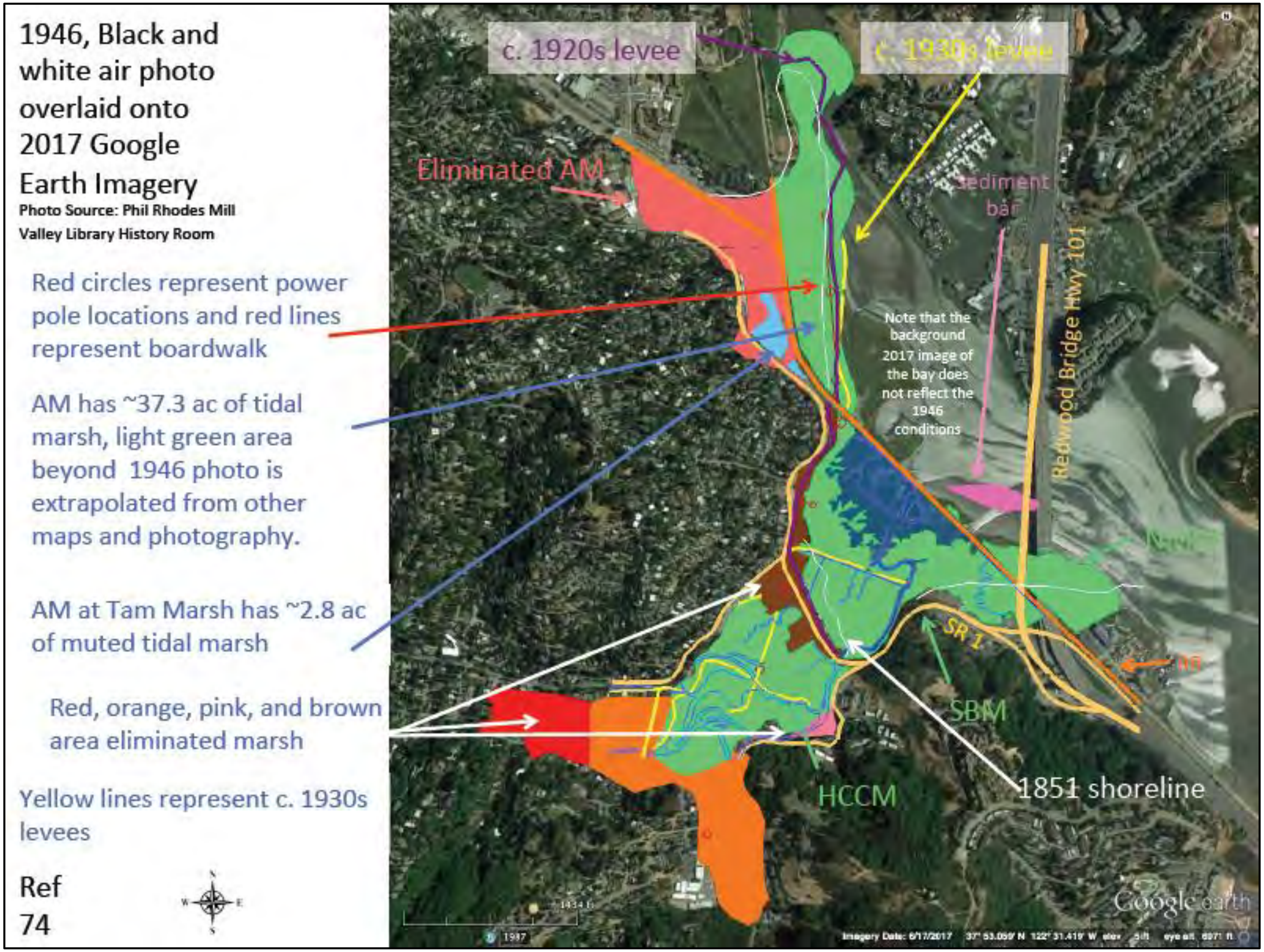


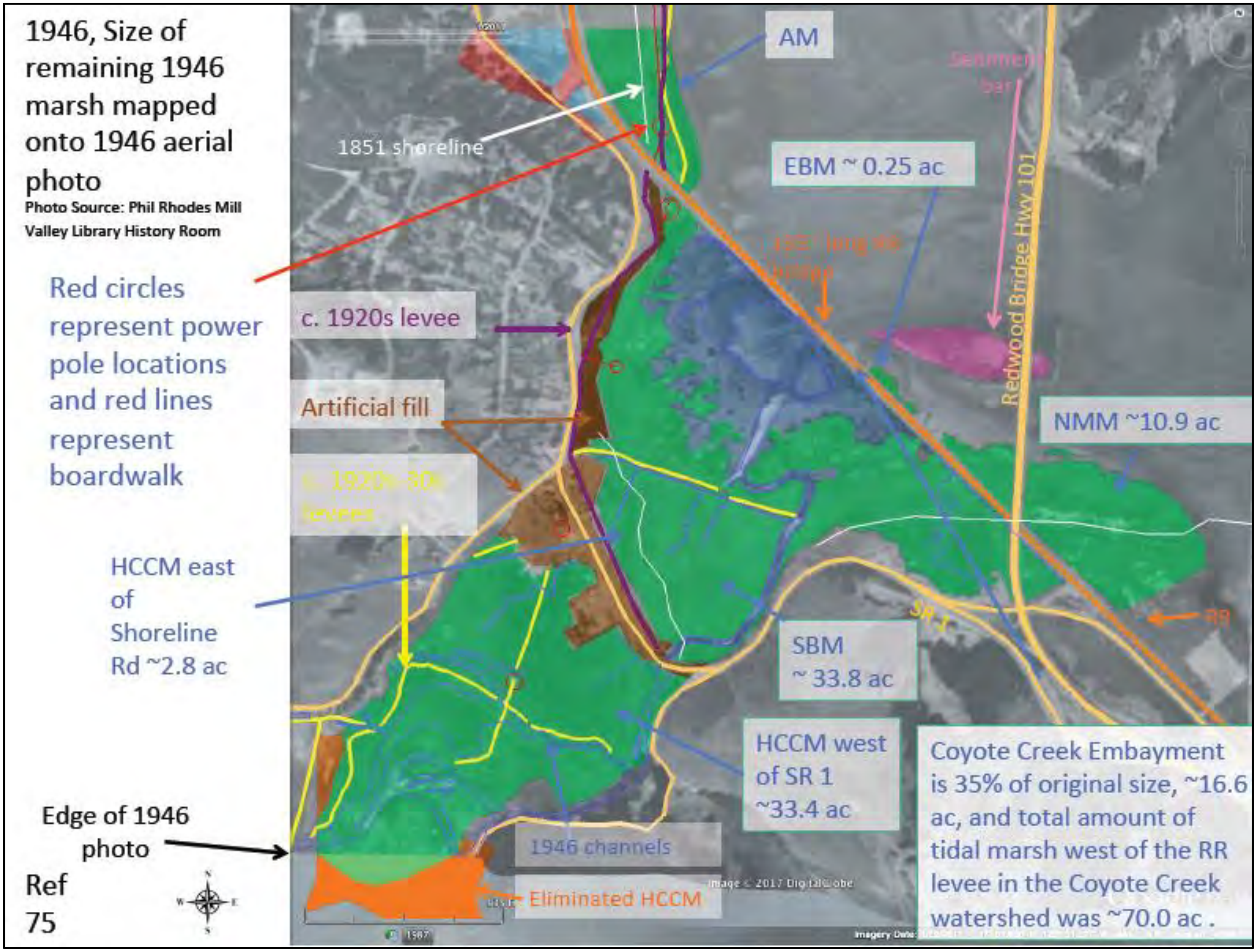
Ref 72

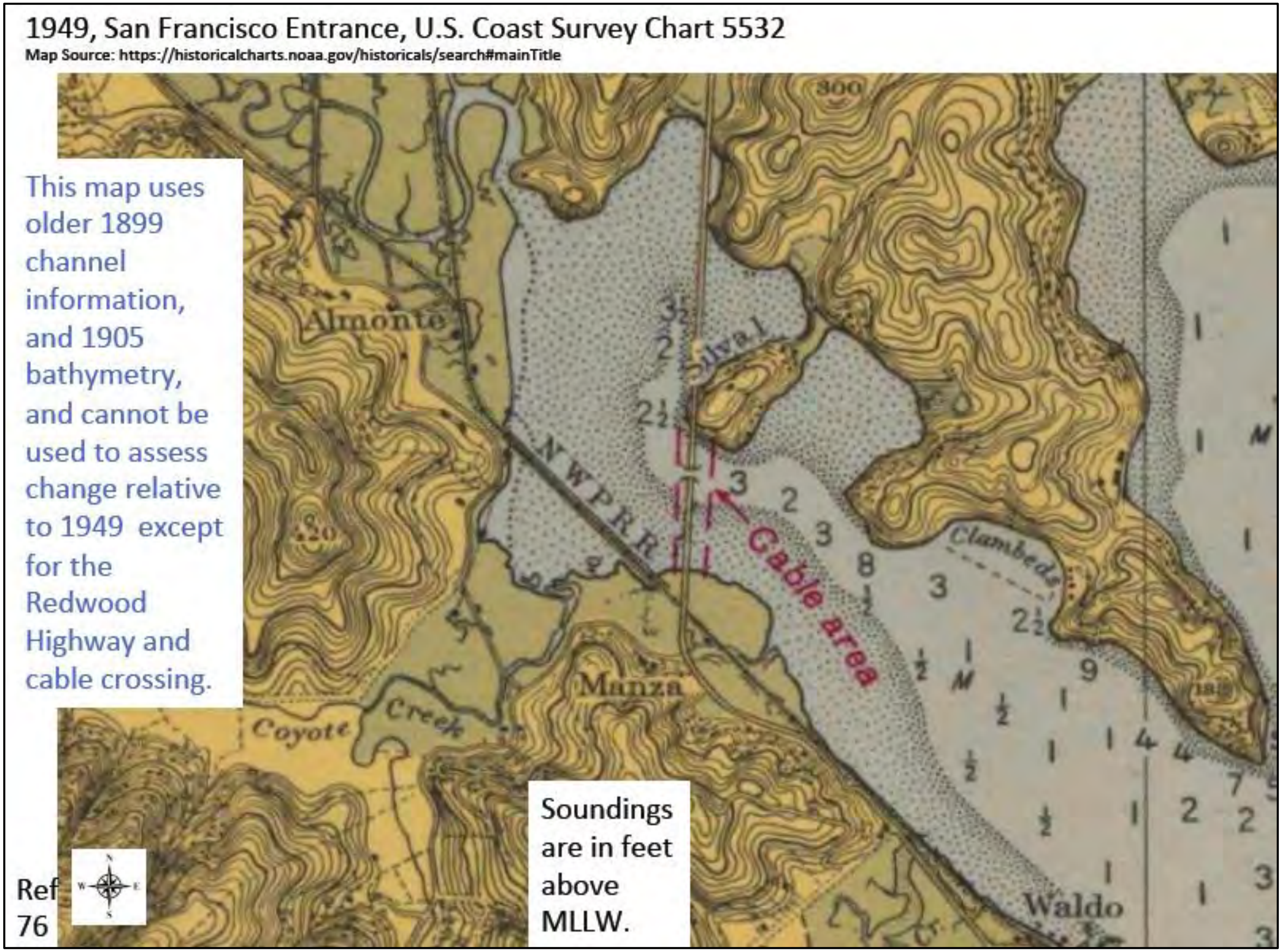
1946
Photo Source: Phil Rhodes Mill Valley Library History Room



Ref 73


1946, Black and white air photo overlaid onto 2017 Google Earth Imagery
Photo Source: Phil Rhodes Mill Valley Library History Room
Red circles represent power pole locations and red lines represent boardwalk
AM has ~37.3 ac of tidal marsh, light green area beyond 1946 photo is extrapolated from other maps and photography.
AM at Tam Marsh has ~2.8 ac of muted tidal marsh
Red, orange, pink, and brown area eliminated marsh
Yellow lines represent c. 1930s levees
Ref 74
c. 1920s levee
c. 1930s levee
Eliminated AM
Sediment bar
Note that the background 2017 image of the bay does not reflect the 1946 conditions
Redwood Bridge Hwy 101
SR 1
SBM
HCCM
1851 shoreline
Google earth


1946, Size of remaining 1946 marsh mapped onto 1946 aerial photo
Photo Source: Phil Rhodes Mill Valley Library History Room
Red circles represent power pole locations and red lines represent boardwalk
HCCM east of Shoreline Rd ~2.8 ac
Edge of 1946 photo
Ref 75
1851 shoreline
AM
EBM ~ 0.25 ac
Redwood Bridge Hwy 101
c. 1920s levee
Artificial fill
NMM ~10.9 ac
SR 1
RR
SBM ~ 33.8 ac
HCCM west of SR 1 ~33.4 ac
1946 channels
Eliminated HCCM
Coyote Creek Embayment is 35% of original size, ~16.6 ac, and total amount of tidal marsh west of the RR levee in the Coyote Creek watershed was ~70.0 ac .


1949, San Francisco Entrance, U.S. Coast Survey Chart 5532
Map Source: https://historicalcharts.noaa.gov/historicals/search#mainTitle
This map uses older 1899 channel information, and 1905 bathymetry, and cannot be used to assess change relative to 1949 except for the Redwood Highway and cable crossing.
Almonte
NWPRR
Cable area
Clambeds
Manza
Coyote Creek
Waldo
Soundings are in feet above MLLW.
Ref 76


1950, Photo
Source: Sausalito Historical Society
Artificial fill increases for commercial area along SR 1
Sediment bar still exists downstream of subtidal channels of Coyote Creek
Ref 77

1950, Looking southeastward at Redwood Highway Bridge crossing Richardson Bay

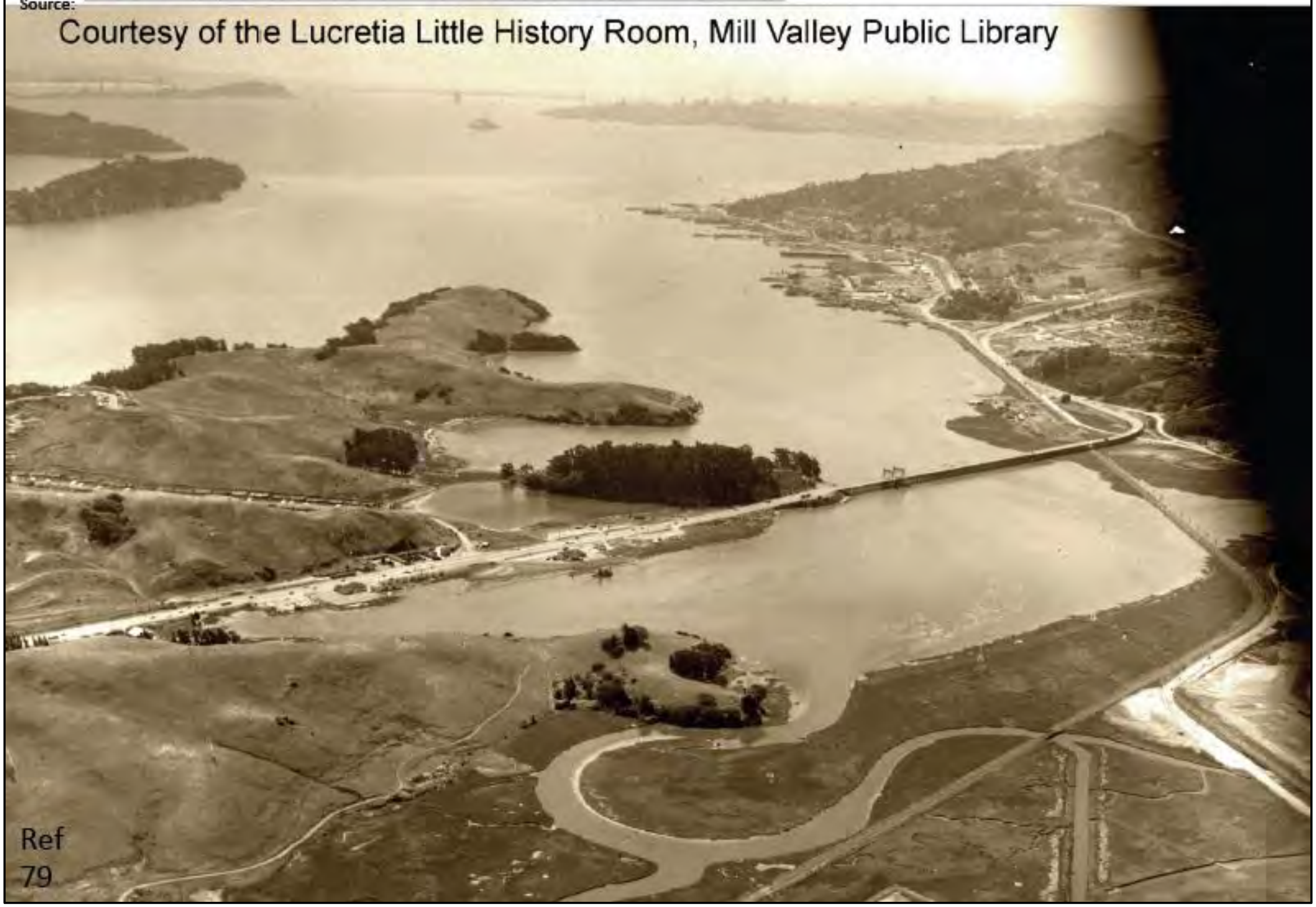
Photo Source: https://mvhistory.org wp-content/uploads/2014/08/ TamHigh1923.jpg

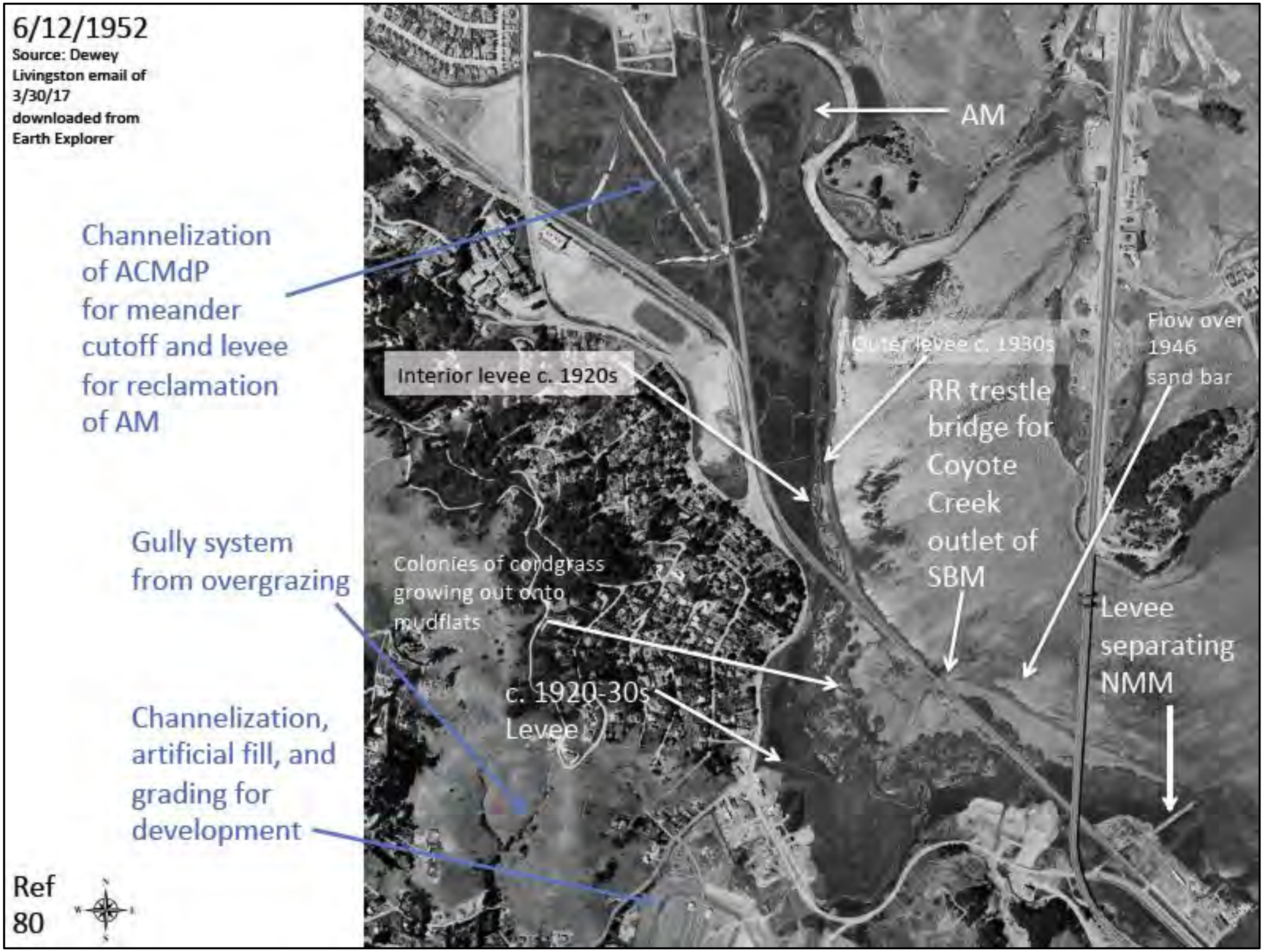
This later c. 1931 sports field is constructed to south of the earlier 1923 track. Artificial fill has been placed over much of the former Almonte Marsh on the west side of Mill Valley RR branch and in the small triangle between the two branches.

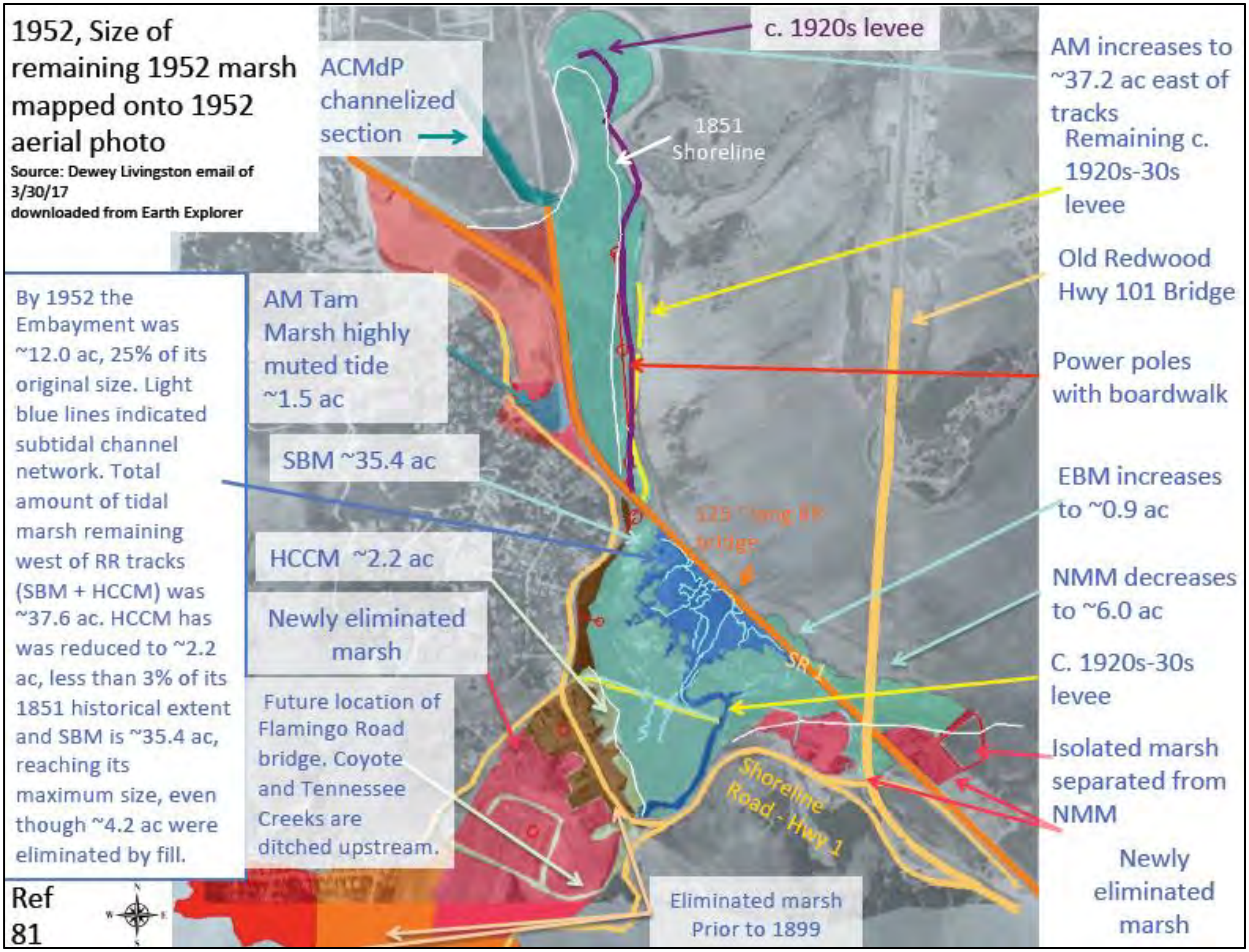
Ref 78

1950, Detail of looking southeastward at Redwood Highway Bridge crossing Richardson Bay

Source: https://mvhistory.org/wp-content/uploads/2015/05/Before-dredging-about-1950.jpg




6/12/1952
Source: Dewey Livingston email of 3/30/17 downloaded from Earth Explorer
Channelization of ACMdP for meander cutoff and levee for reclamation of AM
Gully system from overgrazing
Channelization, artificial fill, and grading for development
Ref 80
AM
Interior levee c. 1920s
Outer levee c. 1930s
RR trestle bridge for Coyote Creek outlet of SBM
Flow over 1946 sand bar
Colonies of cordgrass growing out onto mudflats
c. 1920-30s Levee
Levee separating NMM


1952, Size of remaining 1952 marsh mapped onto 1952 aerial photo
Source: Dewey Livingston email of 3/30/17
downloaded from Earth Explorer
ACMdP channelized section
c. 1920s levee
1851 Shoreline
AM increases to ~37.2 ac east of tracks
Remaining c. 1920s-30s levee
Old Redwood Hwy 101 Bridge
Power poles with boardwalk
By 1952 the Embayment was ~12.0 ac, 25% of its original size. Light blue lines indicated subtidal channel network. Total amount of tidal marsh remaining west of RR tracks (SBM + HCCM) was ~37.6 ac. HCCM has was reduced to ~2.2 ac, less than 3% of its 1851 historical extent and SBM is ~35.4 ac, reaching its maximum size, even though ~4.2 ac were eliminated by fill.
AM Tam Marsh highly muted tide ~1.5 ac
SBM ~35.4 ac
HCCM ~2.2 ac
Newly eliminated marsh
Future location of Flamingo Road bridge. Coyote and Tennessee Creeks are ditched upstream.
EBM increases to ~0.9 ac
NMM decreases to ~6.0 ac
C. 1920s-30s levee
Isolated marsh separated from NMM
Newly eliminated marsh
SR 1
Shoreline Road - Hwy 1
Eliminated marsh Prior to 1899
Ref 81

1956 Flooding
Source: Tamalpais Valley Improvement Club

JANUARY 6. 1956

www.tamvalley.org/images/TheProgressPics/1996TheProgress-Pg7.pdf

Ref 82

MAIN ST. (LAUREL) TOWARDS SHORELINE

SHORELINE BETWEEN PINE & SPRUCE

1956 Flooding
Source: Tamalpais Valley Improvement Club

www.tamvalley.org/images/TheProgressPics/1996TheProgress-Pg7.pdf

Ref 83

SHORELINE BETWEEN POPLAR & PINE ST.

Date 1956?, Richardson Bay looking Northwest

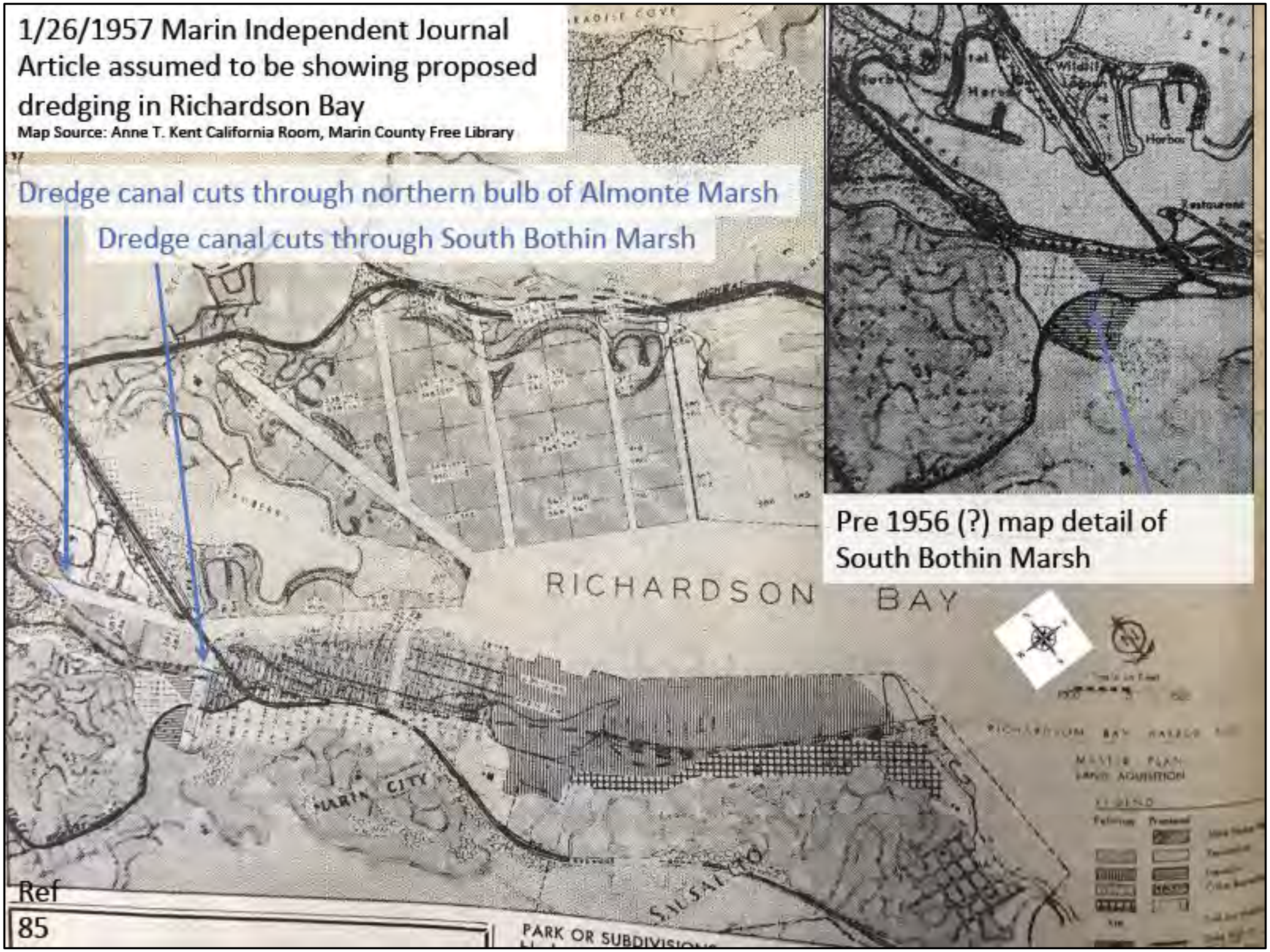
Photo Source: California History Room Marin Civic Center Library

Construction new concrete bridge for Highway 101 started in 1956

Containment levee had been constructed for placement of dredge spoils to continue to fill the bay in front of Almonte Marsh shoreline.

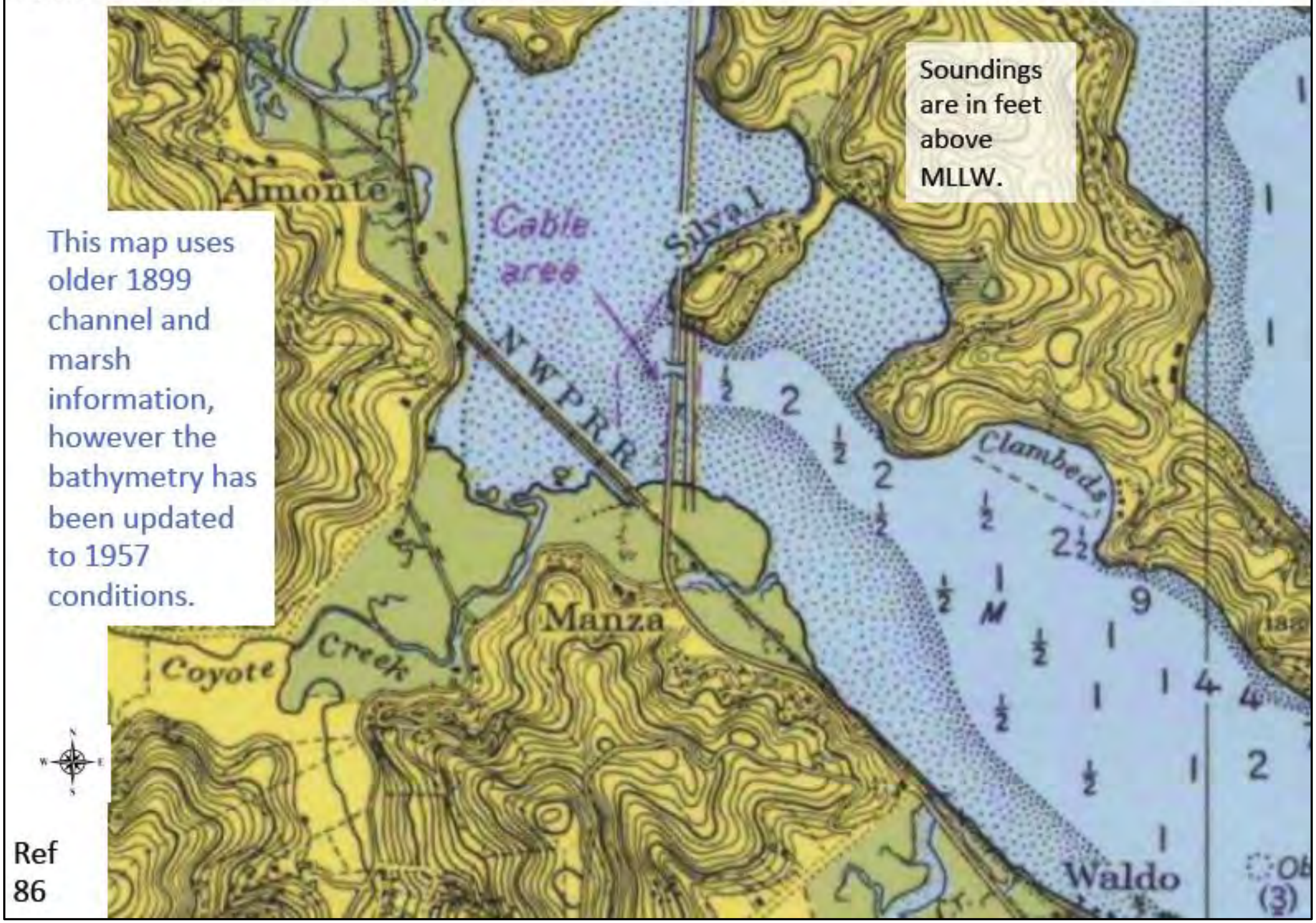
Materials comprising fill in Sausalito.

Ref 84


1/26/1957 Marin Independent Journal
Article assumed to be showing proposed
dredging in Richardson Bay
Map Source: Anne T. Kent California Room, Marin County Free Library
Dredge canal cuts through northern bulb of Almonte Marsh
Dredge canal cuts through South Bothin Marsh
Pre 1956 (?) map detail of
South Bothin Marsh
RICHARDSON BAY
MARIN CITY
SAUSALITO
PARK OR SUBDIVISION
Ref
85

1957, San Francisco Entrance, U.S. Coast Survey Chart 5532

Map Source: https://historicalcharts.noaa.gov/historicals/search#mainTitle



Ref 86

Bathymetric MLLW Boundaries from San Francisco Entrance, U.S. Coast Survey Charts #5532 Projected onto 6/2017 Google Earth Imagery

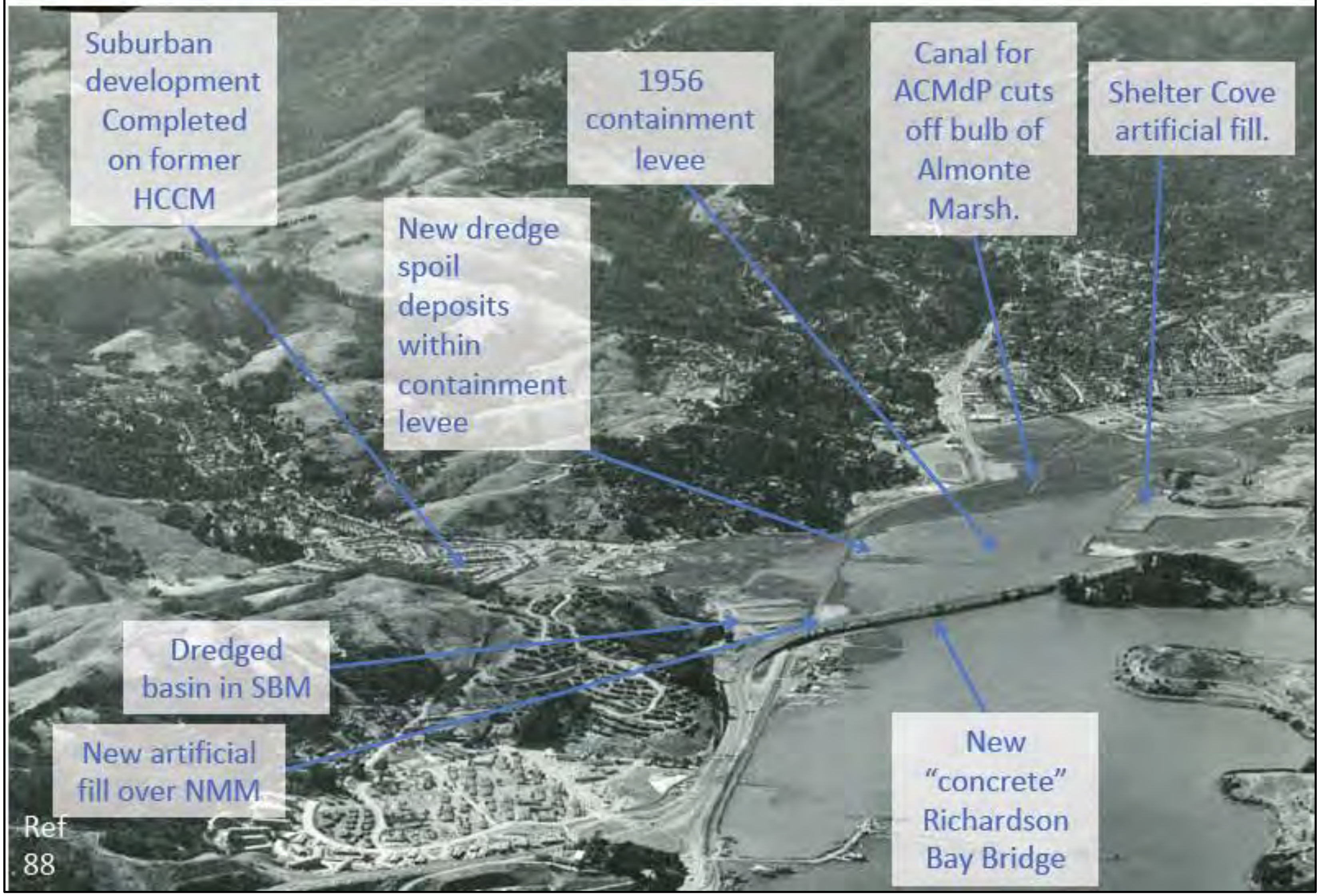
Map Source: https://historicalcharts.noaa.gov/historicals/search#mainTitle

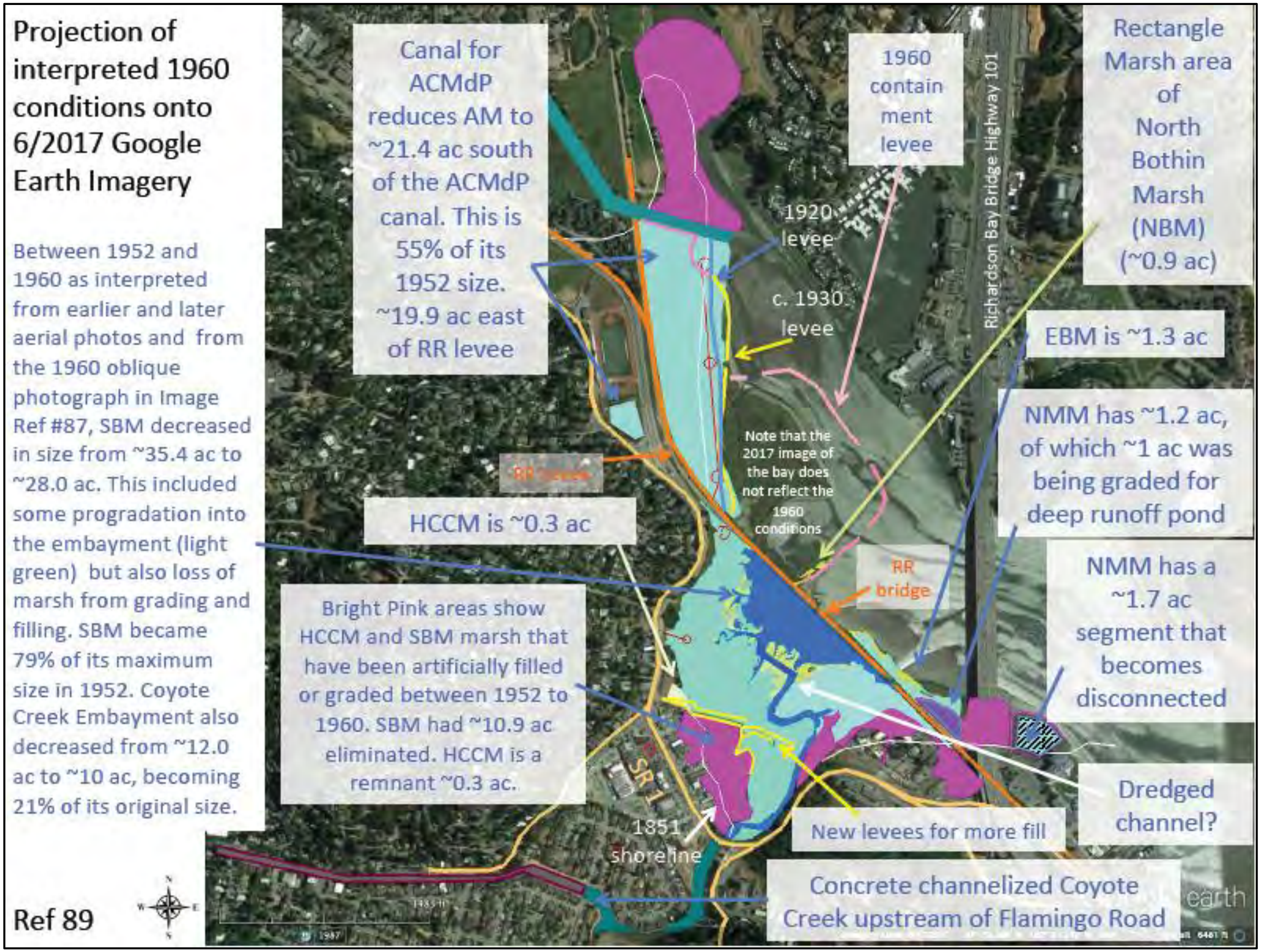
This map shows the changing conditions of the MLLW boundary. It shows that following 1851 (light lavender line) sedimentation in the bay pushed the 1856 boundary significantly southward (violet line). This might have been related to the influx of hydraulic mining sediment from the Sierra and local logging and ranching activities. By 1901 the shallow bay deepens northward (navy blue line), but by 1956 it shallow again, nearly approaching the 1856 boundary of MLLW. The latter period of shallowing might relate to loss of tidal prism from marsh reclamation and bay filling, as well as increased sediment supply from grading for urban development, channel diversion and channelization, and 1956 record flooding.

Ref 87

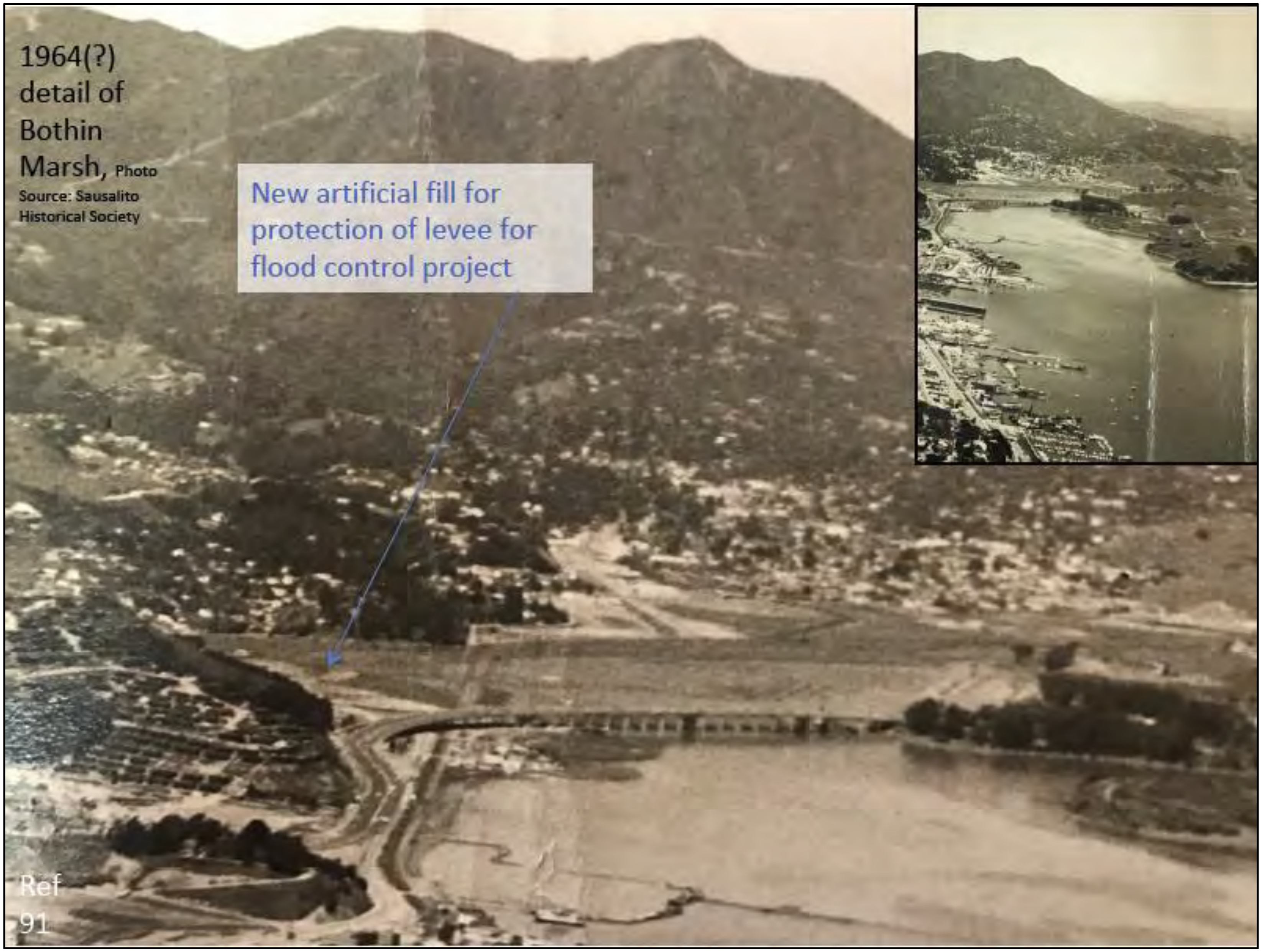
8/2/60 Brady Collection Marin History Museum, detail of photo 6941644175_bbfa0a6966_o

https://www.flickr.com/photos/25539851@N05/6941644175/in/album-72157631793232232/




Projection of interpreted 1960 conditions onto 6/2017 Google Earth Imagery
Between 1952 and 1960 as interpreted from earlier and later aerial photos and from the 1960 oblique photograph in Image Ref #87, SBM decreased in size from ~35.4 ac to ~28.0 ac. This included some progradation into the embayment (light green) but also loss of marsh from grading and filling. SBM became 79% of its maximum size in 1952. Coyote Creek Embayment also decreased from ~12.0 ac to ~10 ac, becoming 21% of its original size.
Ref 89
Canal for ACMdP reduces AM to ~21.4 ac south of the ACMdP canal. This is 55% of its 1952 size. ~19.9 ac east of RR levee
1960 contain ment levee
1920 levee
c. 1930 levee
Richardson Bay Bridge Highway 101
Rectangle Marsh area of North Bothin Marsh (NBM) (~0.9 ac)
EBM is ~1.3 ac
NMM has ~1.2 ac, of which ~1 ac was being graded for deep runoff pond
Note that the 2017 image of the bay does not reflect the 1960 conditions
HCCM is ~0.3 ac
RR bridge
NMM has a ~1.7 ac segment that becomes disconnected
Bright Pink areas show HCCM and SBM marsh that have been artificially filled or graded between 1952 to 1960. SBM had ~10.9 ac eliminated. HCCM is a remnant ~0.3 ac.
SR 1
1851 shoreline
New levees for more fill
Dredged channel?
Concrete channelized Coyote Creek upstream of Flamingo Road
earth


1963, Looking Southeast at Richardson Bay
Photo Source: California History Room, Marin Civic Center Library from Richardson Bay in Transition, A land Use Study Sponsored by the Fish and Wildlife Service
Shelter Cove Artificial Fill
containment levee
bridge
ACMdP channelized, NBM boundary defined
Dredge removing AM bulb at bend of ACMdP
Ref 90


1964(?) detail of Bothin Marsh, Photo Source: Sausalito Historical Society
New artificial fill for protection of levee for flood control project
Ref 91

8/27/65 Brady Collection Marin History Museum, detail of photo 6941654707_a01f6f488d_og

Photo Source: https://www.flickr.com/photos/25539851@N05/albums/72157631793232232/page4

Flood Control Project diversion and trapezoidal tidal channel of Coyote Creek eliminates ~4 ac SBM and ~0.25 ac EBM.

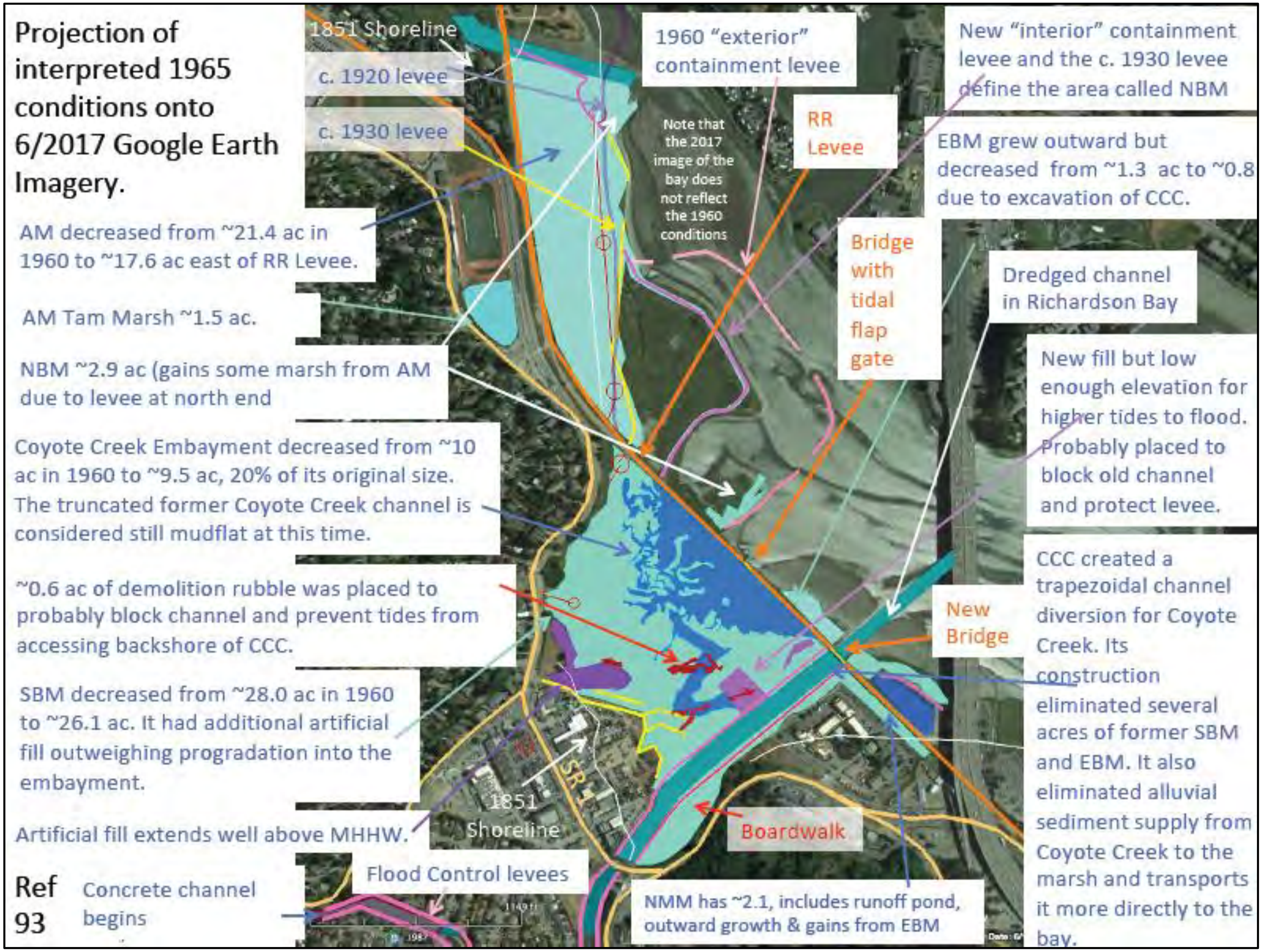
Artificial fill placed for narrowing the opening of Coyote Creek Embayment

New interior containment cell levee under construction (dredge in picture).

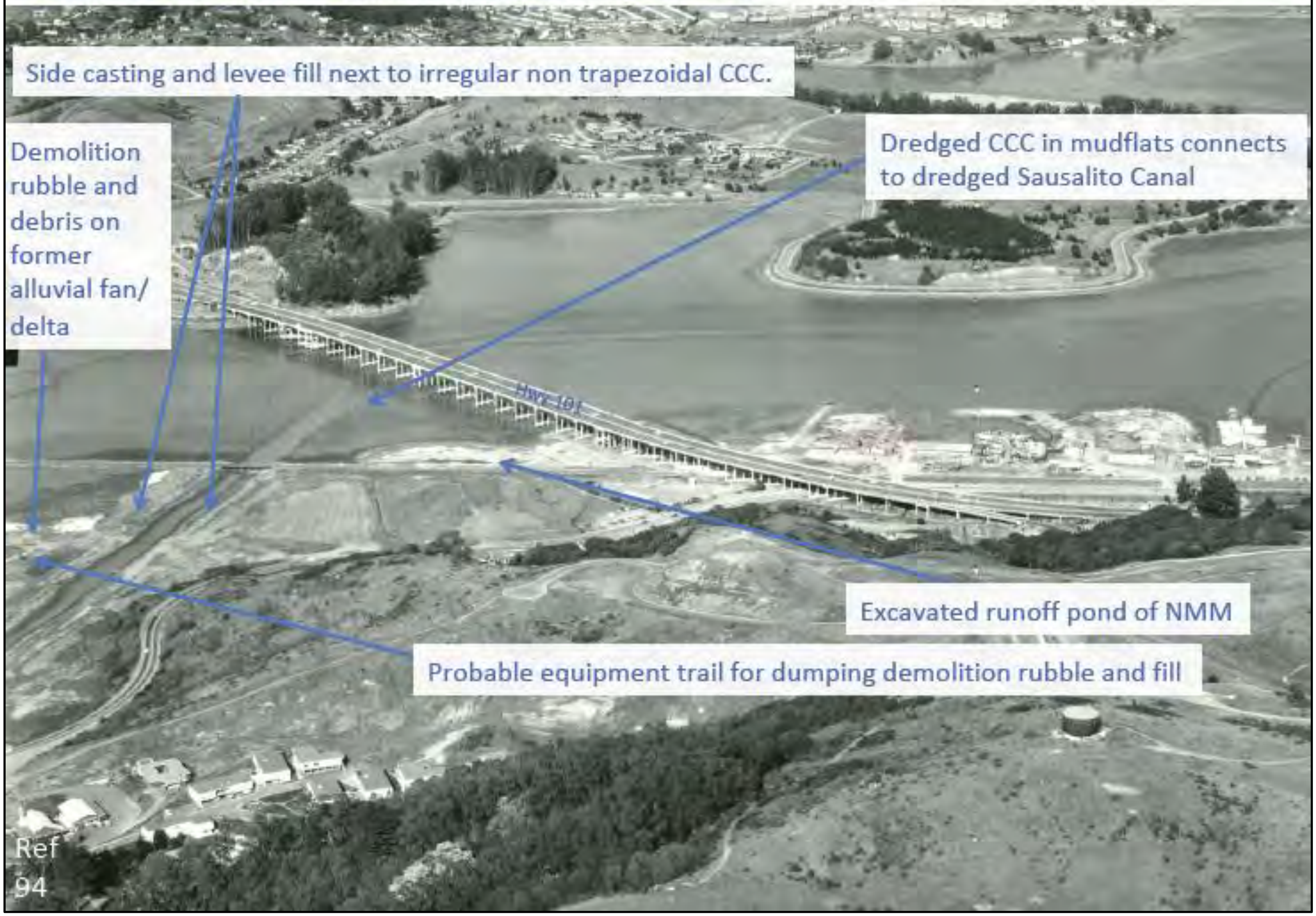
Ref 92

Artificial fill placed c. 1961?

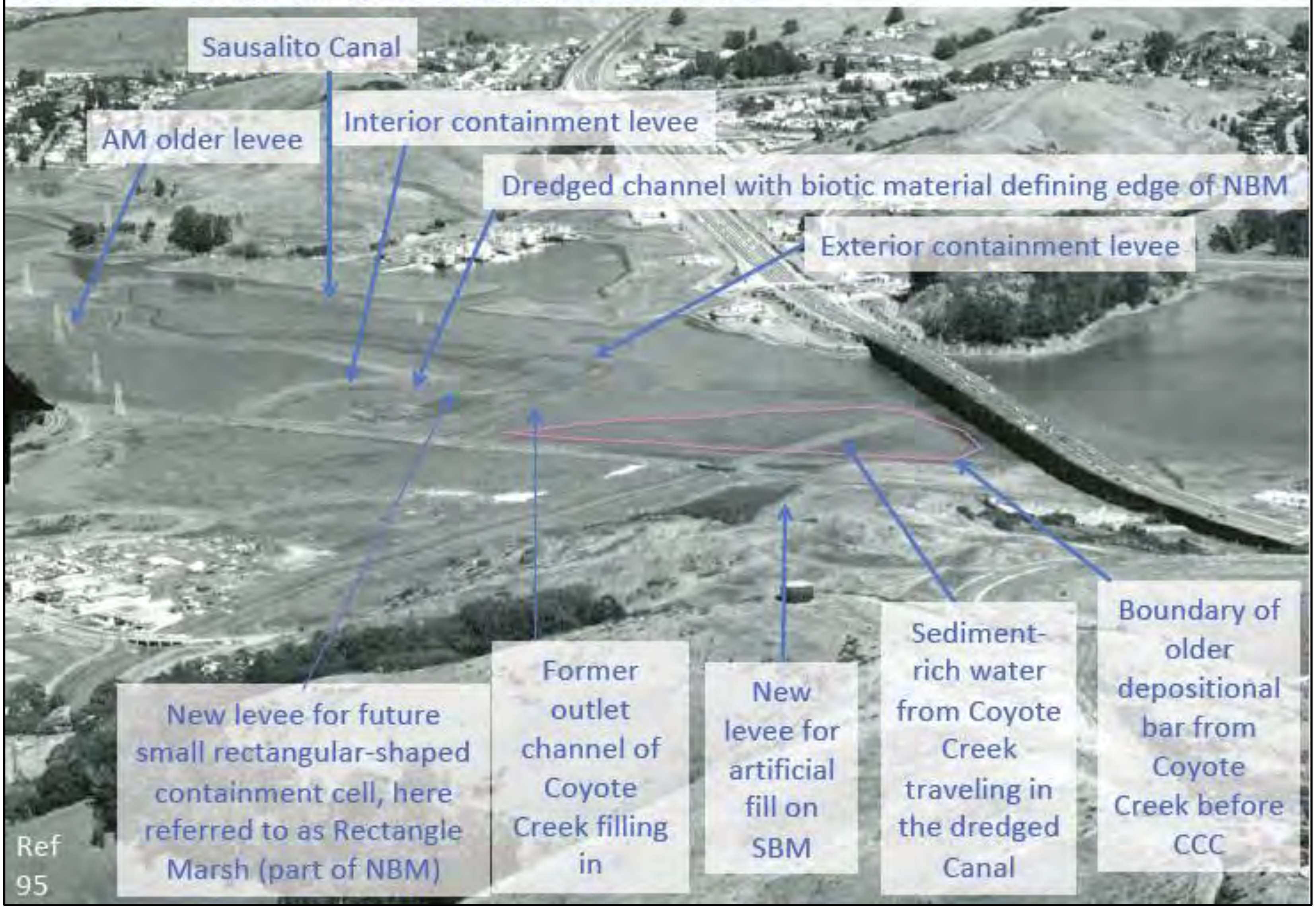
~2.4 ac artificial fill from 1964 (might include much of the demolition rubble and debris that is still present in the marsh. Note path leading to site from the west.


Projection of interpreted 1965 conditions onto 6/2017 Google Earth Imagery.
AM decreased from ~21.4 ac in 1960 to ~17.6 ac east of RR Levee.
AM Tam Marsh ~1.5 ac.
NBM ~2.9 ac (gains some marsh from AM due to levee at north end
Coyote Creek Embayment decreased from ~10 ac in 1960 to ~9.5 ac, 20% of its original size. The truncated former Coyote Creek channel is considered still mudflat at this time.
~0.6 ac of demolition rubble was placed to probably block channel and prevent tides from accessing backshore of CCC.
SBM decreased from ~28.0 ac in 1960 to ~26.1 ac. It had additional artificial fill outweighing progradation into the embayment.
Artificial fill extends well above MHHW.
Ref 93
Concrete channel begins
1851 Shoreline
c. 1920 levee
c. 1930 levee
1960 "exterior" containment levee
Note that the 2017 image of the bay does not reflect the 1960 conditions
RR Levee
New "interior" containment levee and the c. 1930 levee define the area called NBM
EBM grew outward but decreased from ~1.3 ac to ~0.8 due to excavation of CCC.
Bridge with tidal flap gate
Dredged channel in Richardson Bay
New fill but low enough elevation for higher tides to flood. Probably placed to block old channel and protect levee.
New Bridge
CCC created a trapezoidal channel diversion for Coyote Creek. Its construction eliminated several acres of former SBM and EBM. It also eliminated alluvial sediment supply from Coyote Creek to the marsh and transports it more directly to the bay.
SR 1
1851 Shoreline
Boardwalk
Flood Control levees
NMM has ~2.1, includes runoff pond, outward growth & gains from EBM

3/17/66 Brady Collection Marin History Museum, detail of photo 6795542488_fbe0d8e619_o
https://www.flickr.com/photos/25539851@N05/6795542488/in/album-72157631793232232/

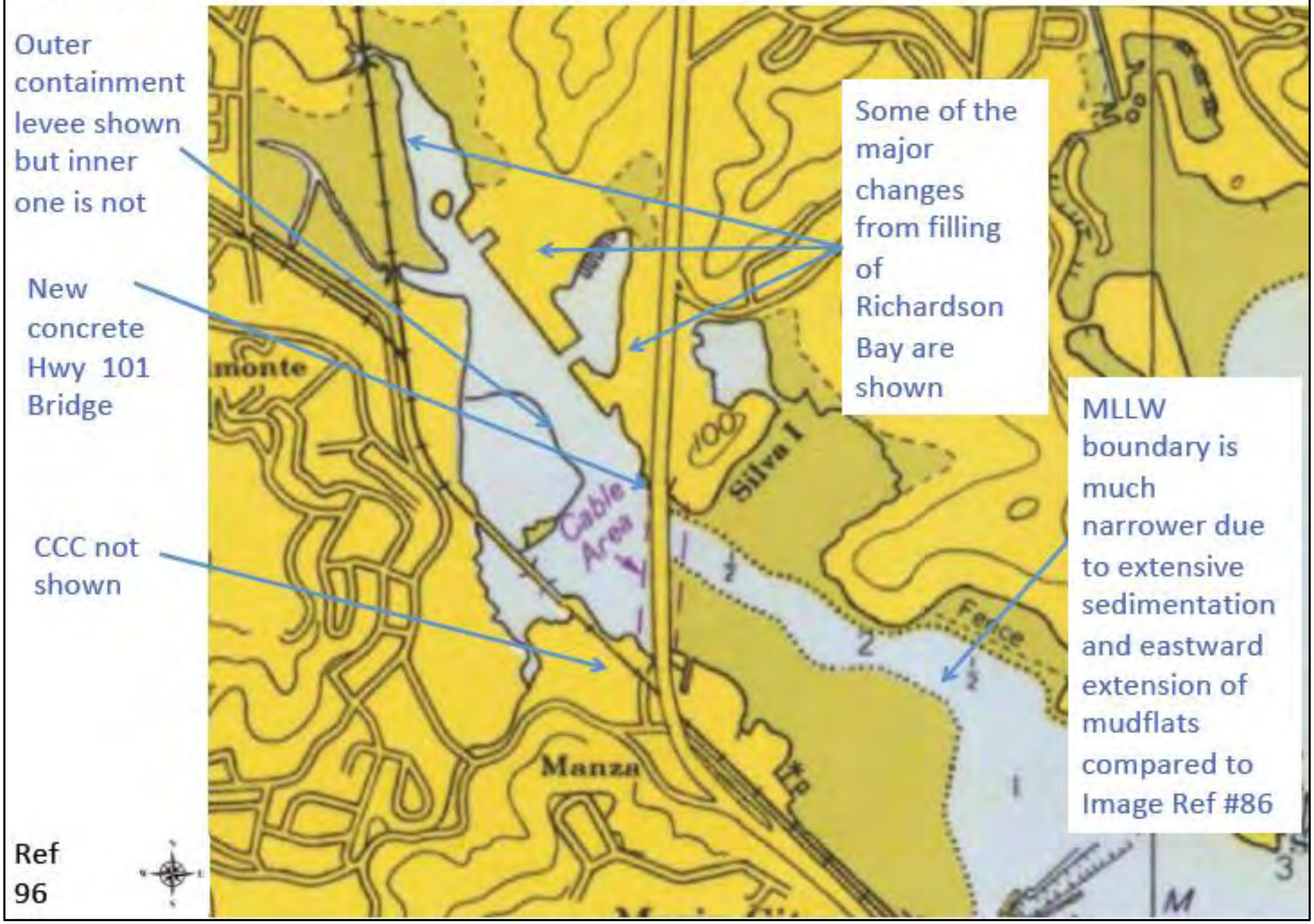


3/28/66 Brady Collection Marin History Museum, detail of photo 6795542182_972fbae8d7_o
https://www.flickr.com/photos/25539851@N05/6795542182/in/album-72157631793232232/



10/1966, San Francisco Entrance, U.S. Coast Survey Chart 5532

Map Source: https://historicalcharts.noaa.gov/historicals/search#searchInput

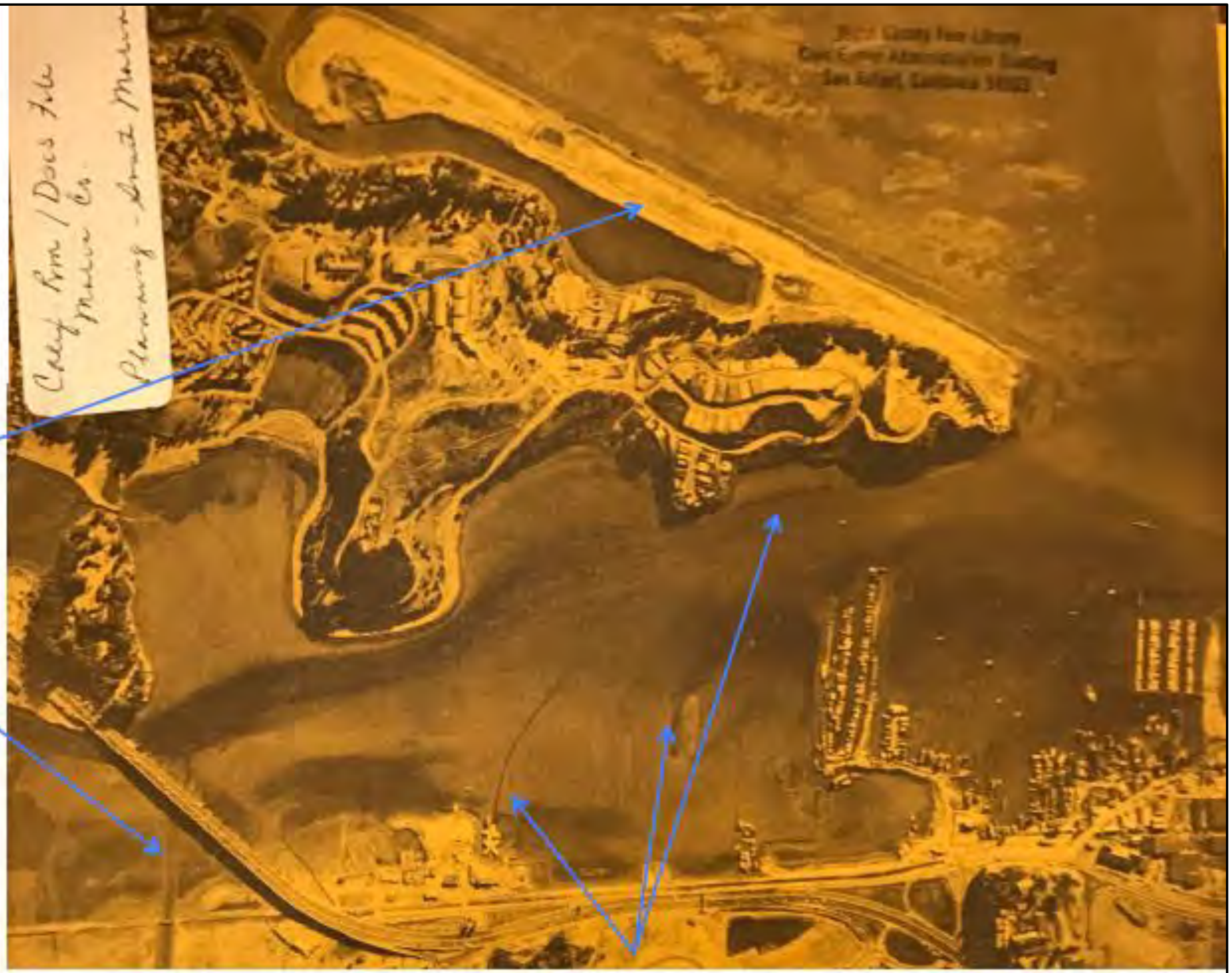


Post 1966, Cover photo of Richardson Bay Specific Plan

Photo Source: California History Room Marin Civic Center Library

Fill for area later known as Aramburu Island

Dredged subtidal channel for CCC



Ref 97

The photo shows abundant evidence of Richardson Bay filling in with artificial fill and sediment deposition of bay bottom, both contributing to need for dredging subtidal channels for navigation.

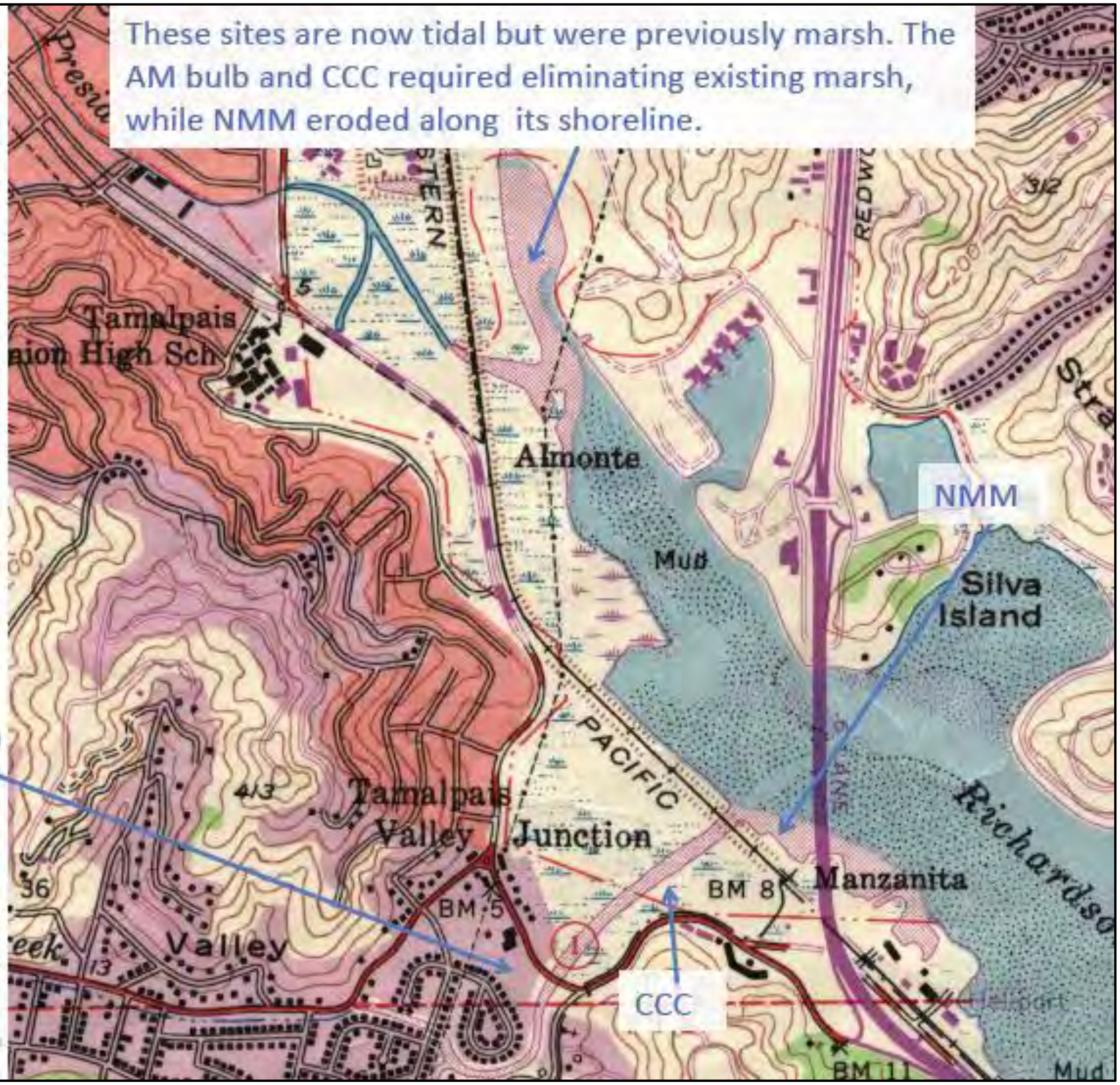
Date unknown, Post 1966 completion of flood control channel
Photo Source: Sausalito Historical Society

1968, USGS San RAFAEL 15' QUADRANGLE

Source: http://servlet1.lib.berkeley.edu:8080/mapviewer/searchcoll.execute.logic?coll=histoposf

Some of the broad scale changes in Richardson Bay can be seen in this map that depicts older information from 1952 and 1968. Topography is from 1952. Urban extension is from 1968 and shown as a purple tint. It does not reflect marsh details of additional containment cells, channels, and levees.

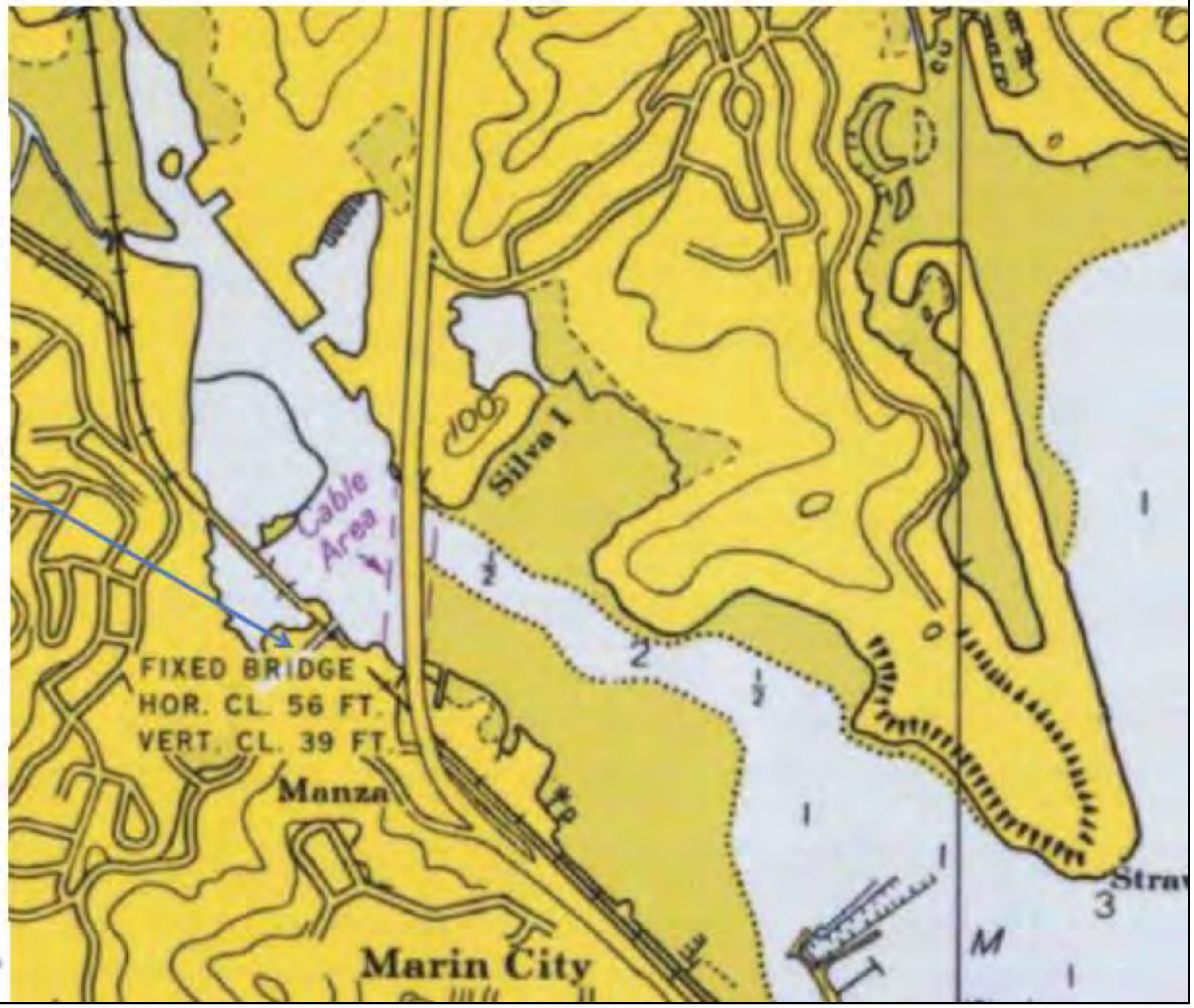
Ref 99



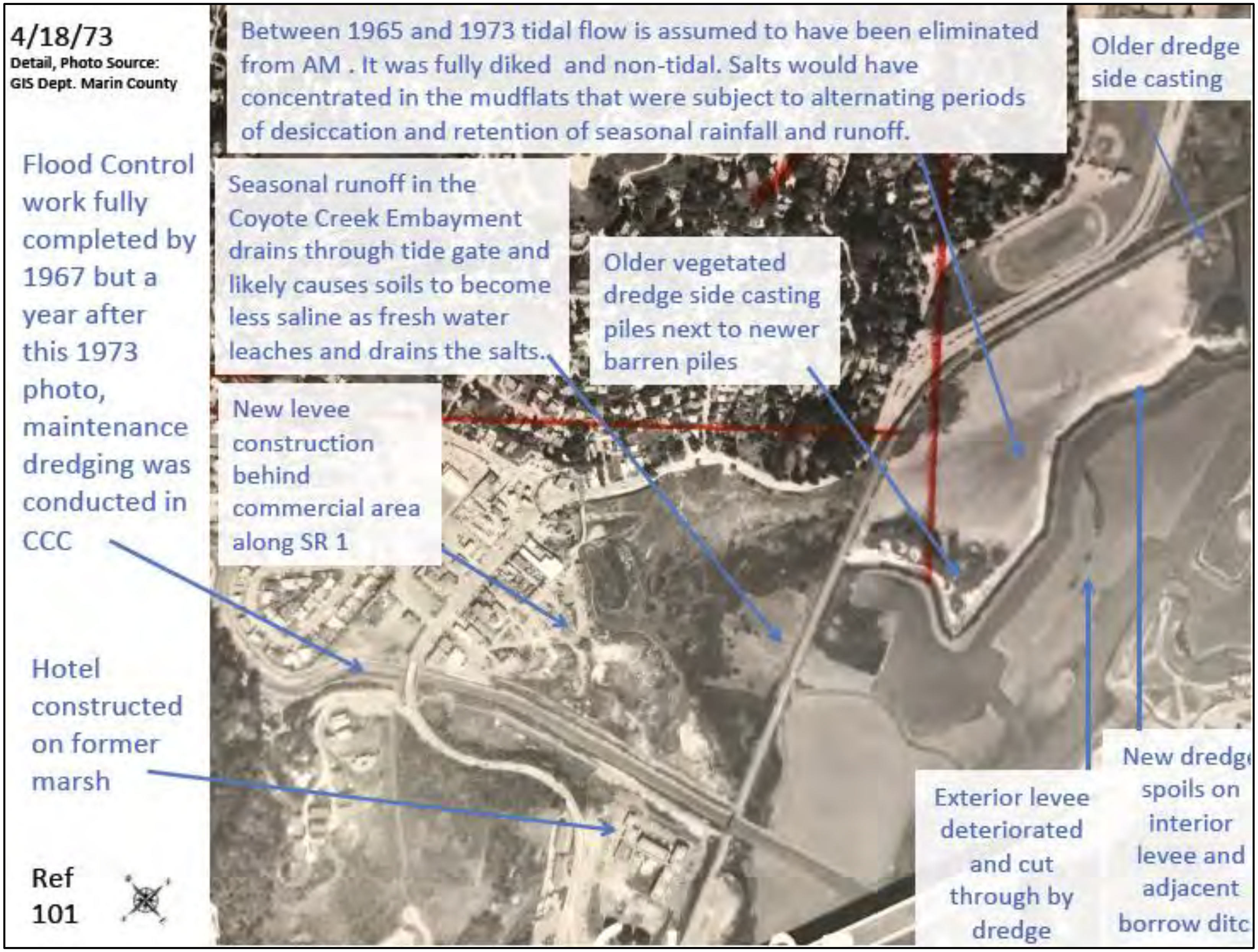
1970, San Francisco Entrance, U.S. Coast Survey Chart 5532

Map Source: https://historicalcharts.noaa.gov/historicals/search#searchInput

This map uses older 1966 bay marsh, and bathymetry information, however CCC and navigation dimensions for Hwy 101 Richardson Bay Bridge are shown at the southwest end of the bridge.



Ref 100


4/18/73
Detail, Photo Source:
GIS Dept. Marin County
Flood Control work fully completed by 1967 but a year after this 1973 photo, maintenance dredging was conducted in CCC
Hotel constructed on former marsh
Ref 101
Between 1965 and 1973 tidal flow is assumed to have been eliminated from AM . It was fully diked and non-tidal. Salts would have concentrated in the mudflats that were subject to alternating periods of desiccation and retention of seasonal rainfall and runoff.
Older dredge side casting
Seasonal runoff in the Coyote Creek Embayment drains through tide gate and likely causes soils to become less saline as fresh water leaches and drains the salts..
Older vegetated dredge side casting piles next to newer barren piles
New levee construction behind commercial area along SR 1
Exterior levee deteriorated and cut through by dredge
New dredge spoils on interior levee and adjacent borrow ditc

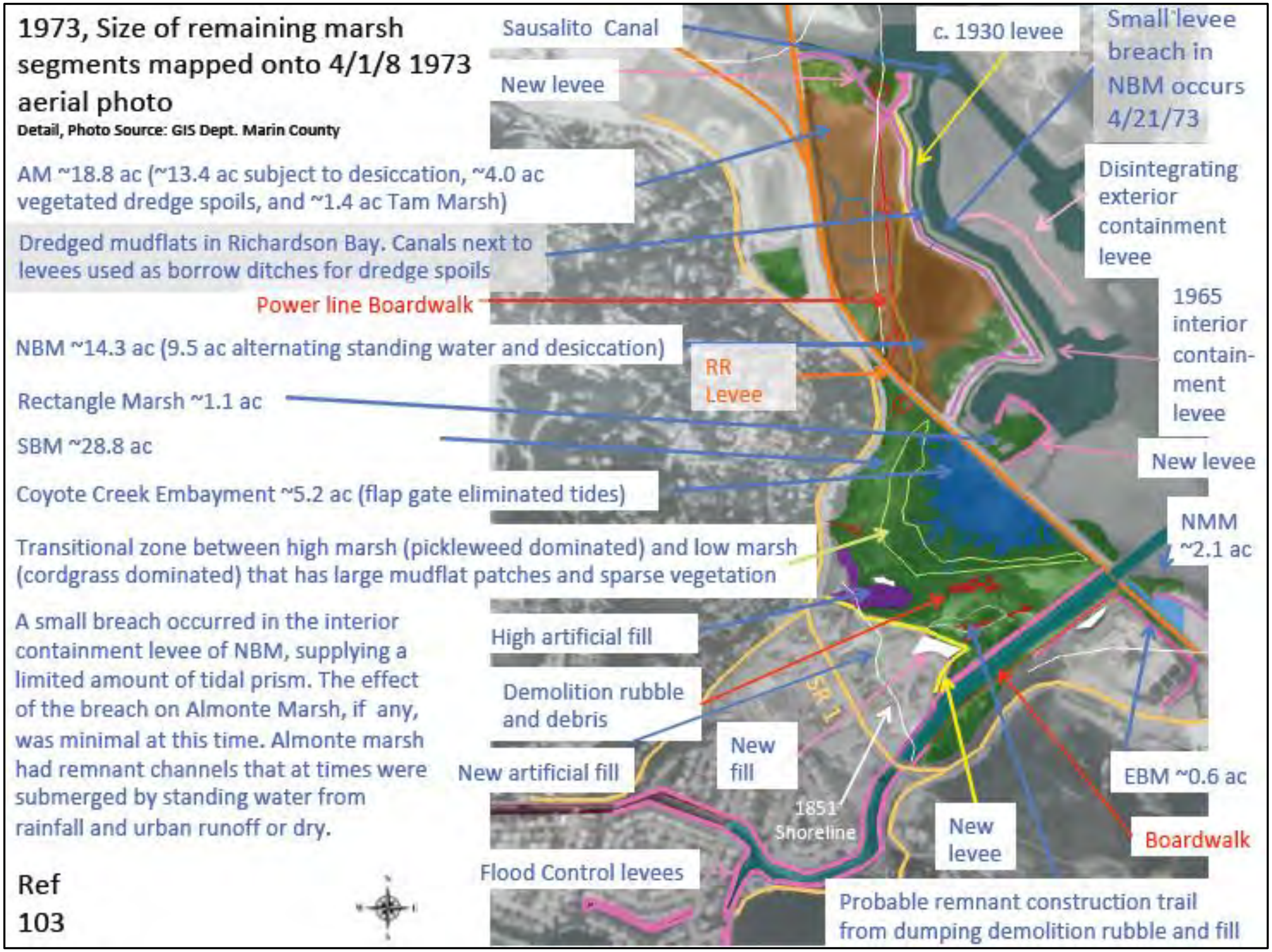
4/21/73, Detail of
Photo Source: GIS Dept. Marin County

This photo that was taken 4 days after the previous Image Ref #101 and indicates a very small, perhaps shallow breach at the eastern edge of interior containment levee.

Oldest dredge spoils possibly place during construction of RR levee.

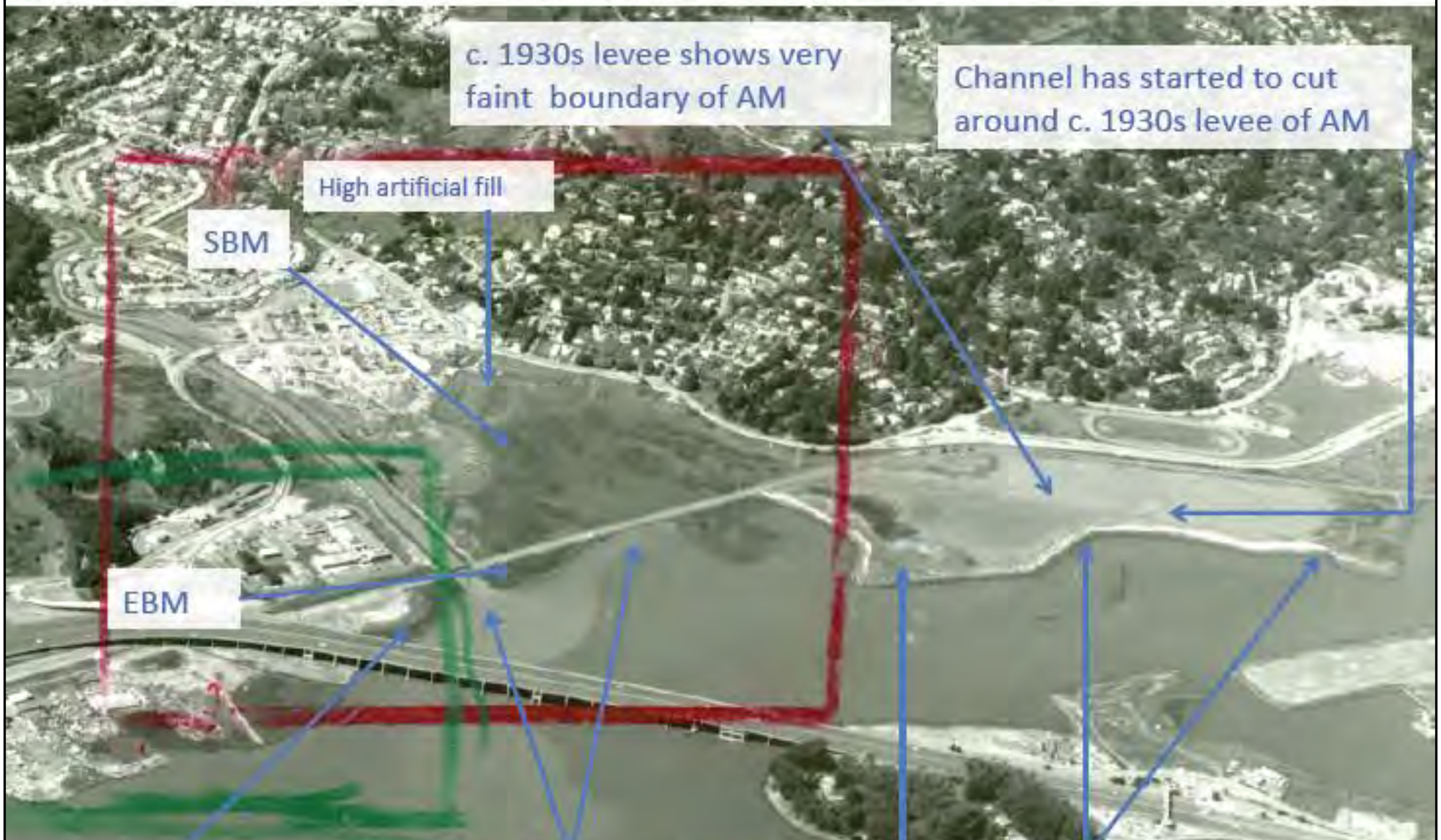
Uniform trapazoidal channel was completed by 1967

Ref 102


1973, Size of remaining marsh segments mapped onto 4/1/8 1973 aerial photo
Detail, Photo Source: GIS Dept. Marin County
AM ~18.8 ac (~13.4 ac subject to desiccation, ~4.0 ac vegetated dredge spoils, and ~1.4 ac Tam Marsh)
Dredged mudflats in Richardson Bay. Canals next to levees used as borrow ditches for dredge spoils
Power line Boardwalk
NBM ~14.3 ac (9.5 ac alternating standing water and desiccation)
Rectangle Marsh ~1.1 ac
SBM ~28.8 ac
Coyote Creek Embayment ~5.2 ac (flap gate eliminated tides)
Transitional zone between high marsh (pickleweed dominated) and low marsh (cordgrass dominated) that has large mudflat patches and sparse vegetation
A small breach occurred in the interior containment levee of NBM, supplying a limited amount of tidal prism. The effect of the breach on Almonte Marsh, if any, was minimal at this time. Almonte marsh had remnant channels that at times were submerged by standing water from rainfall and urban runoff or dry.
Ref
103
Sausalito Canal
New levee
c. 1930 levee
Small levee breach in NBM occurs 4/21/73
Disintegrating exterior containment levee
1965 interior contain-ment levee
RR Levee
New levee
NMM ~2.1 ac
High artificial fill
Demolition rubble and debris
New fill
New artificial fill
SR 1
1851 Shoreline
New levee
EBM ~0.6 ac
Boardwalk
Flood Control levees
Probable remnant construction trail from dumping demolition rubble and fill

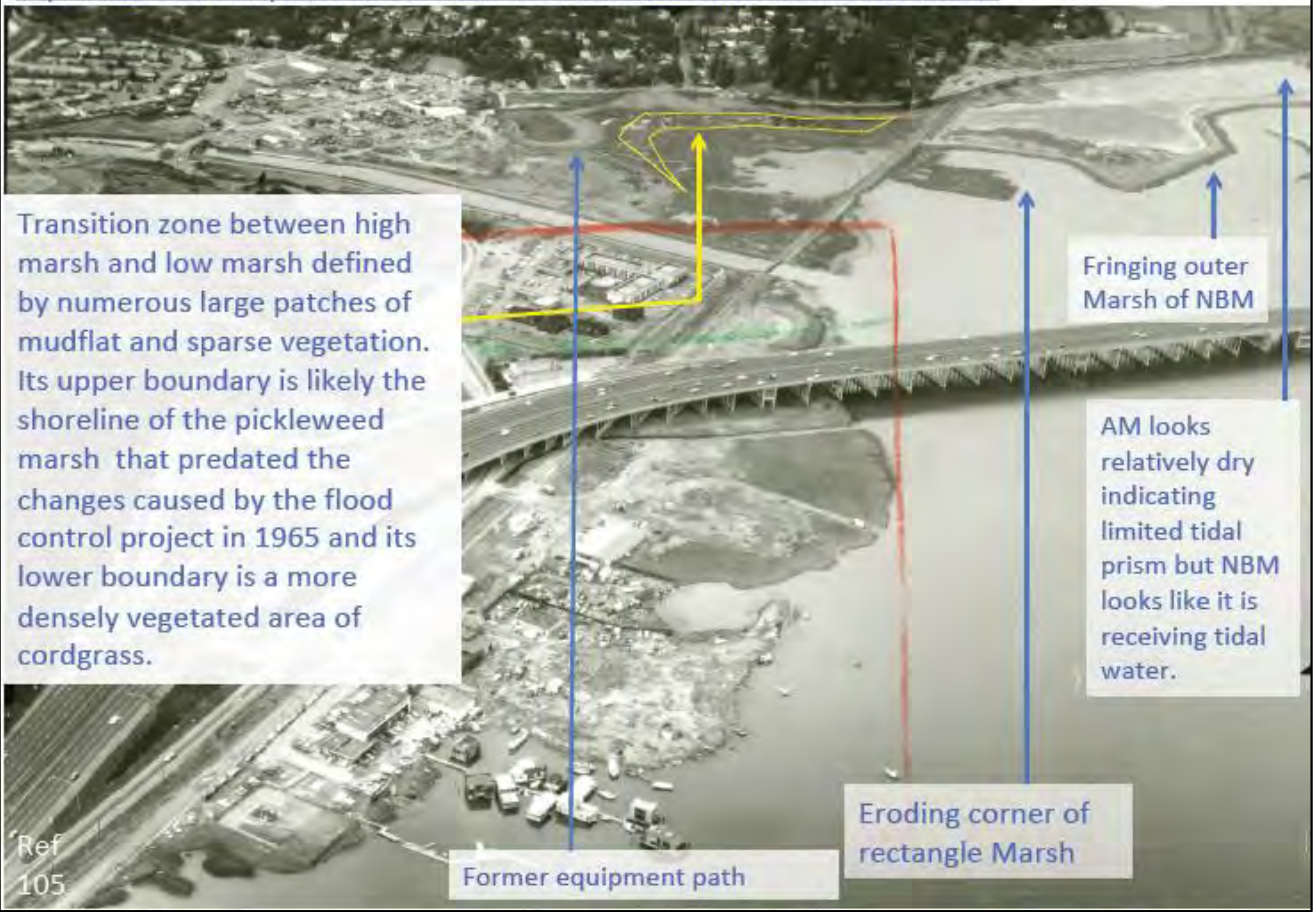
4/3/1974. Brady Collection Marin History Museum, detail of photo 8097543117_4f8658fcca

Photo Source: https://www.flickr.com/photos/25539851@N05/8097543117/in/album-72157631793232232/



Ref 104 NMM Silty water of CCC, some of which recirculates into SBM during flood tide. NBM Breach in interior containment levee of NBM

11/17/1974. Brady Collection Marin History Museum, detail of photo 8097553838_740e449d37_o
https://www.flickr.com/photos/25539851@N05/8097553838/in/album-72157631793232232/



1975, San Francisco Entrance, U.S. Coast Survey Chart 5532

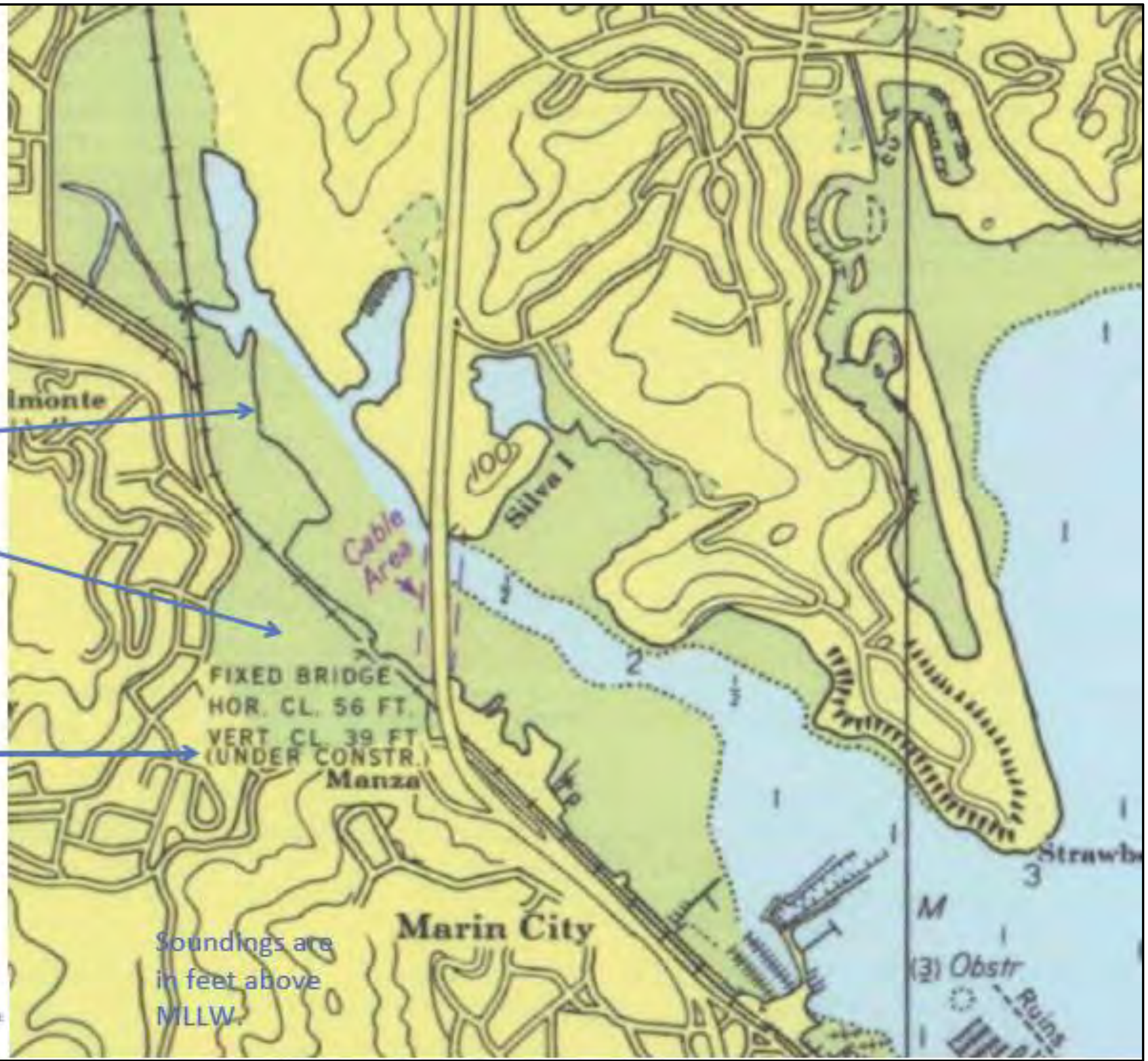
Map Source: https://historicalcharts.noaa.gov/historicals/search#searchInput

Inner containment levee depicted

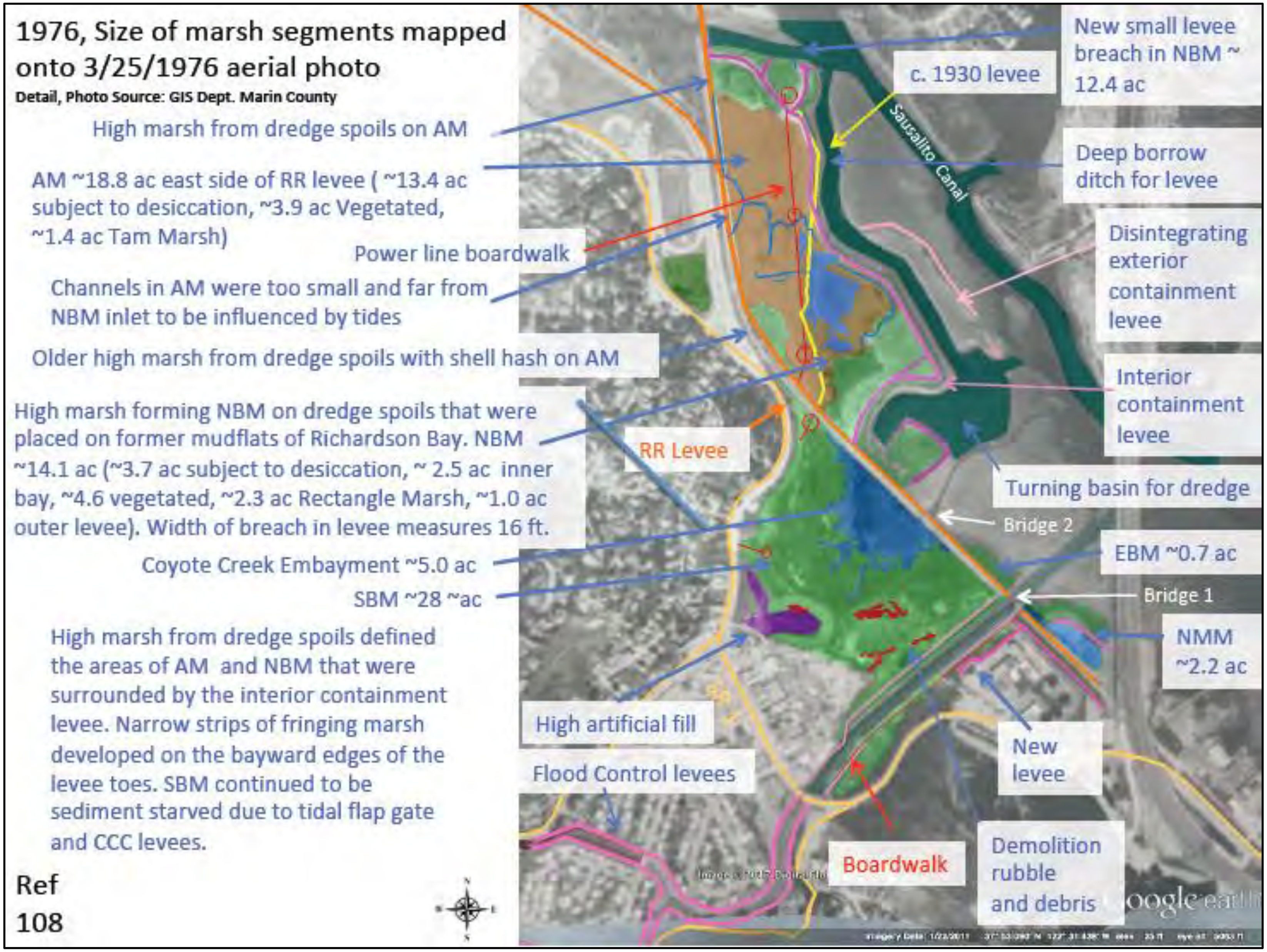
Coyote Creek Embayment not depicted, possibly indicating no tidal connection but CCC is not indicated either.

Richardson Bay Bridge is noted to be under construction

Ref 106




3/25/1976,
Photo Source: GIS
Dept. Marin County
A depositional bar expands at the head of Richardson Bay in the ebb lee of exterior containment levee. Its presence contributes to tidal prism reductions at the head of the Bay
Embayment in NBM
Ref
107


1976, Size of marsh segments mapped onto 3/25/1976 aerial photo
Detail, Photo Source: GIS Dept. Marin County
High marsh from dredge spoils on AM
AM ~18.8 ac east side of RR levee (~13.4 ac subject to desiccation, ~3.9 ac Vegetated, ~1.4 ac Tam Marsh)
Power line boardwalk
Channels in AM were too small and far from NBM inlet to be influenced by tides
Older high marsh from dredge spoils with shell hash on AM
High marsh forming NBM on dredge spoils that were placed on former mudflats of Richardson Bay. NBM ~14.1 ac (~3.7 ac subject to desiccation, ~ 2.5 ac inner bay, ~4.6 vegetated, ~2.3 ac Rectangle Marsh, ~1.0 ac outer levee). Width of breach in levee measures 16 ft.
Coyote Creek Embayment ~5.0 ac
SBM ~28 ~ac
High marsh from dredge spoils defined the areas of AM and NBM that were surrounded by the interior containment levee. Narrow strips of fringing marsh developed on the bayward edges of the levee toes. SBM continued to be sediment starved due to tidal flap gate and CCC levees.
Ref
108
New small levee breach in NBM ~ 12.4 ac
c. 1930 levee
Sausalito Canal
Deep borrow ditch for levee
Disintegrating exterior containment levee
Interior containment levee
RR Levee
Turning basin for dredge
Bridge 2
EBM ~0.7 ac
Bridge 1
NMM ~2.2 ac
High artificial fill
Flood Control levees
New levee
Boardwalk
Demolition rubble and debris

1978, Size of marsh segments mapped onto 3/15/1978 aerial photo

Detail, Photo Source: GIS Dept. Marin County

Breaches in c. 1930 levee provide limited access of tides from reconnected channel to AM which had ~4.4 ac of vegetation on dredge spoils and ~13.4 ac alternately desiccated or flooded, and ~1.4 ac were muted tides of Tam Marsh. In total Am was ~18.8 ac.

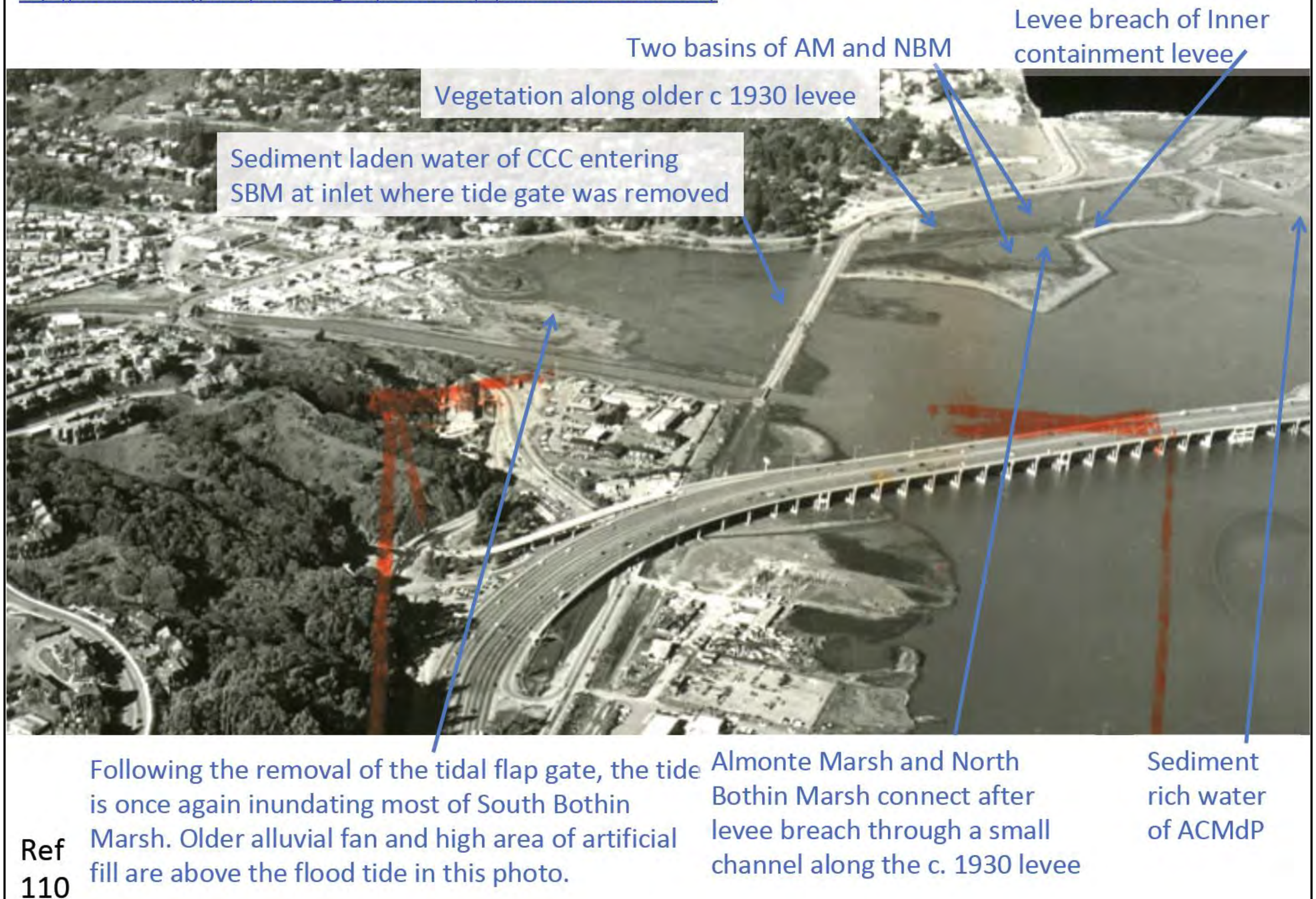
High marsh forming NBM on dredge spoils that were placed on former mudflats of Richardson Bay. NBM ~14.0 ac (4.4 ac subject to desiccation, ~ 1.7 ac inner bay, ~4.9 vegetated, ~2.1 ac Rectangle Marsh, ~0.9 ac outer levee)

Breach of western edge of the former "inner berm" levee provides tidal connection to NBM but still very limited tidal connection to AM due to c. 1930 levee. A portion of the inner mud flat was deep enough that it maintained an open water embayment whereas much of the area that would previously become desiccated was now subject to diurnal tides.

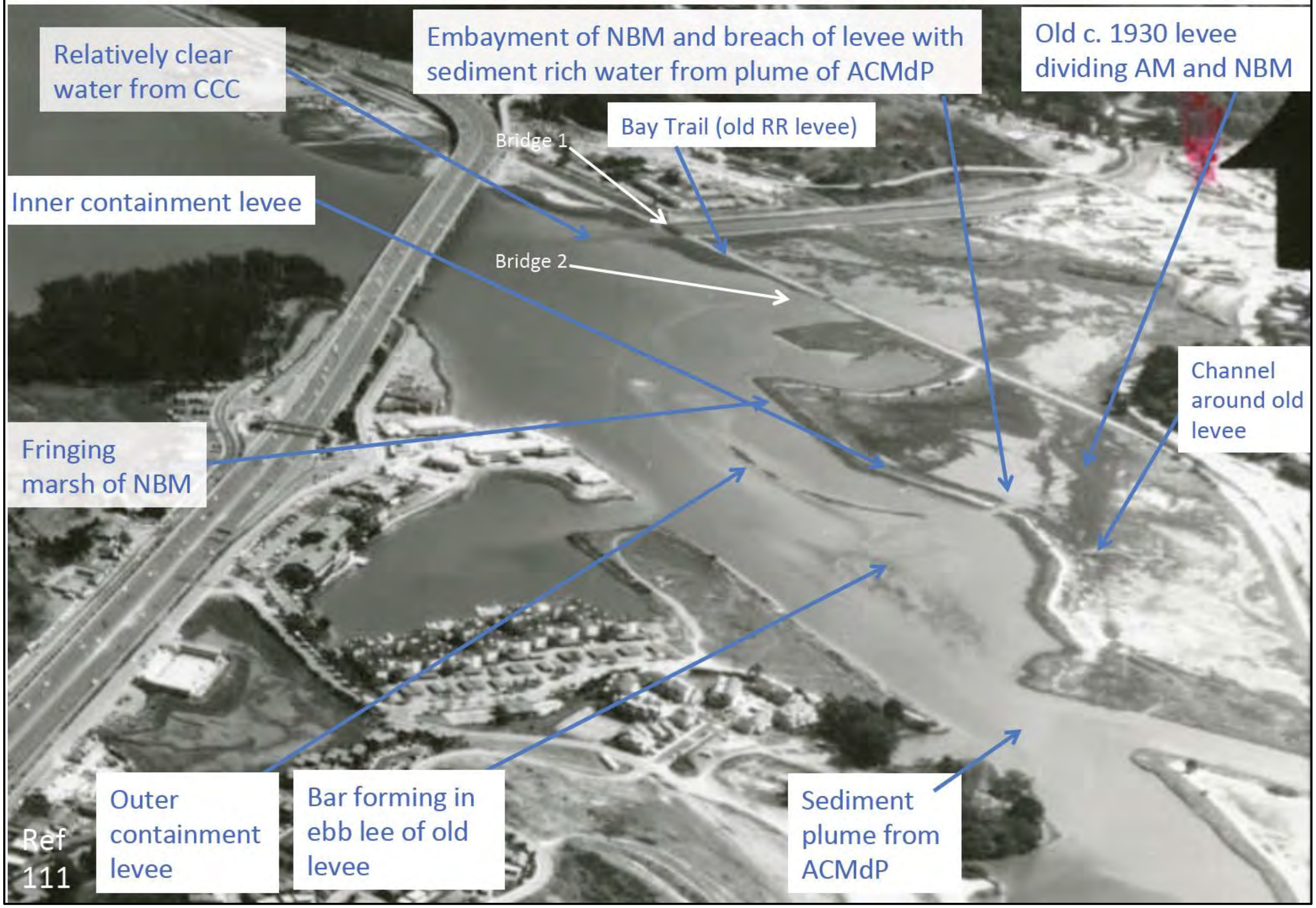
Ref 109

SBM ~28.1 ac It has ~8.9 ac transitional ecotone (buff color) with low areas subject to ponding interspersed with patchy mud flats interspersed with sparse vegetation and that was subject to desiccation. There was ~19.2 ac upper ecotone marsh.

1/7/82 Brady Collection Marin History Museum, detail of photo 9203005392_8a9c940470_o
https://www.flickr.com/photos/25539851@N05/9203005392/in/album-72157631793232232/



5/18/83 Brady Collection Marin History Museum, detail of photo 8097553838_740e449d37_o
https://www.flickr.com/photos/25539851@N05/9186712606/in/album-72157631793232232/



1987, Size of remaining marsh segments mapped onto 6/1987 Google Earth Imagery

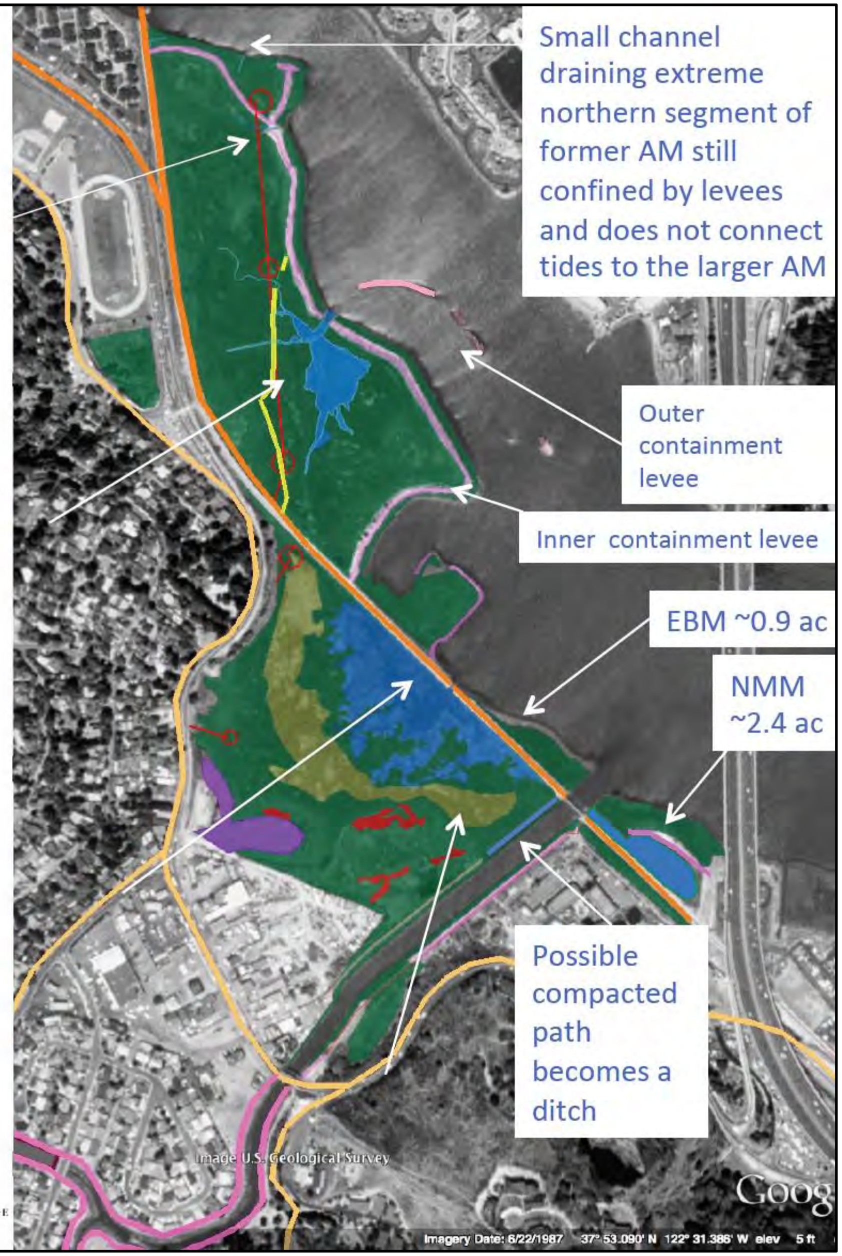
Photo Source: Google Earth

New small channel appears draining the northeastern part of AM, but it has very limited tidal prism and leads into an area surrounded by higher elevation dredge spoils. AM ~18.4 ac (~17.0 ac marsh and ~1.4 ac Tam Marsh)

Daily tides connected AM and NBM through two small channels that emanated from the single levee breach in NBM, which increased in width to 32 ft from its former 20 ft in 1978. The vegetation in NBM marsh increased to ~10.1 ac while the embayment stayed nearly the same in size (~1.6 ac) but probably shallowed. The desiccated area disappeared. The fringe and Rectangle marshes both increased, ~1.5 ac and ~2.4 ac respectively. In total it was ~15.6 ac. The width of the breach increased to 32 ft.

Tide gate had been removed around 1981 when the Bay Trail was constructed and a new 26-foot-wide bridge at the inlet was constructed to drain the Coyote Creek Embayment. SBM maintained its ~28.1 ac and Coyote Creek embayment increased to ~6.1 ac since the water level was now elevated by the tides rather than seasonally desiccated. The transition zone of ~5.7 ac of patchy mudflats and sparse vegetation narrowed as vegetated colonized the lower boundary.

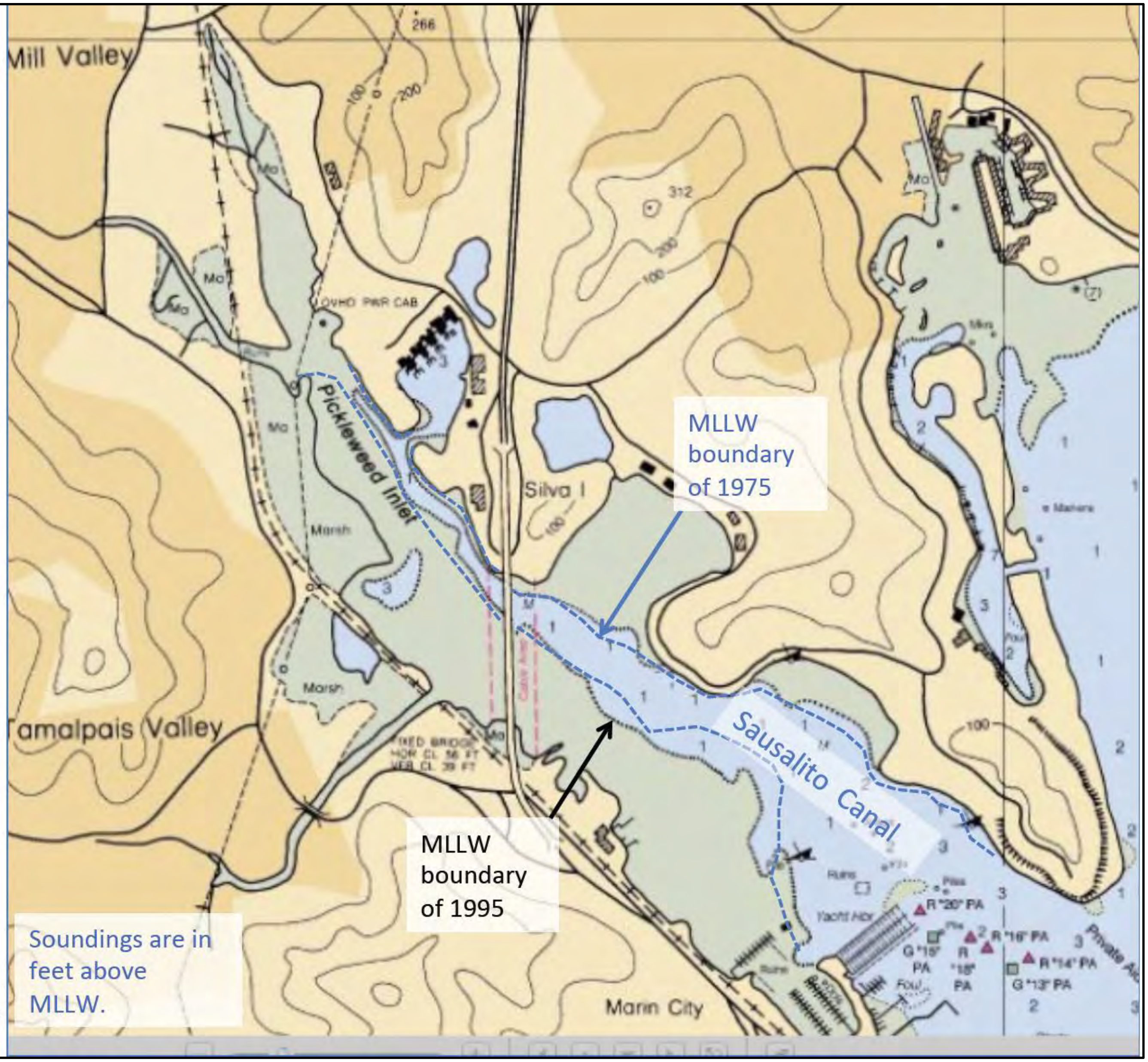
Ref
112



1995, San Francisco Entrance, U.S. Coast Survey Chart 5532 Map Source: https://https://historicalcharts.noaa.gov/historicals/search#mainTitle

The MLLW boundary from the 1975 Chart 5532 (Image Ref #106) was superimposed onto this 1995 chart (blue dashed line). A comparison indicates that the Sausalito Canal MLLW boundary has widened slightly south of Richardson Bridge but narrowed upstream of it where it is now named Pickleweed Inlet. The canal also became more uniformly shallow, eliminating deep areas.

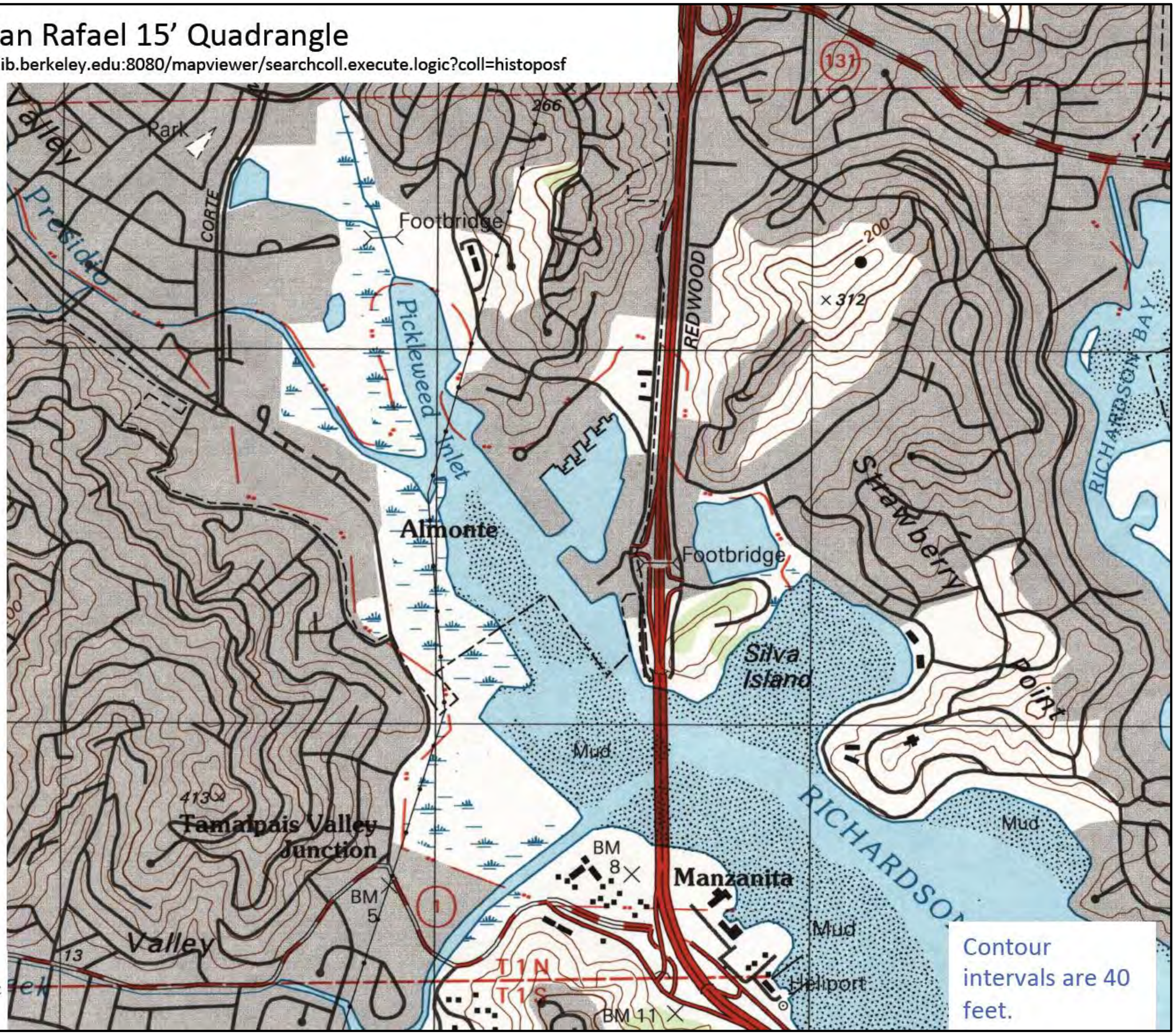
Ref 113



1999, USGS San Rafael 15' Quadrangle

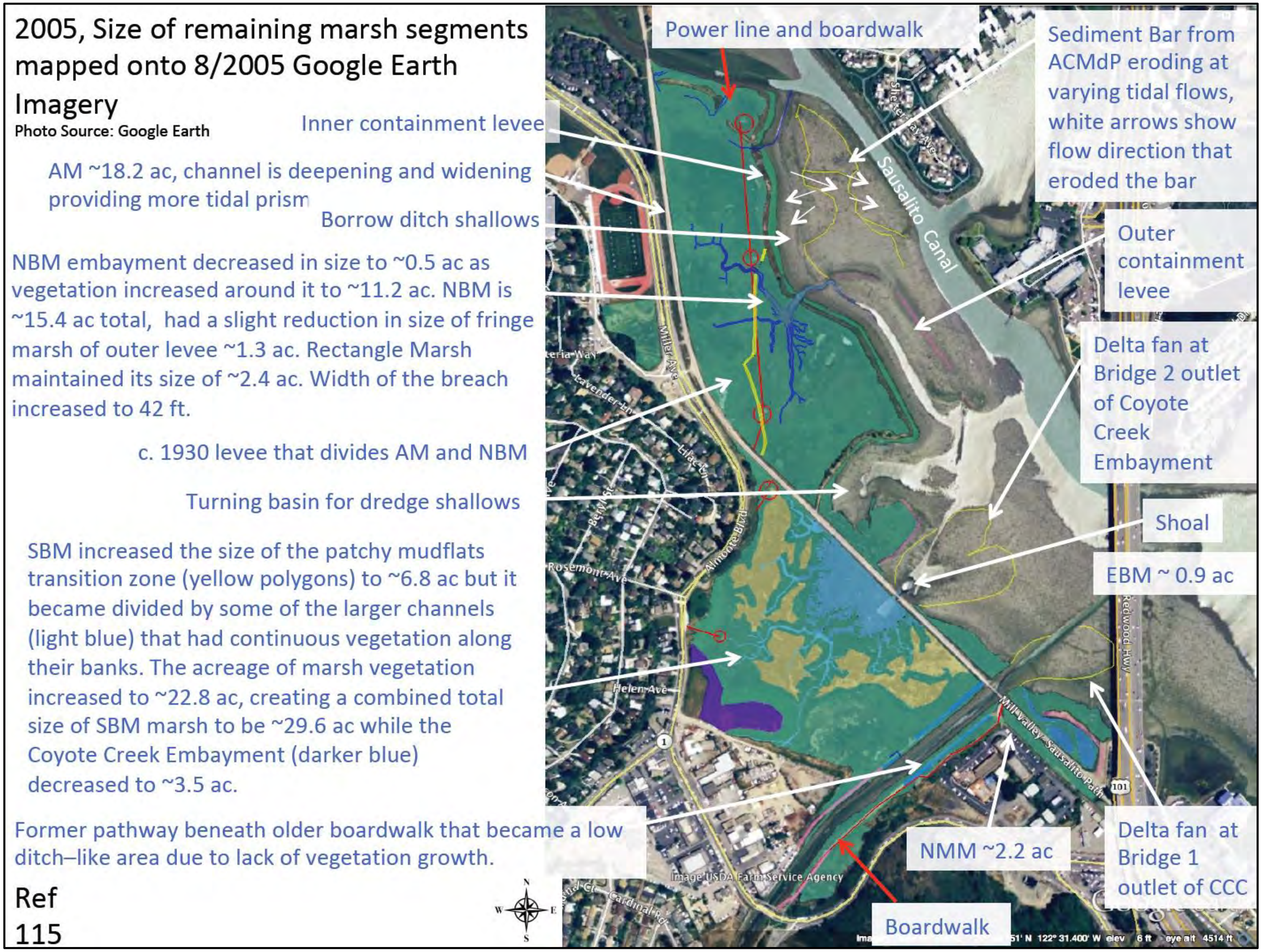
Source: http://servlet1.lib.berkeley.edu:8080/mapviewer/searchcoll.execute.logic?coll=histoposf

The topographic map shows the increased urban development around Richardson Bay (grey areas) and the pattern of dredging and filling that changed its shoreline. The boundary of the mud areas (stippled) versus the deeper water below MLLW do not appear relevant to this date.



Contour intervals are 40 feet.

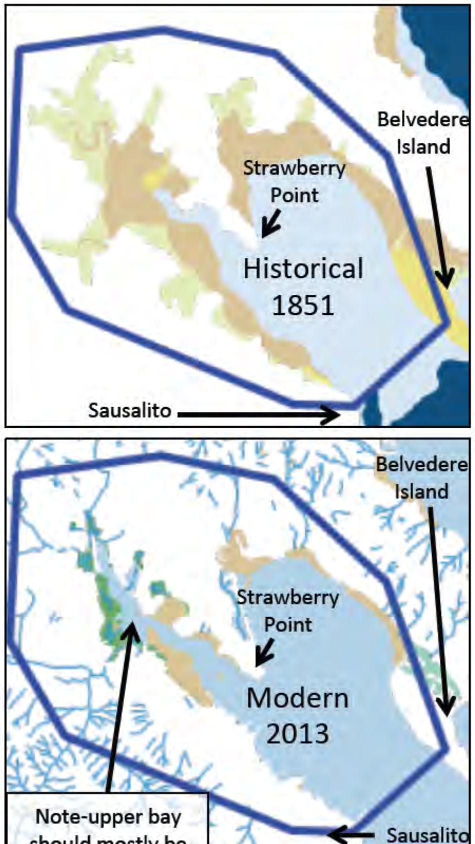
Ref 114


2005, Size of remaining marsh segments mapped onto 8/2005 Google Earth Imagery
Photo Source: Google Earth
Inner containment levee
AM ~18.2 ac, channel is deepening and widening providing more tidal prism
Borrow ditch shallows
NBM embayment decreased in size to ~0.5 ac as vegetation increased around it to ~11.2 ac. NBM is ~15.4 ac total, had a slight reduction in size of fringe marsh of outer levee ~1.3 ac. Rectangle Marsh maintained its size of ~2.4 ac. Width of the breach increased to 42 ft.
c. 1930 levee that divides AM and NBM
Turning basin for dredge shallows
SBM increased the size of the patchy mudflats transition zone (yellow polygons) to ~6.8 ac but it became divided by some of the larger channels (light blue) that had continuous vegetation along their banks. The acreage of marsh vegetation increased to ~22.8 ac, creating a combined total size of SBM marsh to be ~29.6 ac while the Coyote Creek Embayment (darker blue) decreased to ~3.5 ac.
Former pathway beneath older boardwalk that became a low ditch–like area due to lack of vegetation growth.
Ref
115
Power line and boardwalk
Sediment Bar from ACMdP eroding at varying tidal flows, white arrows show flow direction that eroded the bar
Sausalito Canal
Outer containment levee
Delta fan at Bridge 2 outlet of Coyote Creek Embayment
Shoal
EBM ~ 0.9 ac
NMM ~2.2 ac
Delta fan at Bridge 1 outlet of CCC
Boardwalk
Miller Ave
Almonte Blvd
Rosemont Ave
Helen Ave
Redwood Hwy
Mill Valley Sausalito Path
Image USDA Farm Service Agency

Changes in Modern (2013) and Historical Areas of Marine and Estuarine Wetlands

Map and Data Source: California EcoAtlas San Francisco Estuary Institute, www.ecoatlas .org

Richardson Bay Overall



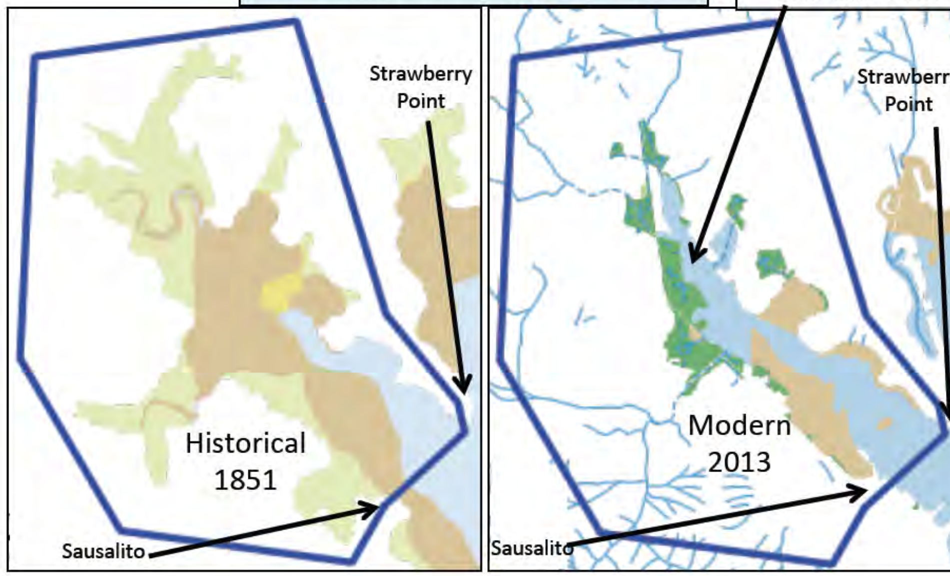
Note-upper bay should mostly be mapped as mud flat not shallow but SFEI map not mapped correct in this area

Marsh
Mudflat
Shallow Bay

Ref 116

Richardson Bay northward of Sausalito and Strawberry Point

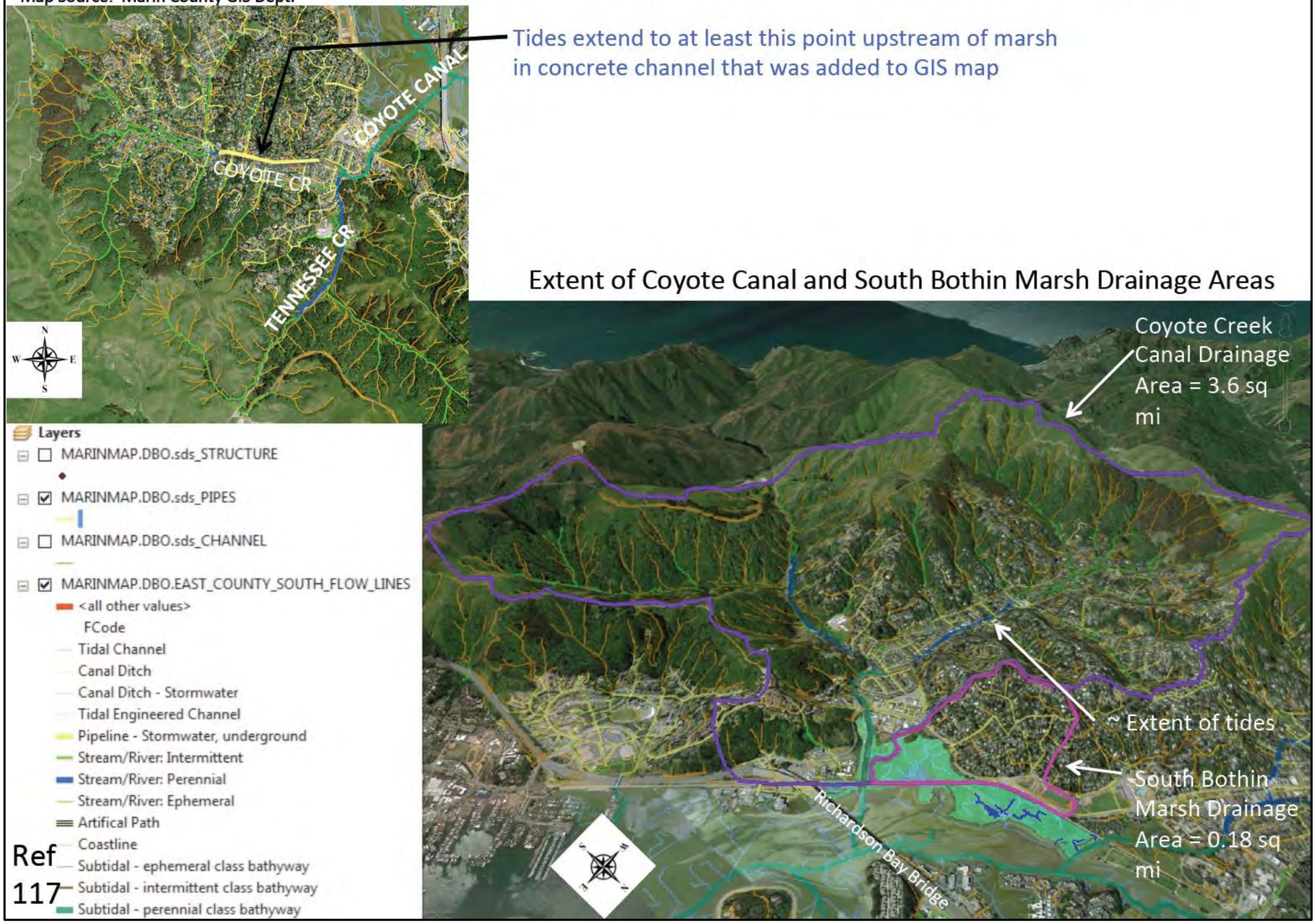
Note- upper bay should mostly be mapped as mud flat not shallow but SFEI map is not correct in this area

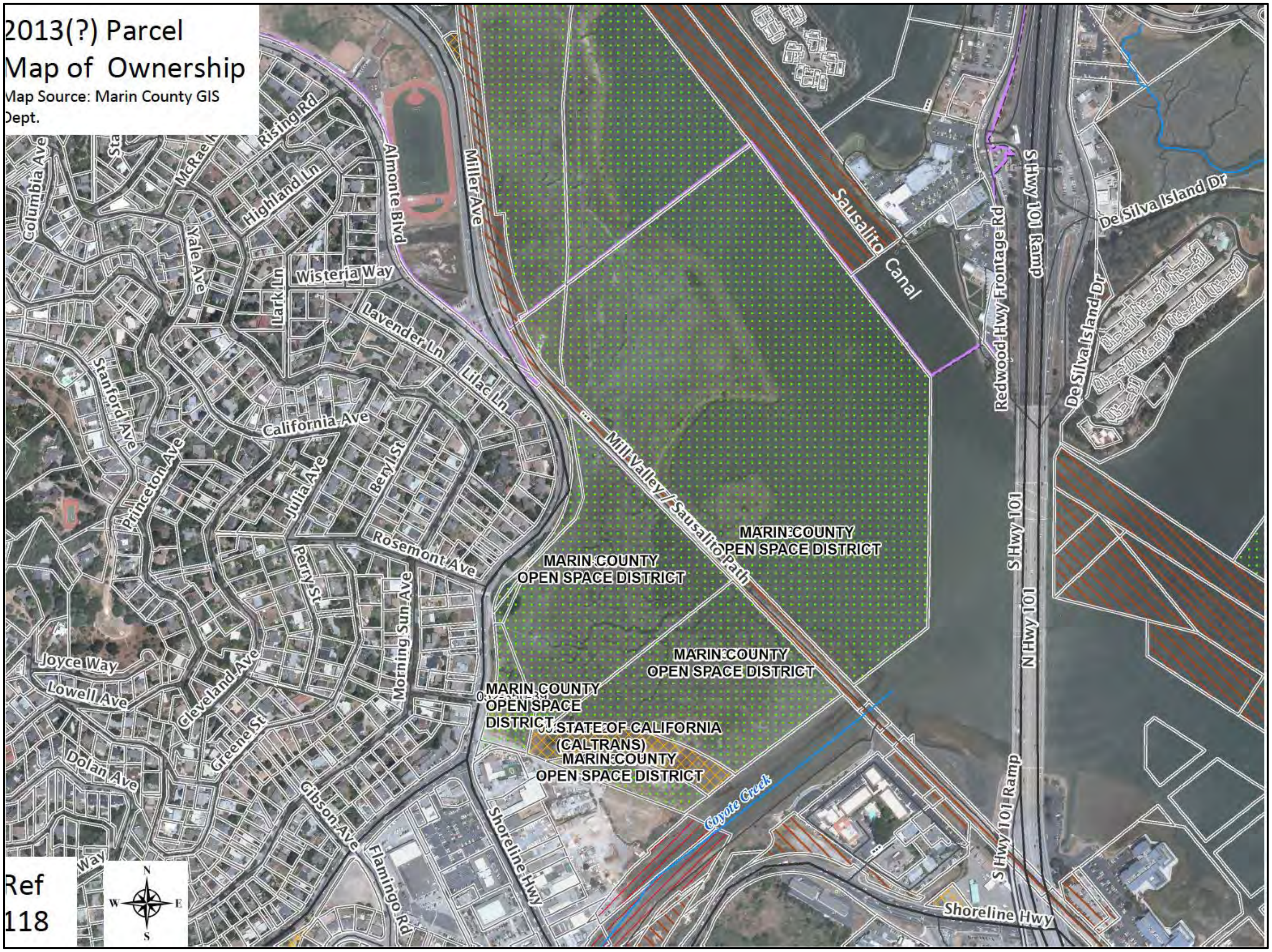


	Modern (acres)	Historical (acres)	Percent Remaining
Richardson Bay Overall			
Marsh	126	620	20
Mudflat & shallow bay	2,455	2,868	86
Total	2,581	3,488	73
Richardson Bay northward of Sausalito and Strawberry Point			
Marsh	124	486	26
Mudflat & shallow bay	431	613	70
Total	555	1,099	50

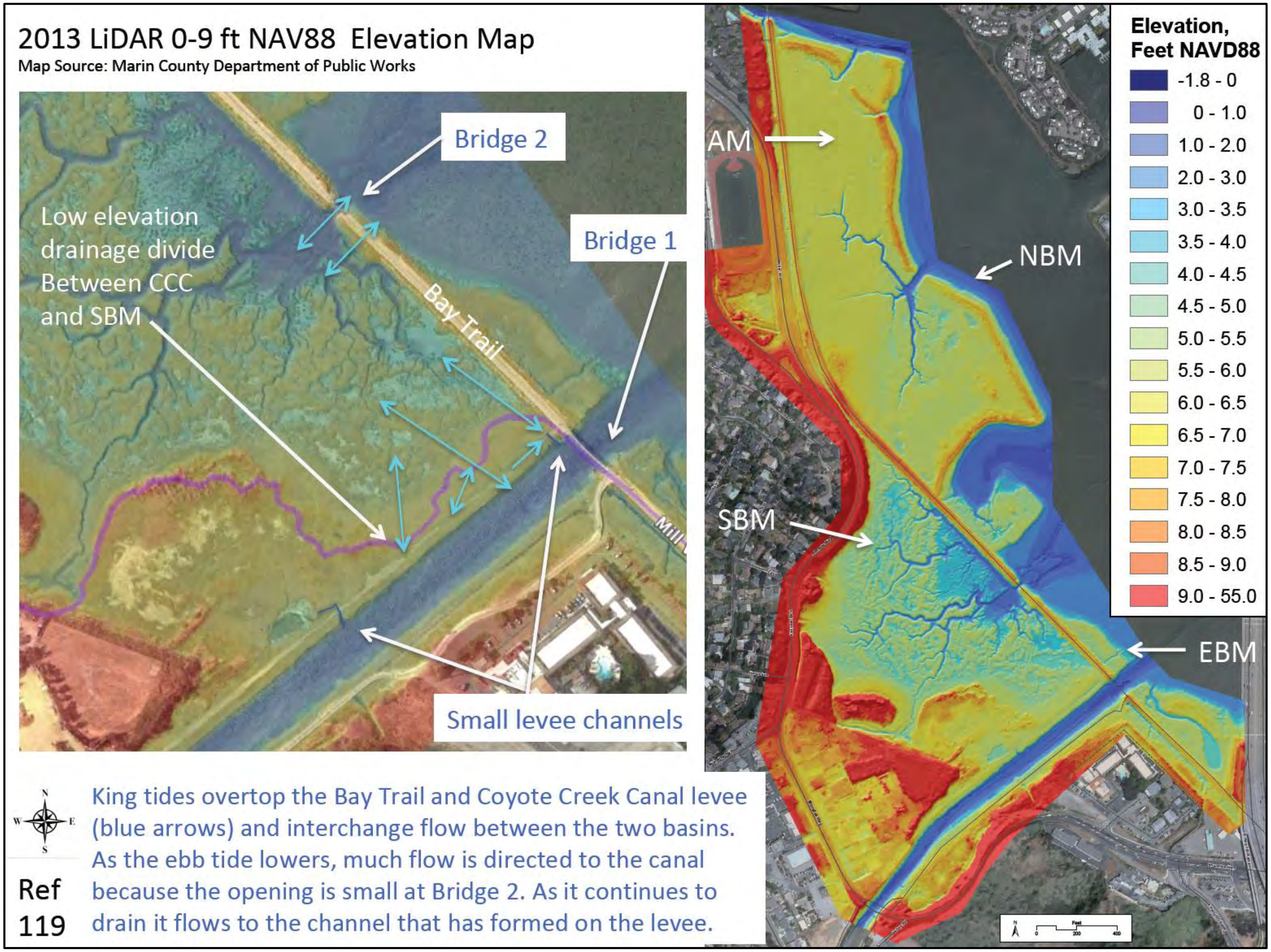
2013 Storm drain map superimposed on aerial photography and Google Earth Imagery

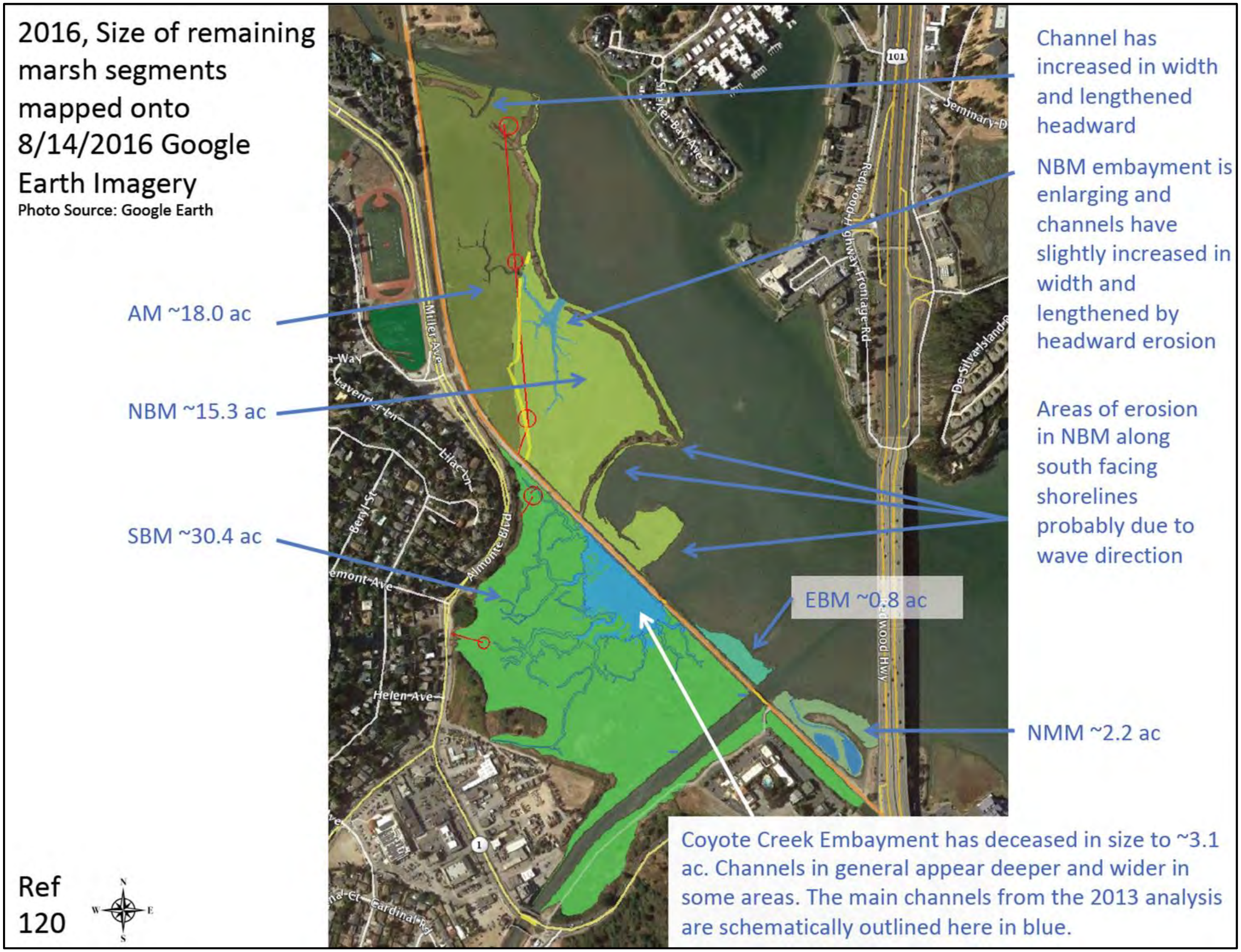
Map Source: Marin County GIS Dept.

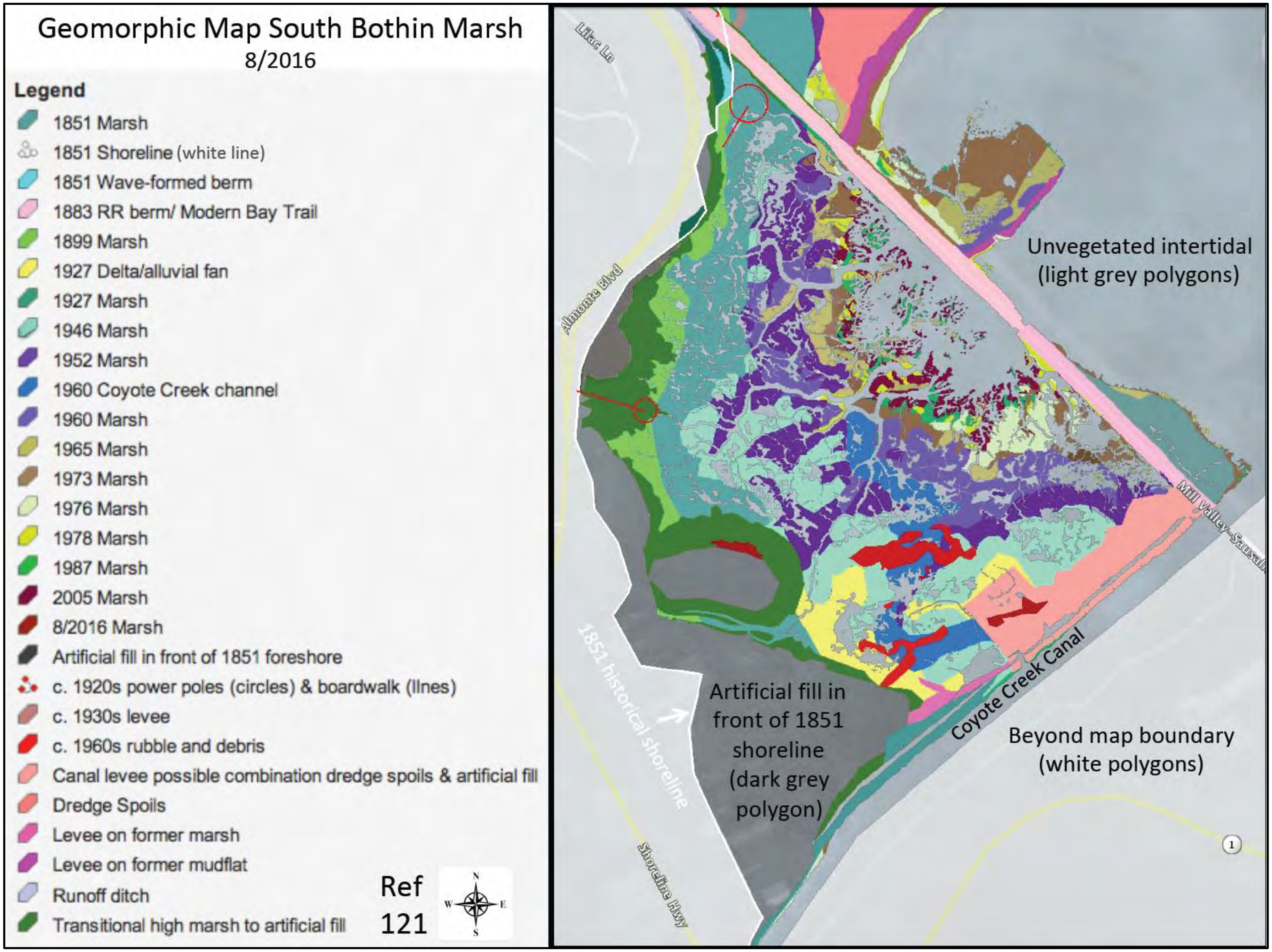


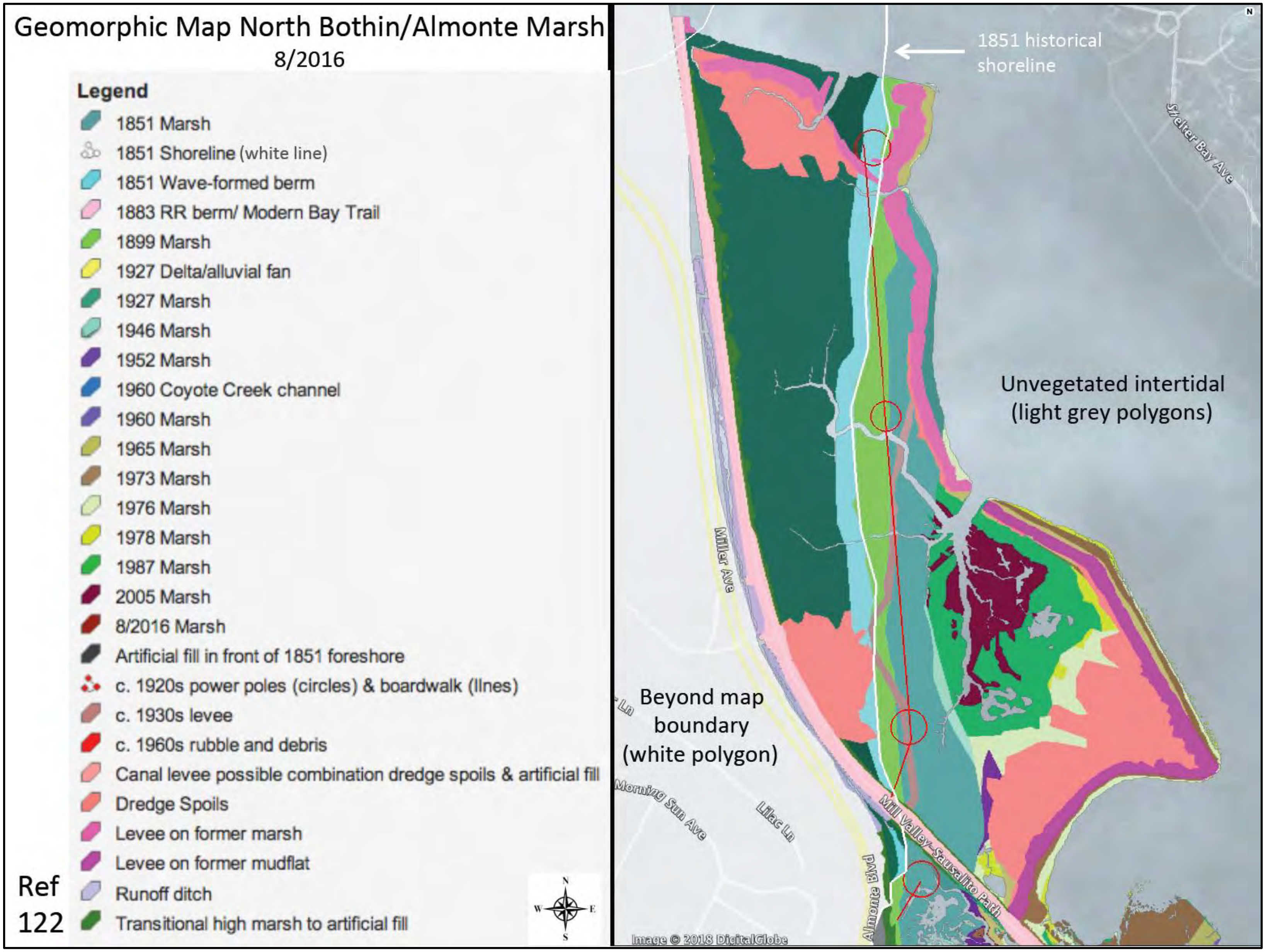


2013(?) Parcel Map of Ownership
Map Source: Marin County GIS Dept.

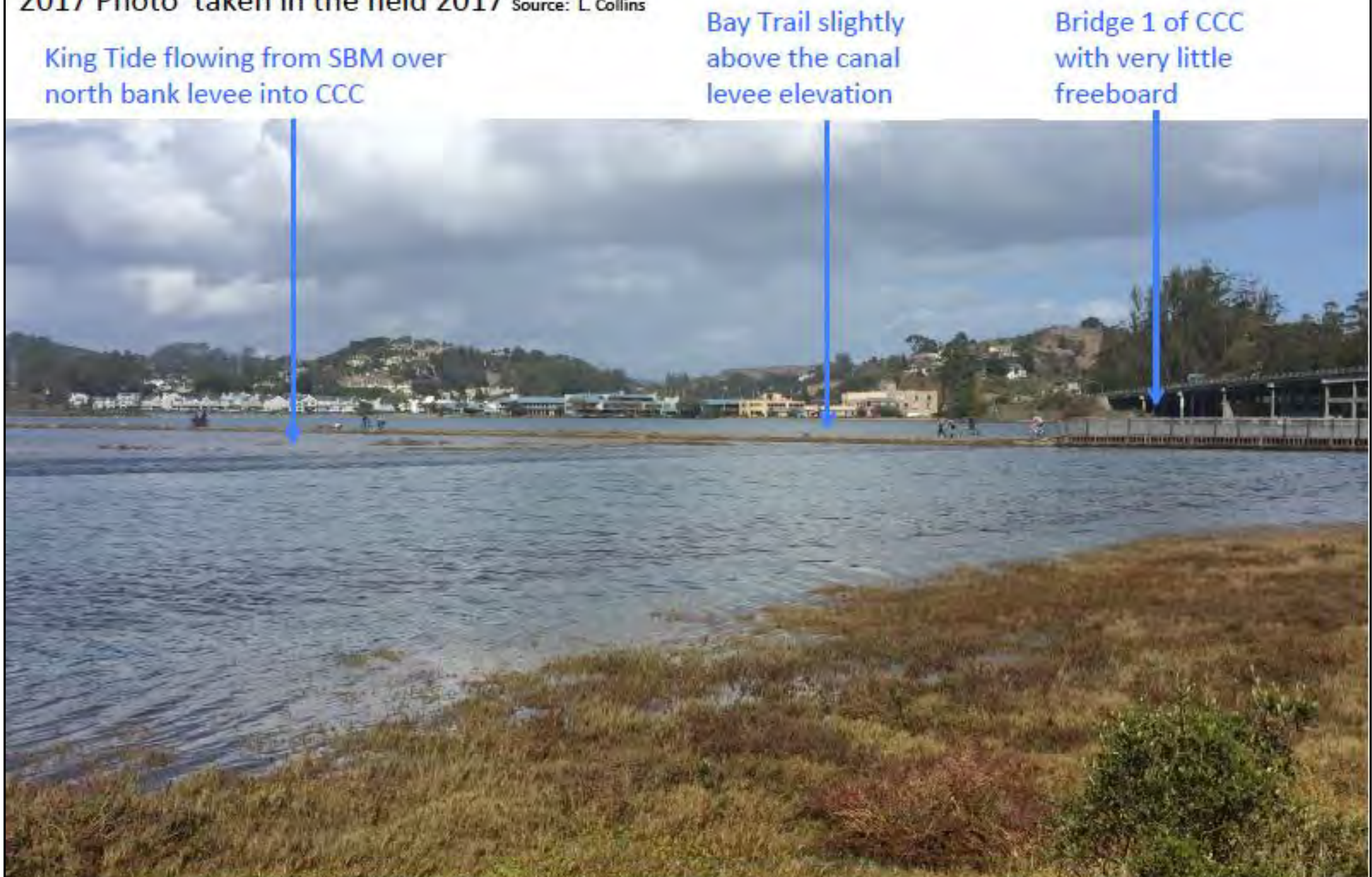

2013 LiDAR 0-9 ft NAV88 Elevation Map
Map Source: Marin County Department of Public Works
Bridge 2
Bridge 1
Low elevation drainage divide Between CCC and SBM
Bay Trail
Small levee channels
AM
NBM
SBM
EBM
Elevation, Feet NAVD88
-1.8 - 0
0 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 3.5
3.5 - 4.0
4.0 - 4.5
4.5 - 5.0
5.0 - 5.5
5.5 - 6.0
6.0 - 6.5
6.5 - 7.0
7.0 - 7.5
7.5 - 8.0
8.0 - 8.5
8.5 - 9.0
9.0 - 55.0
King tides overtop the Bay Trail and Coyote Creek Canal levee (blue arrows) and interchange flow between the two basins. As the ebb tide lowers, much flow is directed to the canal because the opening is small at Bridge 2. As it continues to drain it flows to the channel that has formed on the levee.
Ref 119


2016, Size of remaining marsh segments mapped onto 8/14/2016 Google Earth Imagery
Photo Source: Google Earth
AM ~18.0 ac
NBM ~15.3 ac
SBM ~30.4 ac
Channel has increased in width and lengthened headward
NBM embayment is enlarging and channels have slightly increased in width and lengthened by headward erosion
Areas of erosion in NBM along south facing shorelines probably due to wave direction
EBM ~0.8 ac
NMM ~2.2 ac
Coyote Creek Embayment has deceased in size to ~3.1 ac. Channels in general appear deeper and wider in some areas. The main channels from the 2013 analysis are schematically outlined here in blue.
Ref 120
N
S
E
W
Miller Ave
Almonte Blvd
Redwood Highway Frontage Rd
Redwood Hwy
Seminary Dr
Shelter Bay Ave
De Silva Island Dr
Lavender Ln
Lilac Ln
Beryl St
Helen Ave
Cardinal Rd
101
1


Geomorphic Map South Bothin Marsh
8/2016
Legend
1851 Marsh
1851 Shoreline (white line)
1851 Wave-formed berm
1883 RR berm/ Modern Bay Trail
1899 Marsh
1927 Delta/alluvial fan
1927 Marsh
1946 Marsh
1952 Marsh
1960 Coyote Creek channel
1960 Marsh
1965 Marsh
1973 Marsh
1976 Marsh
1978 Marsh
1987 Marsh
2005 Marsh
8/2016 Marsh
Artificial fill in front of 1851 foreshore
c. 1920s power poles (circles) & boardwalk (lines)
c. 1930s levee
c. 1960s rubble and debris
Canal levee possible combination dredge spoils & artificial fill
Dredge Spoils
Levee on former marsh
Levee on former mudflat
Runoff ditch
Transitional high marsh to artificial fill
Ref
121
N
W
E
S
Lilac Ln
Almonte Blvd
Unvegetated intertidal
(light grey polygons)
Mill Valley-Sausal
1851 historical shoreline
Artificial fill in
front of 1851
shoreline
(dark grey
polygon)
Coyote Creek Canal
Beyond map boundary
(white polygons)
Shoreline Hwy
1


Geomorphic Map North Bothin/Almonte Marsh
8/2016
Legend
1851 Marsh
1851 Shoreline (white line)
1851 Wave-formed berm
1883 RR berm/ Modern Bay Trail
1899 Marsh
1927 Delta/alluvial fan
1927 Marsh
1946 Marsh
1952 Marsh
1960 Coyote Creek channel
1960 Marsh
1965 Marsh
1973 Marsh
1976 Marsh
1978 Marsh
1987 Marsh
2005 Marsh
8/2016 Marsh
Artificial fill in front of 1851 foreshore
c. 1920s power poles (circles) & boardwalk (lines)
c. 1930s levee
c. 1960s rubble and debris
Canal levee possible combination dredge spoils & artificial fill
Dredge Spoils
Levee on former marsh
Levee on former mudflat
Runoff ditch
Transitional high marsh to artificial fill
Ref
122
1851 historical
shoreline
Unvegetated intertidal
(light grey polygons)
Beyond map
boundary
(white polygon)
Miller Ave
Morning Sun Ave
Lilac Ln
Mill Valley-Sausalito Path
Almonte Blvd
Image © 2018 DigitalGlobe

2017 Photo taken in the field 2017 Source: L. Collins



Ref 123 This photo shows that if Coyote Creek was at a very large flood stage during a similarly high or higher tide, the Bay Trail, the small outlet of Coyote Creek Embayment at Bridge 2, and the structure of Bridge 1 would impede the escape and conveyance of flood waters to Richardson Bay. Looking northward. Bridge 1 alt right side of photo.

2017 Photos taken in the field 2017 Source: L. Collins

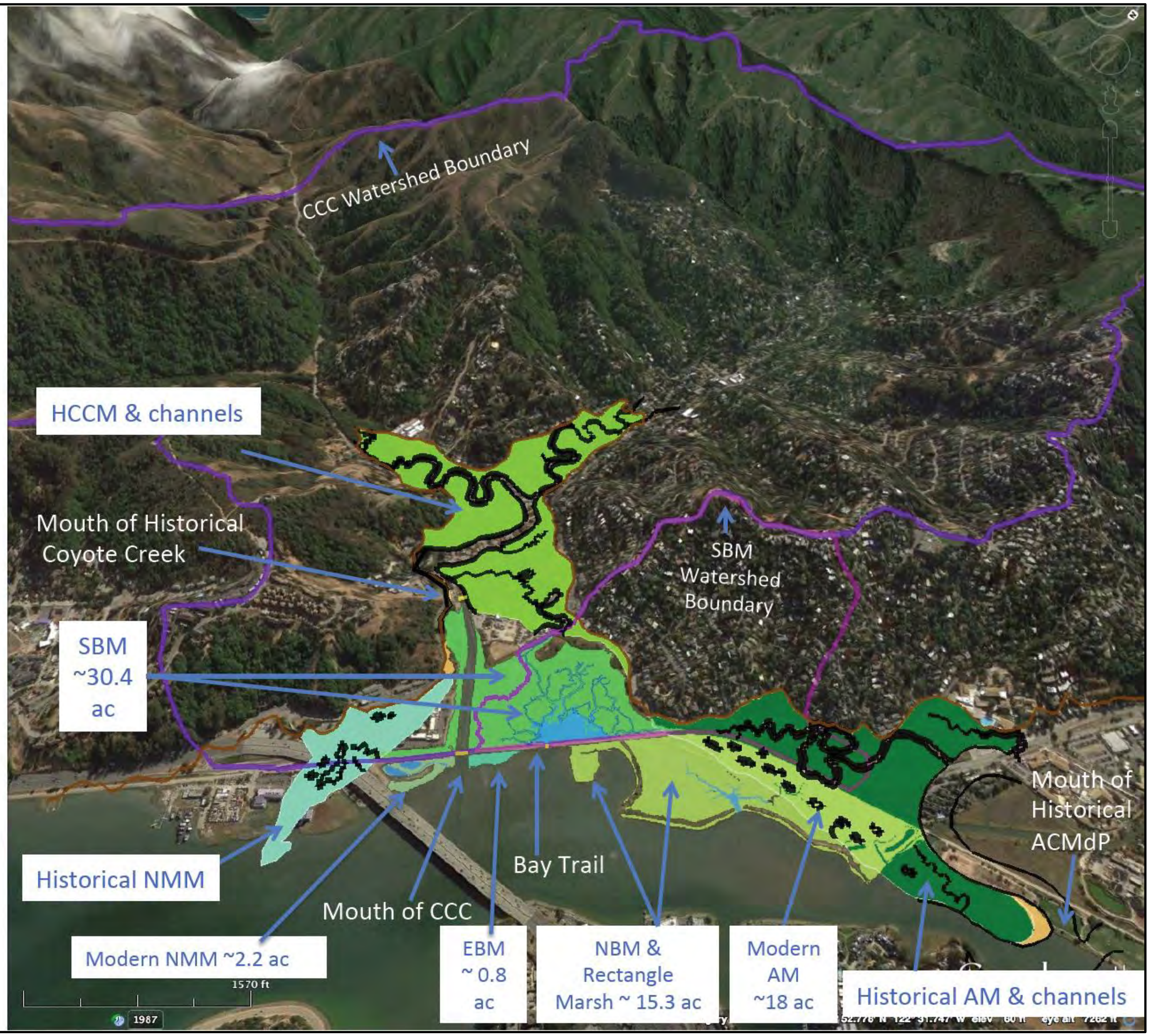

Sediment-rich water in Coyote Creek


Desiccated backshore areas affected by muted tides


Channels deepening and erosion in the mudflats of the Coyote Creek Embayment

Ref 124

Looking northwest at high tide flowing from Coyote Creek Canal into the South eastern corner of Coyote Creek Embayment.



Comparison of 1851 and 2017 Bothin Marsh Complex

Source: 2017 Google Earth Imagery base map

~18 ac of AM exists of its ~50 ac. It is the only historical marsh remaining in the study area.

The total combined area of all the modern marshes is ~66.7 ac. The original combined extent of historical marshes was 141.5 ac, of which HCCM had 761 ac.

The extent of historical marshes is within the future extent of sea level rise.

Ref 125

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Chapter 3 final figure. South-facing view of native brackish tidal marsh vegetation with shallow roots flourishing on the leached sediments at the top of an historical unnatural levee along the southeastern foreshore of North Bothin Marsh, beneath planted shrubbery killed by salt water intrusion into its deeper root zone, due to sea level rise.

Bothin Marsh Geomorphology, Ecology, And Conservation Options

Chapter 6: Summary and Synthesis

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January 2018

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Chapter 6:
Summary and Synthesis

6.0 Introduction

This is the final Chapter of the report titled "Bothin Marsh Geomorphology, Ecology, and Conservation Options," intended to help the Marin County Open Space District conserve the Bothin Marsh Complex of Arroyo Corte Madera del Presidio and Coyote Creek, in the upper Richardson Bay (Bay), California. The five preceding Chapters report the findings of intensive reviews of technical information about tidal marsh formative processes, the risk to marsh survival represented by rapid sea level rise, environmental history of the marshlands and the influence of land use, their current ecological condition, and options for their conservation. This final Chapter summaries the key findings from the preceding Chapters, and synthesizes a general framework for science-based, sea level rise adaptation of the Bothin Marsh Complex and its neighboring environs.

None of the information in this report addresses the social-economic aspects of sea level rise adaptation. Chapter 2 identifies strategies and approaches that are being developed in other coastal regions of the U.S. to facilitate managed retreat or adaptation of built environments threatened by sea level rise. However, this report focuses on conserving the natural functions and related values of the existing tidal marshes.

6.1 Summary of Findings

This is one of many scientific reports focused on the Bay and its marshes. The County has sponsored multiple reports in recent years, some of which reference each other, and all of which reference some subset of past reports. The five reviews conducted for this report covered most, if not all previous technical reports, including the historical and modern scientific literature, environmental plans, and the leading sea level rise forecasts and adaptation strategies of this region and beyond, in relation to the Bothin Marsh Complex. The reviews included more than three hundred documents, and over two hundred maps and other images pertaining to the marshlands and their environs, spanning the period 1795 to the present. In addition, the reviewers have decades of field experience in tidal marshes throughout the region. These reviews support the following summary statements of scientific understanding about the past and present conditions of the Bothin Marsh Complex, and options for conserving them in the future, some of which may be regionally applicable.

6.1.1 General

- Reputable forecasts of future sea level rise range from about five feet to more than eight feet by 2100. Forecasts of sea level rise continue to be adjusted upwards. The rate of sea level rise will accelerate between 2050 and 2100, and will not stabilize for some extended time thereafter. The future stable rate of sea level rise is unknown.

- The marshes depend on fine-grained sediment from local watersheds. It is eroded from the watersheds, carried by their streams to the Bay, temporarily stored in mudflats, and then carried to the marshes by waves and tides. Whatever slows or interrupts the sourcing and transport of fine sediment from local watersheds to the Bay, and hence its marshes, is bad for the marshes. The marshes essentially are the deltas of their watersheds. The Bothin Marsh Complex is an integral part of the local watersheds. Although these is no overall sediment budget to quantify the various sediment sources, the major sources of sediment historically and presently to sustain the marshes are likely Arroyo Corte Madera del Presidio and Coyote Creek.

- Extreme events, natural or not, have had significant environmental impact. Tidal flats and marshes represent a delicate balance between sedimentation and erosion. Sudden changes in sediment supplies or water level can trigger major changes in intertidal habitat abundance and condition. Closing or breaching a levee, installing or removing tide gates, starting or stopping dredging has measurably affected the amount and condition of marshlands.

- Altering one part of Richardson Bay affects what happens elsewhere in the Bay. Ignoring this fact causes the alterations to have unexpected consequences and sometimes to fail expensively.

- Major enterprises have come and gone, but they have forever changed the composition and structure of the upland vegetation, have increased runoff and decreased its quality, have increased upland erosion and hence sediment supplies from local watersheds, and have reduced the integrity and connectivity of intertidal habitats.

- Land development has replaced tidelands, and tidelands have replaced shallow areas of the Bay. The historical Bay was deeper and larger. Half the marshlands and half the Bay remain.

- The natural processes of tidal flat and marsh formation are ongoing. Where the processes have been operating long enough without disruption, marshes are evolving. Methods exist to enhance or even accelerate marsh formation by nurturing the processes that govern conditions in upper Richardson Bay, as well as its marshes.

- Plans for adaptation need to address future extreme events. New levees and sea walls designed to contain the Bay and prevent flooding need to consider the combined height of extreme tides, storm runoff, and wave run-up. Planning around increases in average sea levels will not be sufficient to prevent overtopping of containment structures by floodwaters.

- The factors most limiting the biological diversity of the marshes, including their support of special status plants and animals, are the underdeveloped networks of tidal marsh channels and the lack of high marsh. Most native animals residing in tidal marshes depend on these features during some part of their life cycle.

- The short-term health of the tidal marshes depends on them having adequate channel systems, high marsh habitat, and protection from lateral erosion. Their long-term health depends on these provisions plus adequate rates of sediment delivery and adequate available migration space. Unless they can migrate upstream and inland, the marshes will eventually drown. The timeline for addressing these needs is no more certain than the forecasts of sea level rise. However, due to sea level rise and poor drainage, there is evidence that the marshes have already begun to drown.

- Marshes can beget marshes. The marshes of today are not the marshes of yesteryear. What is done now to conserve the existing marshes will help assure that they become the marshes of tomorrow.

6.1.2 Upper Richardson Bay

- Prehistoric Richardson Bay received minimal suspended sediment from the greater San Francisco Bay. Historically, the waters of Richardson Bay were relatively clear. That changed with the sediment provided by logging and ranching in local watersheds before the earliest detailed maps of the tidelands were made. The Bay shoaled rapidly from 1852 to 1856.

Beginning shortly thereafter, dredging maintained the depth of the Bay. Since dredging ended, the Bay has continued to shoal. In the absence of accelerated sea level rise, and given the current sediment supply, the upper Bay would likely evolve into mostly tidal flats and marshes.

- Levees placed offshore on the Bay mudflats for large-scale reclamation that never happened have devolved into sills that trap sediment and have nurtured the formation of mid-bay bars and development of mudflats, which in turn have helped protect the marshes from lateral foreshore erosion.

- The power of wind-generated waves attacking the northern shores of the Bay are probably diminished by the Richardson Bay Bridge, since it interrupts the southeast storm fetch that otherwise would run the length of the Bay. However, the wind-waves of the fetch would have also resuspended sediment from the mudflats and perhaps thusly increased sediment supplies to the marshes. On balance, the reduction in wave fetch is probably detrimental to the marshes.

6.1.3 Bothin Marsh Complex

- North Bothin Marsh is two marshes in one, partially separated by a nearly imperceptible decaying levee constructed in the 1930s. Almonte Marsh is a remnant of the historical marsh that fringed the Bay along the southern bank of Arroyo Corte Madera del Presidio. North Bothin Marsh resulted primarily from reclamation in the 1960s. Its interior consists of dredged sediments and more recent tidal deposits dating to a 1972 levee breach. Although the breach has been widening on its own, its channel system is not adequate to deliver sediment throughout the marsh, particularly to the historical backshore remnants of Almonte Marsh.

- South Bothin Marsh is evolving in an artificial embayment created by the 1500-foot railroad trestle built offshore from the historical Coyote Creek mouth. The ends of the trestle were replaced with progressively longer levees that blocked tidal flow, and the inlet to the embayment became progressively smaller. The existing inlet is undersized, such that the marsh drains slowly. Successively higher tides during each spring tide series cause tidal water to accumulate in the marsh, increasing its duration of submergence, and inhibiting plant colonization.

- The diversion of Coyote Creek away from the marsh and into the Coyote Creek Canal has greatly diminished the upland supply of sediment directly to the marsh, contributing to its persistence as low tidal marsh and mudflat.

- For a period between the 1960s and 1980s, natural tidal flow was eliminated to South Bothin Marsh by a flap gate at the inlet through the railroad levee. At about the same time, Almonte Marsh had its tidal flow eliminated by a containment levee that later created North Bothin Marsh. During this same period, portions of both marshes were subject to seasonal desiccation, eventually leading to their subsidence, which further limited their ability to gain elevation in pace with sea level rise.

- The Bothin Marsh Complex is clearly already changing due to sea level rise and insufficient sediment supply. The marshes are completely submerged during some of the higher predicted tides, regardless of major storms, El Nino conditions, or other causes of unpredictable, extreme high tides. At South Bothin Marsh, the undersized inlet inhibits drainage, causing flood tides to spill over an old levee into the Coyote Creek Canal. As sea level rises, the Bay Trail and undersized inlet will further impede drainage and increase the risk of upstream flooding.

- The hydrologic, geomorphic, and ecological responses of the Bothin Marsh Complex to historical environmental changes are manifested as a set of unique landscape features termed "eco-geomorphic units" that should comprise the elements of future efforts to enhance the marsh ecosystems and increase their resilience to sea level rise. These eco-geomorphic units collectively support a unique flora including multiple rare species deserving special attention during adaption planning. The enhancement of high marsh habitat will benefit these species.

- There is scant available marsh migration space. Potential migration space consists of commercial and residential developments on reclaimed and in some cases subsided, historical marshland. The risk of flooding on these lands is increasing as sea level rises. At some time in the future, the cost of defending against the flooding will exceed the cost of accommodating and adapting to sea level rise. There is a strong foundation of science and engineering to foster public policies to enable communities to "make way for the Bay".

6.2 Data and information Needs

New data needs will arise as the adaptation strategies and methods are developed and implemented. Care must be taken to assure that the data address the needs as cost-effectively as possible. To understand the efficacy of the adaptation efforts, and to learn from them, a program to monitor their performance will be needed. The feedback between management actions, monitoring, and management response to the monitoring results is generally called adaptive management (Holling 1978, Walters and Holling 1990, Rist 2013). The statewide, multi-agency Water Quality Monitoring Council has produced a framework for developing monitoring programs, called the wetland and Riparian Area Monitoring Plan (WRAMP), that serves adaptive management of wetlands and other aquatic resources at local, watershed, and regional scales (WQMC 2016). The WRAMP framework should be examined as a model for developing the monitoring program that will be needed to assess the adaptation efforts.

In the course of this report, questions emerged that existing data do not seem able to address. These data needs have been partitioned among the near-term, mid-term, and long-term adaptation strategies.

6.2.1 Near-term Data Needs

- *What are the ramifications of channels breaching the north levee of Coyote Creek Canal?* The nascent channel beginning to drain South Bothin Marsh into the Coyote Creek Canal will eventually cut through the historical levee and enlarge to convey a substantial portion of the marsh tidal prism. This would improve drainage for the marsh and thus improve its overall condition. If desired, the channel could be excavated to more quickly achieve the desired drainage. However, the channel would need to be sized, based on the tidal prism it is likely to convey, given that the existing inlet also serves to drain the marsh. A hydrological model is needed to estimate the correct channel dimensions. Furthermore, the existing nascent channel is very near the north footing of the Bay Trail Bridge One across the mouth of the Coyote Creek Canal. An analysis is needed to determine any likely effects of the new channel on the bridge, and if the channel should be moved further upstream to avoid bridge impacts.

- *Is the South Bothin Marsh demolition debris contaminated?* Legacy urban fill along the shorelines of San Francisco Bay pre-date environmental laws for pollution control and might therefore contain a variety of persistent sources of chemical contaminants. The fill should be examined to determine any need for its remediation.

- *Are tidal flows across the Bay Trail impacting its structural integrity or maintenance needs*? Reviews conducted for this report revealed multiple references to tidal flooding of the Bay Trail within the Bothin Marsh Complex. However, no studies of the effects of the flooding on the Bay Trail or its levee were found. A study is needed, if an adequate one does not exist, to determine the timeframe for future repairs and preventive measures. The timeframe will determine when preventive measures should be integrated into mid-term or long-term adaptation strategies.

- *What are the locations and optimal designs of pilot projects for marsh mounds and thin lifts of placed sediment to enhance high marsh habitats?* At this time, additional high marsh is most needed at North Bothin Marsh and Almonte Marsh. To improve tidal circulation for these marshes, excavations of new tidal channels would ideally provide the sediment for marsh mounds. A construction plan is needed that shows the optimal arrangement of channels to convey the maximum expected tidal prism throughout the marsh, given the current tidal elevations of the marsh plains and the total capacity of the existing and additional channels. A pilot project should create a new drainage network confluent with an existing breach. The estimated volume of excavated sediment can be used to decide the size and number of mounds.

- *Is there a need for any future dredging in upper Richardson Bay?* Reviews conducted for this report did not reveal any plans for future maintenance dredging of the subtidal Sausalito Canal upstream of the State Highway 101 bridge, the Coyote Creek Canal, or any other location within upper Richardson Bay. The status of all dredging agreements and plans within the area should be known. Dredging should be discontinued until its benefits to the tidal flats and marshes are ascertained. The potential reuse of suitable dredged sediment to enhance the marshes should be considered as part of the mid-term and long-term adaptation strategies, if natural sedimentation processes need to be augmented. The County should be aware of reuse opportunities provided through the regional program, called SediMatch, that links sediment reuse needs to dredging and upland grading projects (http://www.sfei.org/projects/sedimatch-web-tool#sthash.0dG4szUC.dpbs).

6.2.2 Mid-term Data Needs

- *What are the local tidal datums and what are the tidal elevations of tidal habitats, roads, levees, and other infrastructure within the mid-term potential migration space?* Accurate tidal elevations are essential to implement sea level rise adaptations. The high tide datums, namely Mean High Water and Mean Higher High Water, plus the highest observed tides, are especially important to forecast the frequency, depth, and duration of future flooding. The high tide datums can vary significantly along the shoreline of bays and embayments. They can also vary from foreshore to backshore, if the intervening distances are large (i.e., if the marshlands are broad). Unless the variations are known, the transference of datum values from place to place is suspect. This puts a premium on reckoning the datums very near where they will be used for adaptation design and implementation. Datums should be determined empirically for the foreshore and backshore of South Bothin Marsh and Almonte Marsh. Methods of tidal datum reckoning should follow NOAA protocols, which cover the installation and maintenance of water level recorders, benchmark networks, and the length of record needed to achieve desired levels of precision.

- *What are the sediment budgets for the marshlands and their watersheds?* Protecting public investments in the conservation of the Bothin Marsh Complex will involve managing its sediment budget. This, in turn, will involve knowing the sources of sediment and why sediment supplies vary over time. For the marshes themselves, this will require monitoring the relative contributions of terrigenous, tidal, and allochthonous sediment to marsh accretion. If rates of accretion are inadequate, the supplies of one or more of these kinds of sediment can be augmented. The tidal sediments are likely to be most important to marsh survival, at least in the mid-term. The main sources of tidal sediment are Coyote Creek and Arroyo Corte Madera del Presidio. Therefore, marsh adaptation plans should be consistent with the expected sediment yields of these two watersheds, especially the wet season yields, with recognition that the yields will be affected by climate and land use change. Furthermore, the relationship between wet season sediment yield from local watersheds and the actual availability of sediment at the marshes should also be known. Gaining this knowledge will require wet season measurements of suspended sediment concentration in the upper portion the water column during high tides at the mouths of channels serving the marshes. Know how sediment yields from local watersheds actually affect sediment supplies at the marshes will help determine the degrees to which watershed management might influence marsh accretion.

- *What are the intentions or plans of other agencies responsible for adaptation to sea level rise within the Bothin Marsh Complex or its environs?* The mid-term and long-term conservation of the marshlands of upper Richardson Bay will require coordinated efforts between Marin County Parks and multiple other agencies at all levels of government. It is not too soon to begin aligning their policies and procedures behind agreed-to adaptation strategies. Political and administrative obstacles will complicate this. Removing these obstacles begins with their clear definition. The County should consider sponsoring a regional summit on sea level rise adaptation policies, to compliment the various summits occurring on science-based adaption designs.

6.2.3 Long-term Data Needs

- *What are the minimum thresholds of sediment supply and sea level rise that trigger tidal marsh drowning?* The threat that sea level rise will frown the tidal marshes becomes more manageable if the relationship between the rate of sea level rise and health of marsh vegetation is known. Gaining this knowledge will require, at a minimum, monitoring vegetation cover and the frequency and duration of tidal inundation of the marsh plains. The County should consider participating in efforts to conduct such monitoring as part of the Bay Area Wetlands Regional Monitoring Program (WRMP; http://www.sfestuary.org/wrmp/).
- *What is the timeframe for exploring containment and accommodation strategies?* The periods herein labeled near- to long-term will need to have estimated beginning and ending years. This will start important clocks for planning, including public outreach, policy development, inter-agency coordination, and financial development. The timeframe will depend on available estimates of sea level rise rates, and estimates of tidal marsh response rates (see bullet immediately above). Based on current see level rise projections and expected impacts to natural and built coastal environments, near-term might extend from now to 2030, midterm from 2030 to 2050, and long-term from 2050 to 2100 or 2150 (Griggs 2017).
- *How will forecasts of sea level rise and extreme flood events affect economic drivers such as infrastructure maintenance costs and property values?* The analyses of time and costs to implement adaptation strategies within the Bay and its marshes should be matches by comparable analyses of managed retreat. Models are needed to forecast the effects of sea level rise on the broad range of economic and social factors that affect property values, and hence the availability of migration space, including flood insurance, resale values, and mortgage availability. It is important to foresee when the total costs of battling the tides might exceed the cost of retreating from them, and how the relative costs might be managed to favor retreat.
- *What is the vision?* A common vision of success is needed among the public agencies responsible for the long-term conservation of the Bothin Marsh Complex. The vision might be conceptual at

first, based on a common vision statement and set of principles, but eventually will need to be map-based and quantitative. The Flood 2.0 Program has proven useful in achieving common visions of future healthy coastal landscapes shared among diverse interests (Dusterhoff *et al*. 2017; http://www.sfei.org/flood-control-20). Once a vision is drafted, it will need public advice and review. Each of the possible long-term adaptation strategies involves significant public expenditures and could significantly impact local neighborhoods and communities Political support will be needed for implementation.

6.3 Synthesis of historical change

Historical reductions in the amount of tidal marshland in upper Richardson Bay have resulted almost entirely from efforts to reclaim or otherwise manage the Bay and its marshes for commercial and industrial benefits (see Figures 6.1 and 6.2). Accelerated rates of sedimentation in the Bay likely started earlier than the mid 1800s, and the ongoing losses of marshland began in the 1850s. Dissection of the marshlands and enclosure of small embayments by railroading began in the 1880s.

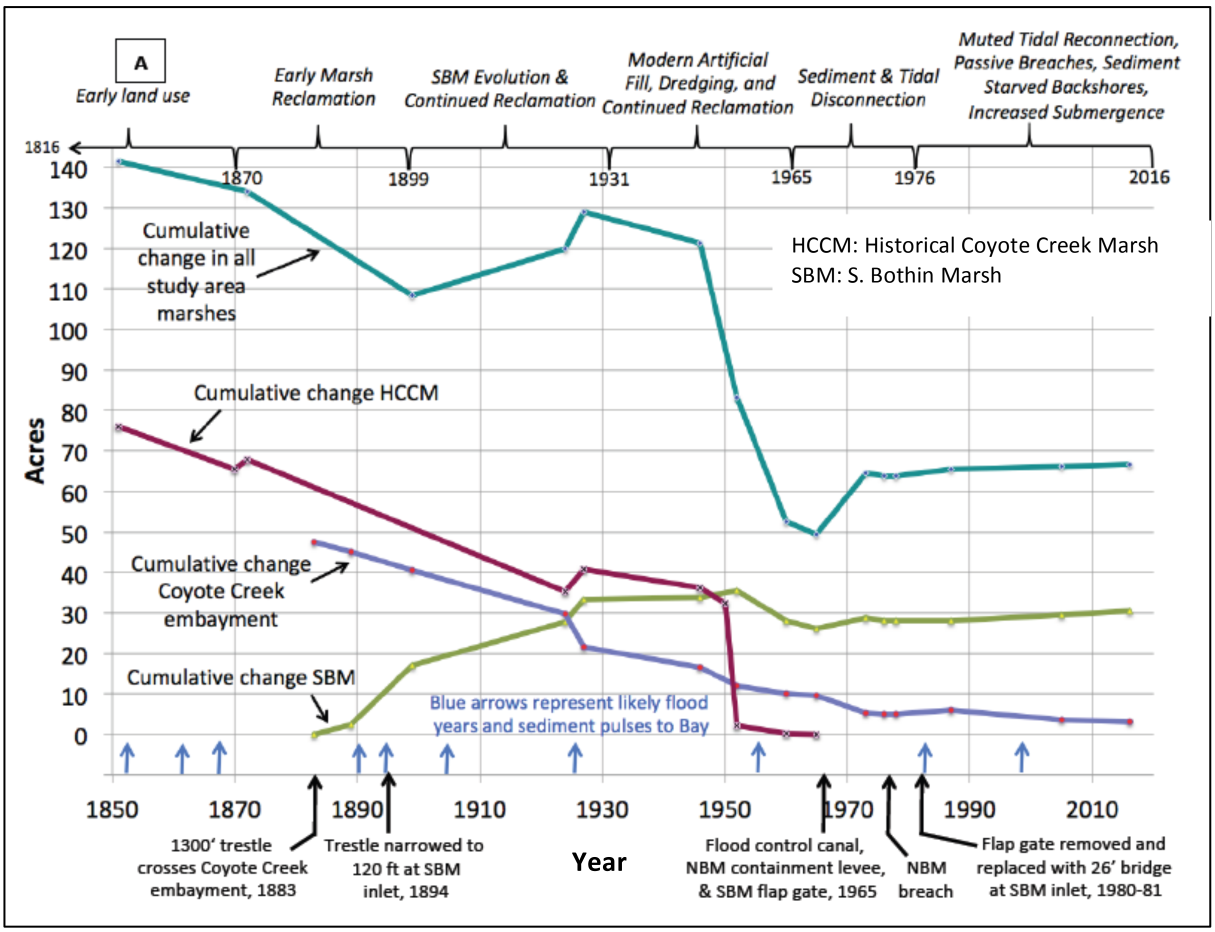

Figure 6.1. Changes in Acreage at South Bothin Marsh, compared to the cumulative total change in all marshlands of the Bothin Marsh Complex study area, with indications of major human interventions (black arrows) and natural events (blue arrows) that punctuate the overall historical decrease in tidal

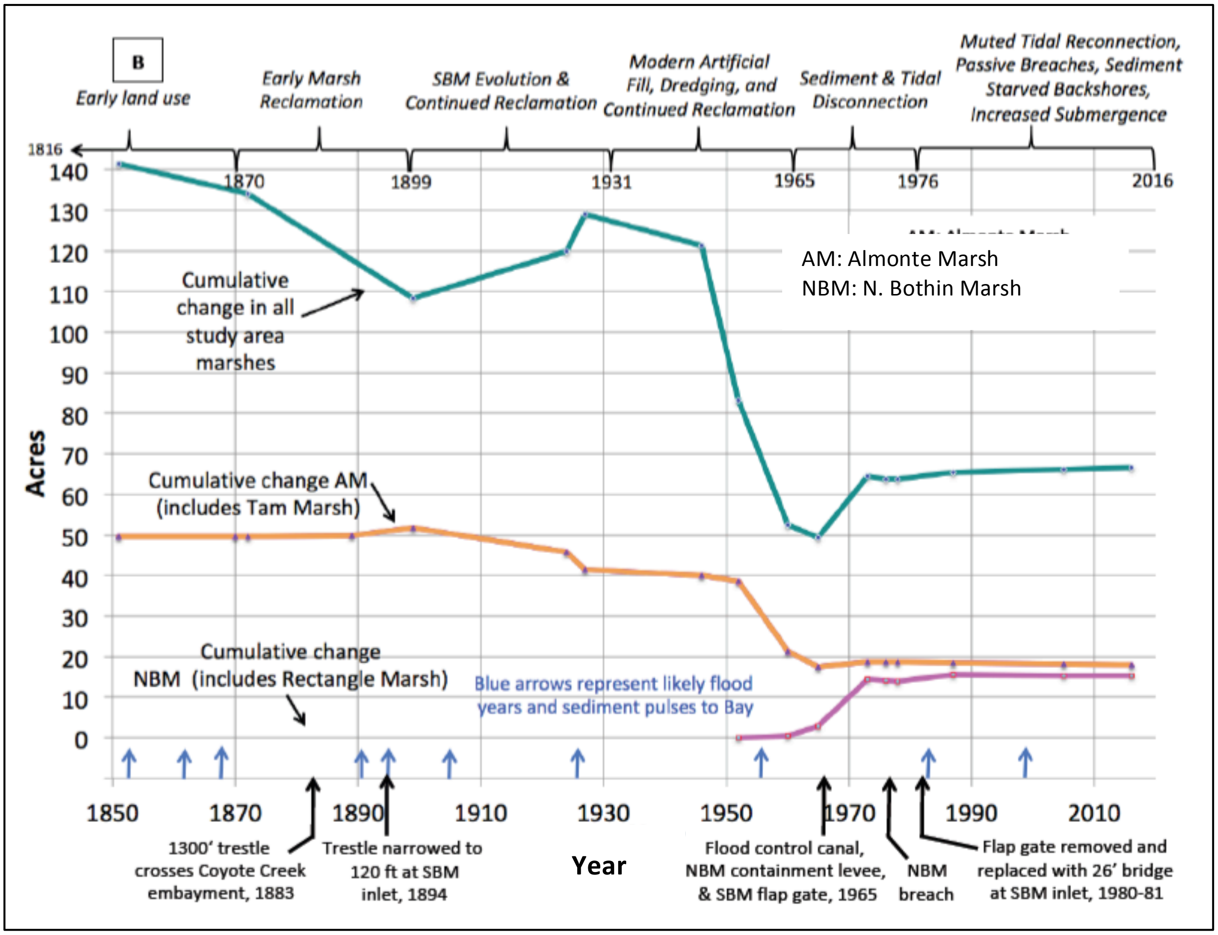

Figure 6.2. Changes in Acreage at South Bothin Marsh, compared to the cumulative total change in all marshlands of the Bothin Marsh Complex study area, with indications of major human interventions (black arrows) and natural events (blue arrows) that punctuate the overall historical decrease in tidal

The losses were punctuated by periods of intensive land use change. A dramatic and sudden loss of marshland resulted from increased reclamation, urbanization, and related dredging post WWII. Some losses were partially mitigated by extreme natural events, especially major storms and floods, with pulses of sediment that helped maintain or even slightly expand the marshlands remaining at the time. This supports the finding that the local marshes depend on supplies of sediment from their watersheds. The evolution of fringing tidal marsh along levees contributed to small local gains in marsh, while old marsh was being destroyed.

6.4 Adaptation Guidance

The preceding Chapters support a guiding set of considerations for conserving the Bothin Marsh Complex, in the context of sea level rise. Of special importance is the application of existing scientific knowledge about marsh evolution and self-maintenance. The following five sets of natural processes are essential to marsh survival. Their expert management through carefully planned intervention will likely be integral to any successful adaptation strategy:

- Ongoing landward and upstream migration of intertidal habitats, including tidal flats and marshes, in pace with sea level rise;
- Landward retreat of the marsh foreshore (the marshes do not necessarily widen due to

migration because their bayward margins tend to erode), in pace with sea level rise;

- Sediment sourcing, conveyance to the Bay, storage as tidal flats, resuspension by wind-waves, and tidal transport to marshes through their channel networks;
- Vertical (in-place) adjustment in marsh elevation relative to the tides by tidal deposition of fine sediments on the marsh surface, and autochthonous sedimentation (development of peat and other organic matter) beneath the surface, in pace with sea level rise;
- Dispersal, colonization, and establishment of both "ecosystem engineer" species (species with dominant direct roles in geomorphic formation and maintenance of tidal marsh), and biological diversity that indirectly or directly maintain the ecological communities in which they operate.

There are additional, strong reasons to prioritize development of high marsh habitats as critical elements in any strategies of sea level rise adaptation for the Bothin Marsh Complex:

- High marsh is strongly indicated as the limiting habitat for salt marsh biological diversity, rare plant habitat, and critical nesting and high tide refuge habitat for special-status wildlife;
- Although high marsh existed historically at Coyote Creek Marsh, Almonte Marsh, and early stages of South Bothin Marsh, it is not forming naturally at present within the Bothin Marsh Complex (almost all existing high marsh habitats at these marshes and nearby marshes are legacies of past artificial fill);
- High marsh is vulnerable to drowning in place, with minimal existing available migration space for its regeneration;
- While the development of high marsh should be emphasized, a mixture of all tidal marsh habitat types, including low marsh and the backshore transition zone, should be sustained, based on natural analogues in the region. The proportions of different tidal marsh habitat types or eco-geomorphic units should be managed to avoid excessive reductions in overall habitat diversity or reductions in the ecological connectivity among the habitat types.

6.5 Synthesis of Conservation Options

Adaptation to sea level is just beginning for most urbanized coastal communities of the U.S. and elsewhere. Many unknowns, including the future rates of sea level rise, complicate planning. As noted above, for San Francisco Bay, reputable forecasts range from about five to more than eight feet by 2100. The prudent assumptions are that sea level rise will accelerate, that sea level will increase by more than six feet before then end of this century, and that sea level rise will not stabilize for some extended time thereafter. It is also prudent to assume that costs for adaptation will rise, such that monies wisely invested now could have maximum returns. However, adaptation will involve learning. Some early methods of adaptation may have limited value except as learning experiences. This highlights the need to monitor and assess the efficacy of adaptation efforts.

For tidal marshes, sea level rise adaptation strategies must be flexible. There are cascading unknowns, starting with the forecasts of sea level rise rates, continuing through uncertain habitat designs and construction plans, and including uncertainties about plant and animal dispersal and colonization. "Build it and they will come," is more of a wish than a promise. The processes of tidal marsh evolution and self-maintenance lend themselves to flexible adaption strategies. The processes are hierarchical through space and over time, such that they can be phased.

A common way to begin adaption is to first identify what *must* be done soon to preserve later opportunities, and then focus on the actions most likely to have long-term benefits (Figure 6.3). Near-term adaption efforts should be consistent with mid-term and long-term objectives. Some near- or mid-term actions may persist into the long-term. Others will not. For example, marsh mounds may be essential near-term actions that will be very difficult to maintain, as sea level accelerates. In contrast, properly excavated and realigned channels may maintain themselves. Financial capacity and human resources are always fundamental concerns, and it should be noted that large options that provide longer-lasting benefits usually take longer to accomplish and cost more.

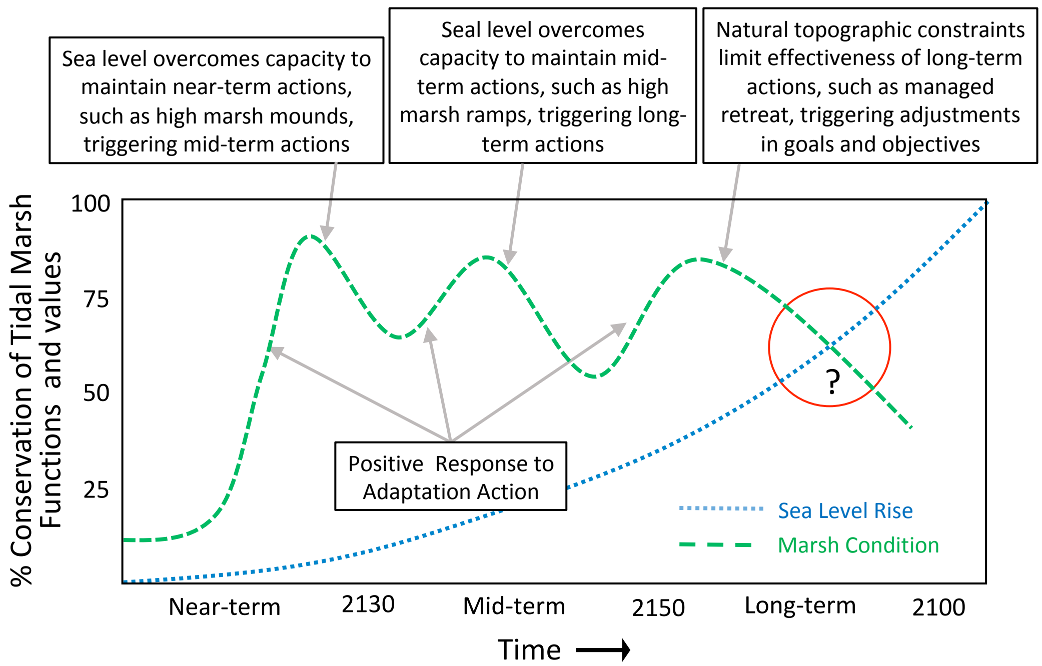

Figure 6.3. Conceptual framework of phased efforts to conserve tidal marshes as sea level rises. Immediate actions to enhance existing marshland will give way to longer-term actions to sustain target levels of conservation. Whether or not to retreat from the migration space (see red circle) will determine the fate of the marshlands.

To illustrate the complexity of more fully incorporating natural processes into landscape engineering, conceptual plans were drafted for North Bothin Marsh to accommodate a few feet of sea level rise while enhancing sediment supplies for marsh development, improving high marsh habitats, and enhancing flood control (see Chapter 5). In concept, the scenarios of integrated landscape design could secure the safety of the lowland development into the latter part of this century. Many elements of these concepts are transferable to other locations.

Restoring and protecting the historical functions and values of the tidal marshes of upper Richardson Bay will become increasingly difficult, as sea level accelerates to unprecedented local heights. Since the valleys of Tennessee Creek and Coyote Creek are small and mostly below the projected Bay levels, they offer little potential long-term migration space. Mill Valley is larger, and mostly above the projected sea level, but densely developed. Actions to conserve the marshes will become increasing costly, as will the efforts to prevent tidal flooding of the built environment with the construction and maintenance of sea walls, levees, pump stations, and other flood control infrastructure. The cost of flood control may eventually exceed the cost of managed retreat, in which case new migration space may be realized. Otherwise, only narrow fringing marshes along the tidal reaches of local streams may survive, and the goals for marsh conservation will need to be drastically revised.

All the political, economic, and engineering strategies being explored in this region and elsewhere can contribute to the inevitable effort to move people and incompatible land uses out of harm's way. The conservation of healthy tidal marshland should be an integral aspect of that effort. The hardest work will belong to the next few generations of environmental scientists, engineers, and planners. The current generation can help by exploring ways for them to achieve success.

Figure 6.4. Flooding of the Bay Trail at South Bothin Marsh during spring 2012. Photo courtesy Tim Porter (http://www.timporter.com/seconddraft/?tag=bothin-marsh).