Factors Controlling Tidal Flat Morphology in South San Francisco Bay between the 1890s and 2005.

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Abstract:

There is currently a project underway to restore many of the man-made salt ponds along the shores of South San Francisco Bay (SSFB) back to tidal marsh, potentially reestablishing these areas as sinks for SSFB sediments. While there have been recent studies examining the evolution of newly restored marsh areas in SSFB, there have been no recent projects focusing on the expected response of valuable tidal flat environments adjacent to the restored marshes. To help fill this void, this project seeks to characterize SSFB tidal flat morphodynamics, both spatially and temporally, through examination of historic morphologic variability and change along with variations in external forcings.

Spatial and temporal trends in profiles of SSFB tidal flats are examined using bathymetric and LIDAR data collected between the 1890s and 2005. Eigenfunction analysis reveals a dominant mode of morphologic variability related to the degree of convexity or concavity in cross shore profile – classically indicative of tidally dominant, sediment rich, or wave dominant, sediment poor conditions, respectively.

Two opposing areas of equilibrium shape – north/south of a constriction in estuary width located at the Dumbarton Bridge – are highlighted by the first mode of variability in the Eigenfunction analysis, accounting for 90% of the overall spatial variation in tidal flat shape. Additionally, the eigenfunction scores which quantify the spatial pattern of increasing/decreasing convexity in the inner/outer estuary are correlated to spatial variability in fetch length, sediment grain size, recent erosion/deposition, and tidal height. Results for spatial variation found herein are generally consistent with theoretical predictions of tidal flat morphologic response to waves, tides, and sediment supply.

Trends for morphologic change between 1890 and 2005 in twelve geographically diverse regions within SSFB are compared to temporal trends in sediment discharge, mean sea level, diurnal tidal range, and Pacific Decadal Oscillation Index (as a proxy for storminess). Overall, convex vs. concave profiles were favored in the inner vs. outer estuary throughout the entire historical period. Furthermore, tidal flat morphology of the outer estuary displayed a steady increase in concavity with time. The trend of increasing concavity in the outer-estuary flats was consistent with temporal changes in hindcasted sediment discharge from the Central Valley. Although consistently convex, tidal flats located in the inner portions of SSFB exhibited greater complexity in their degree of convexity through time, and temporal changes could not easily be correlated to a given external physical forcing, suggesting a possible role for more localized variations in sediment supply.

A set of criteria for establishing dependence between morphology and external factors was created, using results of a stepwise multiple regression. Using this criteria, trends sediment supply from the Central Valley were found to have a consistency with temporal trends in outer-estuary tidal flat shape. Inner-estuary flat shape change was found to be consistent with local patterns in rainfall (as a proxy for local sediment discharge) in the innermost regions, and with recent deposition or erosion in all other regions.
Factors Controlling Tidal Flat Morphology in South San Francisco Bay between the 1890s and 2005.
1. INTRODUCTION

Intertidal zones - mudflats and sandflats - are often overlooked regarding their importance to the biology and morphology of coastal systems. As essential habitat for many benthic organisms, these areas provide a food source and staging area for many migratory bird species (Dyer, 1998; Dyer, 2000; Kirby, 2000). Additionally, mudflats dampen wave and wind energy, thereby lessening coastal erosion (Kirby, 2000). Morphological behavior of mudflats, subject to complex interactions between biologic, geologic, and hydrodynamic processes on short and long time scales, can be difficult to quantify (O’Brien et al., 2000). Global variations in tide and wind patterns, response to sea level rise, and grain size distribution are such that it has been challenging to make generalizations concerning all intertidal systems; each of these variables greatly affect the evolution and morphology of individual systems (Dyer, 1998).

Frequently fringed by marshland on their landward extreme, the hydrodynamics of intertidal zones have become an area increasing interest to sediment and marine scientists and modelers over the past ~10 years.

1.1 Basic Characteristics:

Tidal flats can been broken into three major segments: (1) the lower tidal flat (LTF) extends from lowest low water to mean low water (MLW), and is subject to the largest amount of energy from both cross-shore and along-shore currents (Pethick, 1996; Dyer, 2000; Roberts, 2000, Le Hir et al, 2000); (2) the middle tidal flat (MTF) extends between MLW and neap high water and is subject to mainly cross-shore currents of moderate energy (Pethick, 1996); (3) the high tidal flat (HTF) extends between neap high and mean high water (MHW), or to the first
emergence of vegetation, and is subject to low-energy cross-shore currents (Pethick, 1984; Pethick, 1996) (figure 1-1).

As a result of this gradient in current energy from LTF to HTF, there is a corresponding gradient in sediment size (Pethick, 1996; Dyer, 1998, Yang et al., in press). Coarser sediments located in the LTF are generally less well consolidated, and therefore more easily eroded. In comparison, the HTF is usually characterized by finer-grained, more consolidated sediments (Shi & Chen, 1996; Dyer, 2000; Yang et al, in press). At low tides, the HTF is often exposed, allowing for consolidation and de-watering of sediments, increasing the critical shear stress required for resuspension (Christie et al., 1999; Janssen-Stelder, 2000); conversely, exposure can also lead to cracks and slumping, which can facilitate erosion of large blocks of otherwise consolidated sediment (Dyer, 1998; Kirby, 2000).

1.2 Sediment Transport:
Sediment transport on tidal flats varies depending on a host of conditions. First is the stage and range of tidal influence. In calm conditions, a flood tide frequently results in the onshore transport of sediment due to settling-lag and scour-lag processes (Christie et al, 1999; Pritchard et al, 2002) . Accretion will occur on the upper tidal flat as sediment settles during slack flood and is not resuspended in the early stages of ebb. Spring tides also tend to result in higher suspended sediment loads, and therefore higher rates of accretion (Christie et. al., 1999; Verney et. al., 2006). Black (1998) found that suspended particulate matter (SPM) on an intertidal area of the Humber Estuary, UK, varied greatly over spring tide, peaking at 1.2 g/l during max-flood, stabilizing at ~0.7 g/l until max ebb, when it increased slightly to 0.8 g/l. By
contrast, during neap tide at the same location, SPM measurements maintained a steady value of ~0.4 g/l throughout the entire cycle.

Christie et. al. (1999) measured bed levels and bed stress during a calm tidal period and found a 4 mm increase from the beginning of flood to slack water. During ebb, the bed height decreased by 2.5 mm. Bed stresses were slightly greater during ebb, but were sustained at high levels for a longer period during flood, resulting in net onshore movement. Accretion that occurred during calm periods resulted in a building up of the upper tidal flat and a convex-up profile (Christie et al, 1999; Le Hir et. al., 2000). The same study also observed the tidal flat profile over a period of storminess and wave activity and found that bed sediment was quickly eroded on flood tide and transported out during ebb, resulting in overall erosion and a trending towards concavity (Christie et al, 1999) (figure 1-2).

In stormy or high wind/wave conditions, the tidal influence on sediment motion is greatly reduced. Increasing waves result in higher rates of erosion and offshore sediment motion (Green at. al., 1997; Black, 1998; Christie et. al., 1999; Janssen-Stelder, 2000; Le Hir et. al., 2000; Pritchard et. al., 2001; Verney et. al., 2006; many others). Le Hir et. al. (2000) found greatly increased bed shear stresses over much of flood and ebb during periods of moderate wave height (0.5 m), leading to greater SPM and offshore movement of sediment. Bed levels during a wave event, measured by Christie et. al. (1999), dropped immediately at the beginning of flood by as much as 70 mm, and remained low throughout the tidal cycle. Janssen-Stelder (2000) also showed increasing bed stresses, SPM, and offshore sediment transport (erosion) with increasing wave energy, regardless of tide cycle or range.

Janssen-Stelder (2000) studied differing hydrodynamic conditions and their effects upon erosion and accretion and made general conclusions concerning calm vs. windy conditions in the
Dutch Wadden Sea. It was found that, during calm conditions, current velocities are the primary drivers of sediment transport on tidal flats, resulting in net accretion. Conversely, during rough periods, a combination of tidal currents and wave action leads to net erosion of the tidal flat. A single large storm event can result in sufficient erosion to undo the accretionary effects of long periods of calm weather (Janssen-Stelder, 2000).

1.3 Biology:

Another important factor in the morphologic character of tidal flats is the presence or absence of biologic activity (Dyer, 1998; Widdows & Brinsley, 2002). Tidal flats, especially in the mid to upper regions, are often marked by the presence of mat-forming diatoms, which serve to increase the shear strength of the sediments and decrease the possibility of erosion (Widdows & Brinsley, 2002). Similar results are also obtained through the formation of mussel beds in the lower-flat. By contrast, the MTF and LTF will often contain bioturbating organisms such as Macoma and various other worm species. The burrowing action of these organisms serves to decrease the shear strength of the sediments, allowing for a greater possibility of erosion and entrainment (Widdows & Brinsley, 2002).

In addition to the opposing effect of bioturbating or reef and mat-forming organisms, there are additional hydrodynamic-biologic interactions that occur at the marsh-mudflat interface (Houwing, 2000; Kirby, 2000; Bouma, 2005; Yang et al., in press) (figure 1-3). On incoming tides in flood dominant systems, water is first transported in tidal creeks through the mudflat (Bouma, 2005). As the tide increases, the banks of the creeks overflow, and water spreads in a sheet-like manner across the mudflat (Bouma, 2005). For the majority of a flood tide, the water will flow parallel to the tidal creek. However, as the tide rises above the marsh level, some water
will flow along the marsh-mudflat interface, perpendicular to the creek flow (Bouma, 2005). There is a marked decrease in current velocity at this interface, due to the dampening effect of pioneer plants. As the current slows, fine particles drop out of the flow, allowing for further encroachment of pioneer plant species onto the mudflat (PWA, 2002; Bouma, 2005). Ebb currents at the tidal flat-marsh interface remain perpendicular to tidal creeks until the very end of ebb, resulting in reduced export of sediment from the pioneer zone (Bouma, 2005) (figure 1-4). These interactions lead to accretion on the marsh edge, and less-steep slopes in the HTF (PWA, 2002; Bouma, 2005). Given sufficiently high sediment supply and appropriate hydrodynamic energy, the mudflat will continue to accrete in step with the fringing marsh until equilibrium attained (PWA, 2002) (figure 1-5).

1.4 Morphology:

The morphologic and sediment characteristics of tidal flats have been found to be mainly driven by a few important forces – sediment supply, waves and tidal currents (Dyer, 1998; Christie et. al., 1999; Pritchard et al., 2000; Roberts et al., 2000; Whitehouse et al, 2000). The degree of forcing of each has been shown in many models and observations to determine the equilibrium profile – wherein bottom stresses are nearly uniform across the entire area - of mudflats (Friedrichs & Aubrey; Christie et. al., 1999; Le Hir et. al., 2000; Pritchard et. al., 2002; Kirby, 2000; and many others): wave driven flats are generally concave-up, or erosional, due to the transport of sediment from the upper onto the lower flat or channel; tidally driven flats have been shown to be convex-up, or accretionary, as sediment is transported further onshore on flood-tide than offshore on subsequent ebbs (Dyer, 1998; Christie, 1999).
The two end-member profile shapes favor self-maintainence - convex-upwards profiles leading to increased maximum ebb-currents that favor offshore transport, and concave-upwards profiles enhancing flood currents and onshore transport (Le Hir et al., 2000; Pritchard et al., 2002). In calm conditions, continued accretion leads to shallower waters, which increases the bed stress (Christie et al., 1999). A convex-upwards shape promotes ebb dominance and offshore sediment transport (Le Hir et al., 2000). Conversely, erosional events lead to deeper waters and lower bed stresses, coupled with increased critical shear stress as the deeper, more consolidated layers are uncovered (Christie et al., 1999), and a concave-upwards shape favors flood dominance, and onshore sediment motions (Le Hir et al., 2000).

Two numerical models of tidal flat equilibrium dynamics were created by Roberts et al (2000) and Pritchard et al (2002). Pritchard et al (2002) focused primarily on the role of a variety of sediment supply and tidal conditions. Increased sediment concentrations resulted in decreased slope and increased convexity on modeled flats (see figure 1-6). Additionally, Pritchard et al (2002) demonstrated that flood-dominant conditions favor increased accretion and convexity, especially in the upper tidal flat; ebb-dominance favors sediment export and greater concavity in overall cross-shore profile. Roberts et al (2000) examined many of the same physical forcings, but also included the presence of wind-waves into their model. This model demonstrated that increased tidal range results in steeper slopes (in tidally driven situations, morphology remains convex-upwards in these cases) (see figure 1-7). When wind-waves are added, resultant cross-shore morphologies become increasingly concave-upwards (Roberts et al., 2000)(figure 1-8).

Friedrichs and Aubrey (1996) showed that, in addition to wave and tidal forcings, tidal flat is also dependent on pre-existing shoreline conditions. Embayment of a shoreline can
increase convexity in tidally-driven situations, and reduce expected concavity in wind-driven
cases. In contrast, a lobate shoreline will have the opposite effect, reducing convexity in tidally-
driven cases and increasing concavity of wind-driven tidal flats (Friedrichs and Aubrey, 1996)
(figure 1-9).

In general, numerical models designed to predict cross-shore equilibrium shapes have
examined conditions that are always tidally driven (Pritchard, 2002) or always wind/wave driven
(Lee & Mehta, 1997; Roberts et al., 2000). While these experiments are useful, most systems
are not solely wave or tidally dominated in regards to hydrodynamics. The South San Francisco
Bay system, for example, undergoes periods of steady, strong winds (late Spring-early Fall) and
periods of less steady wind action (Fall - early Spring). Additionally, over the time period
examined in this study (100+ years), other physical forcings may have changed significantly,
such as sediment supply or tidal range. It may be necessary therefore to consider a state of
dynamic, or quasi-equilibrium, where profile morphology follows constantly changing physical
forcings (Roberts et al., 2000).

1.5 Salt Ponds Project:

The South Bay shoreline has been utilized heavily for the building of salt ponds (figure 1-
10). The first salt pond was created in 1854, and by 1960 over 50,000 acres of salt ponds existed
the South Bay. Post-leveeing, the flooded marsh areas underwent massive subsidence, in some
places up to 3 m (Williams presentation, June 2006). This was accompanied by general
subsidence due to groundwater removal (PWA, 2002). This effectively destroyed a majority –
80% of the tidal wetlands in SSFB (figure 1 - 11) (Foxgrover, 2004). In 2003, 16,500 acres of
privately held salt ponds were sold to a conglomerate of non-profit environmental and governmental organizations, the intended outcome of this sale being the conversion of salt ponds back into tidal saltmarsh (figure 1-10). The intended restoration focus areas are the Eden’s Landing, Alviso, and Ravenswood salt pond complexes, located respectively in the northeastern, southern, and western portions of SSFB.

Much of the restoration and monitoring work to date has been undertaken by Philip Williams & Associates (PWA). In 1986, PWA oversaw the breaching of a salt pond levee in the Warm Springs pond (Alviso Complex), as well as the subsequent monitoring. Since that time, the Warm Springs area has shown large scale sedimentation – filling in from roughly 15 ft below sea level to an average height of 5 ft above sea level (figure 1-12) (Williams presentation, June 2006). Another salt pond at Cooley Landing (Ravenswood) was breached in late 2000 and also monitored. It showed similar patterns of infilling. In addition, historical marsh creeks were reestablished. Similar monitoring projects are ongoing in the newly breached ponds of the Alviso Complex (e.g. Callaway et al., presentation, June 2006).
1.6 Objectives, Hypotheses and Outline

The explicit objectives of this thesis are as follows:

1. Using EOF analysis of bathymetric data, quantitatively determine the principal components variation in tidal flat morphology.

2. Characterize spatial variation in SSFB tidal flat shape within each year; relate spatial trends of morphology to spatial trends in tidal energy, wind energy, sediment grain size, tidal flat width, and recent erosion/deposition.

3. Characterize morphologic change of SSFB tidal flats between the years of the dataset; relate temporal trends of morphology to trends in tidal range, mean sea level, sediment discharge, and storminess over the last 100+ years in SSFB.

The main hypotheses being tested include:

1. SSFB tidal flat morphology varies primarily based on the convexity/concavity of cross shore profile.

2. Tidal flats within the innermost portion of SSFB exhibit the greatest amount of convexity over all yearsets; tidal flats in the outer regions of SSFB exhibit concave-upwards morphology over the same time periods.

3. Spatial trends in tidal flat morphology are consistent with patterns of wind and tide energy, as well as sediment size and recent erosion/deposition.

4. Inner/outer-estuary tidal flats have increased in convexity/concavity over the period of time studied herein.
5. Temporal trends in morphology are consistent with trends in sediment discharge, mean sea level, tidal range, and storminess.

The following two chapters are written as self-contained papers, each with an abstract, introduction, methods, results, etc. The first chapter relates the results found in analysis of the spatial variation in SSFB tidal flats using the most recent bathymetric and LIDAR data – collected in 2004-2005. The next chapter relates the results of analysis of temporal variation in SSFB tidal flats using five sets of bathymetric data collected in the 1890s, 1930s, 1950s, 1980s, and 2004-2005. Because of this format, there is some redundancy of information and figures presented.

Following chapters 2 & 3 is a discussion of the overall conclusions and relevance of this study, as well as a projection of the types of future analyses that could be performed to bolster the findings herein. Tables and figures related to this work are located at the end of this document, split into sub-headings based upon the chapter to which they relate.
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2. Spatial Trends in SSFB Tidal Flat Morphology

Spatial trends in profiles of South San Francisco (SSFB) Bay tidal flats are examined using bathymetric and LIDAR data collected in 2004 and 2005. Eigenfunction analysis reveals a dominant mode of morphologic variability related to the degree of convexity or concavity in cross shore profile – indicative of tidally dominant, sediment rich, or wave dominant, sediment poor conditions, respectively. Two opposing areas of equilibrium shape – north/south of a constriction in estuary width located at the Dumbarton Bridge – are recognized. Additionally, this pattern of increasing/decreasing convexity in the inner/outer estuary is correlated to spatial variability in fetch length, sediment grain size, recent erosion/deposition, and tidal height. Results found herein are consistent with theoretical predictions of tidal flat morphologic response to waves, tides, and sediment supply. Motivation for this work stems from modern wetland restoration efforts in SSFB that may result in an increased tidal prism and a significant sink of sediment.

2.1 Background

Response to Hydrodynamic Conditions:

Tidal flat morphology has been shown to be connected with patterns of tide height, tidal range, wind/wave forcings and sediment supply (Friedrichs & Aubrey, 1996; Kirby, 2000; Le Hir et al, 2000; Janssen-Stelder, 2000). Accretionary profile, indicative of tidally-dominated systems and/or abundant sediment supply, tend to exhibit a convex-up morphology; erosional profiles, indicative of wind/wave-dominant systems and/or sediment loss, tend to exhibit concave-up morphology. Convex-up morphology is more effective for attenuation of wave energy, habitat for fish and benthos, increased accretion, and extension of marsh and mangrove
at the upper tidal flat (Kirby, 2000). Concave-up tidal flats can lead to further erosion, loss of habitat, and an increase in wave energy along coastlines (Kirby, 2000).

Flats exposed to high tidal energy and low wind/wave energy are generally convex-upwards (Friedrichs & Aubrey, 1996; Pethick, 1996; Dyer, 1998; Christie et al, 1999; Kirby, 2000. On a single tide-scale, sediment is transported onto the flat during flood, with settling lag favoring increased suspended sediment concentrations towards the end of flood (Dyer, 1998; Christie et al, 1999). Settling and scour-lag processes cause a landward movement of sediments over multiple tides, resulting ultimately in the building of a convex-upward profile and the associated reduction in spatial gradient in peak tidal velocity (Kirby, 2000; Roberts et al, 2000; Pritchard et al, 2002). Tidal flats with high exposure to wind-driven waves are characterized by a concave-upwards profile. Wave energy simultaneously transports sediment from the regions of highest bed stress – often the middle flat into the sub-tidal regions - into the uppermost tidal flat, and, where applicable, into adjacent tidal marshes (Dyer, 1998; Kirby, 2000). Friedrichs and Aubrey (1996) further equated convex-up profiles with embayed shorelines and concave-up profiles with lobate shorelines due to spreading or focusing of incident waves and tides.

In addition to natural forcings, man made structures can affect tidal flat morphology. Defense structures such as dykes or levees can result in concavity of the upper tidal flat (Dyer, 1998), due to unnaturally high water depths and resultant wave activity (in windy cases) at high tides.

Past field observations suggest that for tidal flats to maintain a convex-upwards equilibrium, a sufficient supply of sediment is necessary (Friedrichs & Aubrey, 1996; Dyer, 1998; Kirby, 2000). A well-fed, convex-upwards, tidal flat system will prograde seaward if conditions remain stable; sediment starved tidal flats are frequently concave-upwards, and over
time the profile will move landward (Pritchard et al, 2002). It is additionally the case that sediment diameter is correlated with morphology of tidal flats (Petchick, 1996; Yang et al, in press). Generally, tidal flats exhibit a fining of sediment from the lower to upper portions. However, erosional (concave-upwards) flats are characterized by coarser sediments, as the fines are winnowed out by the higher energy currents generally present (Yang et al, in press).

Past studies have associated tidal flat width with overall energy – either from tides or waves (Dyer, 1998; Yang et al, 2006). Assuming an open-coast situation where a flat can grow indefinitely, tidal flat width may increase in order to evenly distribute increasing wave or tidal energy. Pethick (1996) found tidal flat width and morphology to be affected by location within an estuary; flats closer to the more exposed estuary mouth are generally wider and more concave-upwards, while moving landwards, towards the more sheltered interior, brings about a decrease in width and an increase in convexity.

**Geographic/Sedimentary Environment:**

The South San Francisco Bay (SSFB) (Figure 2-2) is a meso-tidal, mixed tide system with semidiurnal tides ranging up to 2.5 meters, and is characterized by a long flood, short ebb, short flood, and another short ebb (Pestrong, 1972). Due to a contraction in estuary width and reflection of tidal wave at the inner end, tidal range increases substantially from the Golden Gate (~1.2 m) to the southern head of SSFB (~2.5 m); tidal range on the western shore is slightly larger, due to Coriolis (Disney & Overshiner, 1925). Over the last ~150 years there has been a steady upward trend in mean sea level (145 mm/century since 1855) as well as an increase in diurnal (MHHW-MLLW) and mean (MHW-MLW) tidal range (64 and 60 mm/century, respectively) (Flick et al, 2002).
Pestrong (1972) examined sedimentation on the tidal flats of SSFB at Cooley Landing and determined that: (1) sediment is preferably moved across the entire tidal flat on flood tides, with the highest transport rates occurring at the marsh edge and in tidal channels; (2) significant accretion occurs at the tidal flat/marsh interface when the flood tide has inundated the mudflat and as the ebb tide drains the marsh, resulting in an extension of the marsh front; (3) sediments eroded from the flat on flood tide are deposited in the adjacent marsh; (4) salt marsh/mudflat equilibrium is attained when the flood-flow sedimentation rates are reduced due to a decreased tidal prism; (5) fine sediments are sequestered in the higher flats due to settling and scour lag.

Sediment in SSFB is derived from two sources: (1) transported from the Sacramento-San Joaquin Basin (the Inland Delta) after passing through the northern and central Bay, or (2) brought in from the many smaller tributaries that directly fringe SSFB. The Inland Delta is the commonly, though not universally, accepted source for the majority of sediment influx into SSFB, as the local tributaries are thought not to have the discharge necessary to contribute a substantial portion, except during very wet winters (Conomos, 1979; Krone, 1979; Porterfield, 1980; Schoellhamer, 1996; Wright & Schoellhamer, 2002; PWA 2002; Jaffe & Foxgrover, 2006 Mckee et al, 2006).

Regardless of their source, suspended sediments are advected into SSFB in small quantities, and in the deeper channels. Resuspension by tidal currents and wind-wave action then moves the sediments up onto tidal flats and marshes (or from the tidal zones back into the channel), where they are sometimes deposited, depending on tidal stage, wave conditions, and other such hydrodynamic factors (Krone, 1979; Conomos, 1979; PWA, 2005; Schoellhamer et al, 2005).
Foxgrover (2004) showed that SSFB has undergone a net sediment loss from 1858 to 1983. While the loss was not a steady process over the studied period, the system has been erosional since 1956. This loss of sediment was accompanied by a large loss in tidal flat area in all areas except for the aforementioned outer SSFB. In contrast, the innermost portion of SSFB - the area beneath the Dumbarton Bridge - has seen a slight, steady, increase in sediment volume over the entire time period studied (Foxgrover et al., 2004). This increased sediment volume in the innermost portion of the estuary contradicts the assertion of Krone (1979) that SSFB was entirely erosional from 1897 to 1950.

2.2 Methods:

Using the combination of bathymetric sounding and LIDAR data gathered in 2005 and digitized by Foxgrover et al., multiple cross sections were drawn with an ARCMAP platform (figure 2-3). Spaced at roughly 50 m intervals, the profiles were drawn in order to remain largely normal both to shore and the predominate contours. Profiles range in length from 120 to 3100 meters in length; this length is not necessarily indicative of the tidal flat width, as lines were drawn to well exceed the intertidal zone.

Once all transects were drawn, horizontal and vertical information was extracted and normalized. In order to perform an eigenfunction analysis, each line was normalized to the same number of horizontal points. The normalization procedure involved replotting the horizontal extent of each profile onto a series of 30 unit-less horizontal points and then performing a spline interpolation that fit a piecewise polynomial function to the vertical data (figure 2-4).
Additionally in this process, profiles were bound at predetermined upper and lower vertical values.

In order to evaluate the morphologic character of the profile lines, four sets of boundaries were individually extracted: (1) between MHW and MLLW; (2) between MHW and 0.5 m below MLLW; (3) between 1.7 m above and 0.5 m below MLLW; and (4) between MHW and 1 m below MLLW. The first set of boundaries represents what is classically considered to be a tidal flat; two sets of boundaries below MLLW were also extracted in order to examine the effect of including the near subtidal areas; the standardized upper limit of 1.7 m (representing the mean max vertical datum of all profiles) was tested for use in the larger temporal study (see chapter 3), as none of the other yearsets besides 2005, which includes both bathymetric and LIDAR data, have bathymetric data that extend all the way to MHW.

In the case that the available bathymetric data for a given profile did not extend all the way to 1.7m or MHW, the profile was extrapolated upwards to the desired higher boundary. Any profile with an upper edge less than 1.0 meters above MLLW was discarded, as the interpolation tended to assign unrealistic upper slopes in such cases. Figure 2-4 shows an example of a mudflat profile in its pre and post-normalization forms.

To identify the principal components of variation, an eigenfunction analysis, also known as empirical orthogonal function (EOF) analysis, was performed. EOF analysis allows for large quantities of data to be compressed into a few dominant modes, without compromising the most significant variability within the data. Since the components of variability identified through EOF analysis are orthogonal, they are uncorrelated, and can be examined individually.

Of great use in spatial analysis is the pattern of scores that pertain to the individual eigenfunctions, or modes of variability. EOF analysis has been used in the examination of
morphologic variability of beach profiles (Winant et al., 1975; Aubrey, 1980) estuaries (Karnunathna et al, 2007), and mudflats (Yamada, 2004; Yamada et al., 2006), among other environments. When compared to variation in other physical factors, the spatial patterns of the scores can suggest connections between morphology and external forcing. In the case of this EOF analysis, the profile set was de-meaned in order that that first eigenfunction would identify variability among profiles rather than the shape of the mean profile (under normal circumstances, the primary mode of variability would represent the mean profile).

The 744 profiles were broken up into twelve distinct geographic sections, using such features as tributary mouths and steep intertidal zones wherein no tidal flat was evident (figure 2-3). In order to ensure that the boundaries of regions by which the profiles were separated were rigorous in the face of analysis, the individual regions were plotted against a running cumulative sum of the eigenfunction scores. For the most part, the regions showed consistent patterns of morphologic score, and the boundaries were found to be justifiable. In the few cases where the pattern of cumulative scores reversed directions mid-region, the lines were re-assigned to what was deemed a more morphologically distinct region.

Fetch lengths were acquired from the GIS database by drawing 100 sets of 16 lines, beginning at 0° and progressing in direction by 22.5° to create a compass rose-type of design. Fetch lengths for each of the 16 lines were logged for all 100 sets, and the mean and median lengths were calculated. Tidal range data was obtained from NOAA (2008) at all available stations, and interpolated for profile regions that fell in between the locations of known tidal data.

Sediment data was collected from the surface layers and from depth in the fall of 2004 and summer of 2005 by scientists from USGS Santa Cruz using bottom grab methods (Jaffe,
personal comm.). Samples were collected from the channel edge to as close to shore as possible. The sediments were analyzed for bulk density as well as the Folk and Ward mean grain size.

Although the 2005 data set is the focus of this paper, elevations for these same profiles were gathered from ARCMAP for the 1980s, 1950s, 1930s, and 1890s as part of our broader analysis. By comparing profile elevations from the 1980’s and 2005, we were able to estimate changes in elevation proceeding the 2005 survey.

2.3 Results:

Comparison of Boundaries:

Eigenfunction analysis was performed on four sets of normalized bathymetric data, each with slightly different upper and lower tidal flat boundaries, 2958 bathymetric profiles in all. It was found through this analysis that the profiles vary most intensely in terms of their degree of concavity/convexity, represented by a negative/positive first eigenfunction (figure 2- 5a). Figure 2- 6a shows the primary mode of variation – referred to here as morphologic score - of that variation averaged by region for all four boundary scenarios. While the primary pattern – that of concavity/convexity in the outer/inner-estuary flats - remains the same in all scenarios, the values of the scores in each situation varies. Concavity increases (and the scores become more negative) if area is added onto the lower tidal flat, while convexity increases (and the scores become more positive) if area added to the upper flat. The analysis using the boundaries of MHW to MLLW shows the highest scores (greatest convexity) across the board, while the analysis of the flats bound by MHW and 1 meter below MLLW are more concave, especially in the outer regions of the study.
In the interest of capturing as full a picture of the profile as possible, while simultaneously not straying too far from the classic definition of an “intertidal” flat, the rest of this paper highlights results using the tidal flat extent from MHW to 0.5m below MLLW water. See discussion section for further justification. Figures 5b and 6b display the most energetic eigenfunctions and regionally averaged mode 1 scores when the MHW to -0.5 m data set is analyzed alone rather than being combined with all four sets of bathymetry. As can be seen from comparing parts a and b of figures 5 and 6, there is relatively little difference in the shape of the dominant modes or the associated scores for the MHW to -0.5 m data whether the data set is considered alone or is considered together with the other sets of bathymetry. However, limiting the analysis to a single set of bathymetric endpoints notably increases the percent of variance explained by the dominant mode of variability.

**Eigenfunction/Regression Results**

The eigenfunction analysis showed there to be two major modes of variability (eigenfunctions). When considering the MHW to -0.5 m data set alone, the first mode explained 90% of the entire variability, and is indicative of a switch between convex and concave-upwards morphology. Figure 2-7 shows the response of the mean tidal flat shape along with the average cases with positive and negative first component scores, respectively. As is clearly shown by Figure 2-7, the positive response is a strongly convex-upwards profile, while the negative response is a strongly concave-upwards profile.

All the first-model scores for the 766 individual profiles (for the MHW to -0.5 m case) are shown in figure 2-8a, with the profiles increasing in number from the northwestern to northeastern ends of SSFB. There is a trend of negative score – concave upward morphology – in both the far northwestern and far northeastern portions of the bay shore, while the
southernmost profiles exhibit strongly positive – convex-upward – scores. Smoothing the scores using a 10 point moving average helps to make these trends more clear (figure 2-8b). Referring to the profile numbers on the location map (figure 2-3), it is evident that the switch from negative to positive and then back again occurs at the “pinch” that occurs at the Dumbarton Bridge in the inner SSFB.

In order to examine the relation between physical factors and patterns of morphologic variation, the scores were averaged across the regions displayed in figure 2-3, as were the fetch, sediment size, elevation change, and tide height data. A comparison of each physical factor and average eigenfunction score can be seen in figures 9a-e.

The strongest relationship between the spatial trend in the first-model score and the potential forcing variables (r-squared = 0.85) was found for changes in elevation preceding the 2005 bathymetric survey. In regions where erosion/elevation loss was documented, profiles tended to be concave-upwards; in accretionary regions, they tended to be convex-upwards. There was also a strongly positive relationship (r-squared = 0.71) between tide height (MHW) and morphologic mode value; areas with higher tidal range are characterized by convex-upwards profiles. A negative relationship (r-squared = 0.60) was found to exist between fetch length (used as a proxy for wind/wave energy) and morphologic mode score.

Less strong were the negative relationships between morphologic mode score and flat width (r-squared = 0.33) and mean sediment size (r-squared = 0.39). Sediment data is missing from the two innermost regions of SSFB (regions 7 & 8), which lowers what qualitatively looks to be a potentially strong connection between decreased sediment diameter and increased convexity.
After the individual regressions were run on each of the six physical factors separately, a multiple linearly regression was performed including all of the factors at once (except for sediment size, which was not available for all twelve regions). Those components with best-fit slopes less than their associated standard errors were then removed one at a time, that with the lowest ratio was removed first. In the end, three components remained with important contributions to the multiple regression: fetch, elevation change, and tide height. The results of the final multiple regression are seen in table 2-1 and figure 2-10. A net r-squared value of 0.89 was obtained from this multiple regression, and the modeled scores are qualitatively similar to the observed results.

2.4 Discussion/Conclusions:

Although judging morphologic trends based upon historic data and morphodynamic model output has provided qualitatively consistent trends in the past (REFS), the use of EOF analysis also allows for objective investigation into the major modes of variability found within large bathymetric datasets. In the case of the bathymetric information presented here, access to such a large and well organized dataset allows for the systematic morphologic assessment to be qualitatively rigorous and thorough.

Eigenfunction analysis of the various tidal flat boundary scenarios considered provided predictable results. As more of the lower tidal flat and subtidal area was added into the analysis, the resultant morphology showed greater concavity – as in the profiles bound by MHW and 1m below MLLW. Similarly, greater emphasis on the upper profile led to greater convexity – as in those profiles bound by MHW and MLLW. These findings agree with those in Kirby (2000),
wherein convexity increases with amount of flat found above mean tidal level (MTL). Expanding the boundaries over the scenarios considered here effectively increased or decreased the height of MTL.

While the traditional definition of tidal flat extends from MLLW to MHW (or less, depending on elevation of pioneer zone), we believe the morphologic activity of the near-subtidal to be an important aspect of the SSFB system. We therefore chose to use the boundary scenario of MHW to 0.5m below MLLW as our normalizing parameter. Extending the lower tidal flat allows for a greater range of morphologic information to be gleaned from the digitized bathymetric data, and presents a more complete picture of the morphologic behavior present therein.

**Regression:**

The strong consistency between morphologic scores and elevation change is supported by frequent mentions in available literature of the connection between erosion/deposition and concave/convex upwards tidal flat profile (Friedrichs & Aubrey, 1996; Kirby, 2000; Le Hir et al, 2000; Pritchard et al, 2002; etc). Similarly, the relationships seen here between tidal height/fetch length and profile morphology falls within the theoretical (Friedrichs & Aubrey, 2000), analytical (Roberts et al. 2000, Pritchard et al. 2002) and empirical (Christie et al., 1999, Dyer et al., 2000) understanding of tidal flat morphodynamics. The connection between fetch length, as a proxy for wave height, and morphology may be less well represented in our results, as the average fetch lengths calculated for the innermost portions of the estuary – those beneath the Dumbarton pinch – are unrealistically high, when compared with anecdotal observations of wave height, thus skewing the results. Fetch length, although only one of three (fetch, wind speed, wind direction) variables used in modeling wave heights, it has been used solely as a proxy for
winds in past studies (Ryan & Noble, 1998). Assuming that the observed profile shapes are near a dynamic equilibrium, confirmation of these relationships allows for better informed predictions about future elevation behavior of SSFB tidal flats, given either similar physical conditions or a changing physical regime caused by rising sea levels, increased winds, etc.

The literature suggests that profile width is affected by the total hydrodynamic energy to which a tidal flat is subjected (Pethick, 1996; Dyer, 2000; Yang et al., 2006). The weak correlation seen here between width and morphology could be due therefore to an the confounding inverse relationship in SSFB between tidal range and exposure to waves. In the case of SSFB, tidal flat width is also limited by geographic conditions, and flat width therefore may not be a reliable metric by which to gauge spatial hydrodynamic variability. Within the limited context of the widest northeastern tidal flats, however, changing flat width may prove to be a useful variable when examining morphologic change over time.

As also shown in Foxgrover et al., 2004 there has recently been net accretion in the innermost estuarine portions of the SSFB estuary, with erosion on both mid-estuary shores. This is consistent with the morphologic patterns found in this follow-on study. To explain the resulting tidal flat morphology by looking at only one physical factor, however, would neglect the larger picture. The areas of accretion – those regions south of the Dumbarton bridge pinch – are subject to a notable confluence of multiple converging positive forcings: sediment motion in SSFB is southward overall, eventually converging in these regions; additionally, the innermost areas are most protected from wind-waves due to the limited fetch, and they are also subject to the strongest tidal range in SSFB. One could look at these conditions without knowing any bathymetric information, and one might expect this region to contain the most strongly convex profiles. A companion study associated with this analysis focuses on temporal patterns of tidal
flat morphology (Bearman et al, 2008). Assuming patterns of forcings favoring tidally driven deposition in the inner estuary and wave-driven erosion in the outer estuary remained relatively consistent throughout the time period of available data, one might expect an increase in tidal flat concavity in the mid and outer estuary, and an increase in convexity in the inner SSFB.
Figure 2 - 1: Theoretical Response of Tidal Flat Morphology to a variety of forcings (adapted from Dyer, 1998).
Figure 2: From Foxgrover et al, 2004, South San Francisco Bay, including areas of projected salt pond restoration
Figure 2 - 3: Cross-shore profiles drawn in ARCMAP. Of the 800+ originally drawn, 766 were used for the spatial analysis.
Figure 2 - 4: Example of the normalization process. Profiles are regridded onto a unitless scale of 30 points. It is necessary for EOF analysis that all profiles have equal x-axes.
Figure 2 - 5: (a) Modes of morphologic variability determined through EOF analysis of all boundary scenarios; (b) modes of morphologic variability determined through EOF analysis of tidal flats bound by MHW on upper edge and -0.5 m on lower edge.
Figure 2 - 6: (a) Regionally averaged scores of first eigenfunction for each boundary scenario; (b) regionally averaged scores of first eigenfunction.
Figure 2 - 7: Mean morphologies of SSFB tidal flat cross-shore profiles. Pictured here are the overall mean profile shape, mean shape of all positively-weighted (convex-upwards) profiles, and mean shape of all negatively-weighted (concave-upwards) profiles.
Figure 2 - 8: Spatial trend in first morphologic mode - (a) all profile scores; (b) smoothed with 10 point moving average. Positive/negative score indicates convexity/concavity. Dotted vertical lines represent region borders, profiles within solid vertical lines are inner-estuary flats, south of the Dumbarton “pinch.”
Figure 2 - 9: (a-e) Comparison of regionally-averaged first eigenfunction (signifying convexity/concavity) to physical forcings.
<table>
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<th>$r^2$ in individual regression</th>
<th>Importance in Multiple Regression?</th>
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<td>Increased Sediment Diameter</td>
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</tbody>
</table>

**Table 2 - 1**: Results of individual and multiple regression analyses.
3. Temporal Trends in SSFB Tidal Flat Shape

Temporal trends in morphology of South San Francisco Bay (SSFB) tidal flats are examined using five sets of bathymetric and LIDAR data collected in the 1890s, 1930s, 1950s, 1980s, and 2005. Motivation for this research stems from a desire to better understand baseline tidal flat behavior in the face of impending restoration efforts that will alter tidal prism and sediment dynamics in SSFB. Eigenfunction analysis reveals a dominant mode of morphologic variability related to the degree of convexity or concavity in cross-shore profile – indicative of tidally driven, sediment rich or wave driven, sediment starved conditions, respectively. Spatial trends among individual yearsets are generally similar to those established for the most recent data in chapter 2; SSFB tidal flats can be broken into two main varieties – predominately concave-upwards, erosional profiles in the outer estuary, and convex-upwards, accretionary profiles in the inner-estuary. Additionally, temporal changes in the degree of concavity or convexity in twelve geographically distinct regions through time are compared to long term trends in Central Valley sediment discharge, local rainfall, diurnal tidal range, tidal flat deposition/erosion, rainfall averages, and Pacific Decadal Oscillation Index (as a proxy for storminess). Linear and stepwise multiple regression, performed on all physical forcings, allowed for exclusion of all but three important variables: sediment input from the Central Valley – most important in outer estuary regions; sediment input from local sources – most important in inner estuary regions; and localized deposition or erosion – most important in the central to inner estuary. Over decadal time-scales, it appears that local and Regional changes in sediment supply, rather than changes in hydrodynamics, have been most responsible for observed changes in tidal flat morphology.

3.1 Introduction:

Response to Hydrodynamic Conditions:

A detailed examination of the history and understanding of physical drivers is presented in Chapter 2. In short, end-member tidal flat profile shapes manifest two dominant morphologies (Figure 3-1): concave-upwards morphologies are indicative of erosional, sediment-starved environments with higher wave energy conditions; convex-upwards morphologies are indicative of accretionary, sediment rich environments with lower wave and higher tidal energy (Friedrichs & Aubrey, 1996; Christie et al., 1999; Kirby, 2000; O’Brien et al., 2000; etc). Overall energy,
whether from wind or waves, has been shown to be linked to overall tidal flat width in open coast conditions (Masselink et al., 1993; Dyer, 1998)). Sediment size is also correlated to morphology – coarser sediments being a sign of increased erosion (Yang et al., in press).

Time Scale of Morphologic Change:

Tidal flats are subject to morphodynamic forcings on time scales ranging from a single wind event or smaller to multi-year. On the scale of a single tidal cycle, there can be daily accretion and erosion associated with the flood/ebb cycle (Christie et al., 1999; Janssen-Stelder, 2000). Erosion tends to occur on the front edge of the flood tide as high currents encounter loosely consolidated sediments deposited during the preceding slack tide. (Christie et al., 1999; Janssen-Stelder, 2000). This is often followed by a period of deposition that extends from the end of flood through slack high water. Erosion associated with ebb tide typically results in a removal of a portion of what was deposited on the flood. However, even in ebb-dominant cases, tidally driven sediment exchange can result in net accretion onto the tidal flat, as velocities in tidal flats are generally less than those seen in adjacent channels (Christie et al., 1999; Dyer et al., 2000; Janssen-Stelder, 2000). This activity in calm conditions leads to a convex-upwards profile.

In contrast, activity during a tidal cycle characterized by high wind and waves brings about very different morphologic results. During flood tide, sediment eroded from the top layers by wave activity is advected shoreward, similar to calm conditions; however, settling is inhibited by larger amounts of turbulence (Christie et al., 1999; Dyer, 2000; Kirby, 2000). Slack water allows for some settling, but these sediments are more likely to be resuspended during ebb. Ultimately the sediments eroded by superimposed waves and tides end up advected offshore.
(Christie et al., 1999). In areas where there is a high frequency of significant wind and wave events, this will eventually lead to concave-upwards morphology.

Beyond the daily response to flood/ebb variations in suspended sediment concentration and current velocity/direction, there is further tidal flat response on a spring/neap time scale. During spring tides, maximum sediment concentration is more likely to occur during peak flood and ebb currents, whereas on neap tides the maximum concentration is generally at the very beginning and end of inundation (O’Brien et al., 2000). Additionally, spring flood tides transport greater quantities of sediment to the upper tidal flat, areas that are frequently exposed and prone to increased consolidation and drying (Pritchard et al., 2002).

On an annual timescale, morphologic response of temperate tidal flats is controlled by seasonal variations in wind direction and intensity, as well as sediment load (O’Brien et al., 2000; Christiansen et al., 2006). Summer and fall are characterized in many locations by calm conditions, leading to accretion, as described above. Winter and spring are characterized by stronger winds, and therefore result in erosional patterns associated with wave-dominated profiles. Spring, however, is accompanied by an increase in SSC that facilitates deposition across the entire mudflat (O’Brien et al., 2000; Christiansen et al., 2006).

Mudflat profiles have been found in models to take from 1000 tides (~3 years) to 60 years to attain equilibrium shape (Roberts et al., 2000; Pritchard, 2002; Waeles, 2004). There is scant observational analysis that examines tidal flat morphologic change on a time scale longer than a few years, much less multi-decadal. We assume here that the same forcings important in a yearly scale - frequency and strength of wind/waves events, changes in the tidal range, sediment supply - are also relevant on a multi-year scale. With time scales of the length represented in this study - ~100yrs – the need for records of wind, storms, sediment supply, and tidal range
becomes very important, while information on the tidal, spring/neap, or even yearly time scale becomes less useful in the gleaning of decadal patterns.

**Geographic/Sedimentary Environment:**

The South San Francisco Bay (SSFB) (Figure 3-2) is a meso-tidal system with semidiurnal tides ranging up to 2.5 meters, and is characterized by a long flood, short ebb, short flood, and another short ebb (Pestrong, 1972). Due to a contraction in channel width and an extensive tidal flat system, tidal range increases substantially from the Golden Gate (~1.2 m) to the southern head of SSFB (~2.5 m); tidal range on the western shore is slightly larger, due to Coriolis (Disney & Overshiner, 1925). Over the last ~150 years there has been a steady upward trend in mean sea level (145 mm/century since 1855) as well as increases in diurnal (MHHW-MLLW) and mean (MHW-MLW) tidal range (64 and 60 mm/century, respectively) (Flick et al., 2002).

The majority of suspended sediments transported into SSFB are brought in during very high discharge events in the Inland Delta, generally in late winter (Krone, 1979). Recent studies have reevaluated the ratio of sediments derived from the larger fluvial systems to those derived from local tributaries. McKee et al. (2006) report that 57% of sediments entering San Francisco Bay are Central Valley-derived, less than the 76% found previously by Krone (1979). Additionally, there is an anticipated trend towards lower ratios as total sediment discharge from the Central Valley continues to decline – nearly 50% in the last 50 years - due to water diversion projects and other yet to be determined factors. (Krone, 1979; Wright & Schoellhamer, 2004; McKee et al., 2006). Recent examinations of sediment load from local tributaries – particularly the Guadalupe River – have documented a large decrease in sediment loads from the early
1960’s to the present (Schoellhamer, personal communication 2008) suggesting published relationships between streamflow and sediment load (Porterfield, 1980) are overestimated. This calls into question the assertion by McKee et al (2006) that the percentage of Central Valley-derived sediments is lower than once thought, as an unchanging sediment load from local tributaries was one of the primary assumptions that led to this finding.

The loss of sediment was accompanied by a large loss in tidal flat area occurred in all areas except for the inner SSFB. In contrast, the innermost portion of SSFB - the area beyond the Dumbarton Bridge - has seen a slight, steady, increase in sediment volume over the entire time period studied (Foxgrover et al., 2004). Since the end of hydraulic mining in the 1880’s, most human induced change in the region has resulted in a decrease in sediment load, in contrast to the massive increase associated with the mining. Of the 2000 km$^3$ of tidal marsh that historically fringed the San Francisco Bay, only 125 km$^3$ remained as of the mid 1980’s (Nichols, 1986). In SSFB, the amount of marshland decreased roughly 80% from the 1850s to 1980’s surveys (Foxgrover, 2004). Most of this loss was due to diking and reclamation for the purposes of agriculture, salt pond formation, and suburban development in later years. This loss of marshland was accompanied by a loss in tidal flats, the area of which has decreased 40% (from 92 km$^2$ to 58 km$^2$) in SSFB since the 1850’s (Foxgrover, 2004).

While marsh loss can be attributed to urban, agricultural, and industrial (i.e. salt pond) reclamation, tidal flat loss is less easily linked to specific events. Changes in sediment supply, frequency and nature of storm events and wind patterns, reduced tidal prism as a result of salt pond levees: there are many possible forcing factors. With impending marsh restoration, establishing a baseline for “normal” tidal flat behavior will allow for a more complete
understanding of the effects of an instantaneous increase in tidal prism and the increased sediment sinks associated with restored marshes.

3.2 Methods:

The bathymetric data analyzed in this research were collected in five USGS surveys taken from 1898 to 2005 and initially presented by Foxgrover (2004). Included in the 2005 dataset is LIDAR data containing bathymetry and topography for the upper intertidal and shoreline; this area is absent from the earlier datasets due to the constraints of bathymetric surveying. Bathymetric and, in the case of the most recent data, topographic information was manually digitized from the original hydrographic and topographic sheets collected by the USGS. Depth and shore contours were added as separate layers, as were marsh and tidal flat data. These data were gridded using a 50m cell-size, with the exception of the 2005 data, which has a horizontal resolution of 25m. For a more in-depth discussion of the methods used in the compilation and digitizing process, as well as results from broad analysis of sediment volume and bathymetric change, see Foxgrover et. al. (2004, 2005).

Using the combination of bathymetric sounding and LIDAR data gathered in 2005 and digitized by Foxgrover et al., ~800 cross sections were drawn with an ARCMAP platform. Of the original ~800 profiles, 654 crossed flats that were well resolved in all five surveys. Next, the 654 profiles were broken up into twelve distinct geographic sections, using for boundaries such features as tributary mouths and steep intertidal zones wherein no tidal flat was evident (Figure 3-3). Spaced at roughly 50 m intervals, the profiles were oriented in order to remain reasonably normal to both the shore and the predominate bathymetric contours. Profiles range in length
from 120 to 3100 meters in length; but this length is not necessarily indicative of the tidal flat width, as lines were drawn to well exceed the intertidal zone.

Normalization and Eigenfunction Analysis

To identify the principal components of variation, an eigenfunction analysis, also known as empirical orthogonal function (EOF) analysis, was performed. EOF analysis allows for large quantities of data to be compressed into a few dominant modes, without compromising the most significant variability within the data. Since the components of variability identified through EOF analysis are orthogonal, they are uncorrelated, and can be examined individually.

Of great use in spatial and temporal analysis of morphology is the pattern of scores that pertain to the individual eigenfunctions, or modes of variability. EOF analysis has been used in the examination of morphologic variability of beach profiles (Winant et al., 1975; Aubrey, 1980) estuaries (Kurnanathna et al., 2007), and mudflats (Yamada & Kobayashi, 2004), among other environments. When compared to variation in other physical factors, the spatial and temporal patterns of the scores can suggest connections between morphology and external forcing. In the case of this EOF analysis, the profile set was demeaned in order that the first eigenfunction would identify variability among profiles rather than the shape of the mean profile.

In order to perform an eigenfunction analysis, each line must be normalized to the same number of horizontal points. The normalization procedure performed a spline interpolation function that fitted a piecewise polynomial function to each line, replotting it onto a series of 30 unitless horizontal points. This normalization process also bound the profile at high and low points: 1.7 and -0.5 meters relative to MLLW. The higher boundary represents an average of the highest points of actual data found in all 3600 profiles; the lower boundary extends 0.5
meters beyond MLLW in order to include a representative portion of the subtidal morphologic data. In the case that the profile did not extend up to 1.7 meters, the profile was extrapolated upwards to the higher boundary. For an in-depth justification of these boundaries, see Chapter two of this thesis, focusing on spatial trends. Any profile with an upper edge less than 1.3 meters was discarded, as the interpolation tended to assign unrealistic upper slopes in such cases. Figure 3-4 is an example of a mudflat profile in its pre and post-normalization forms.

Normalized profiles, 3215 in all (643 from each yearset), were analyzed using EOF analysis, allowing for compression of a large quantity of data without compromising significant variability. For the temporal analysis performed in this leg of the study, all five yearsets were run simultaneously to ensure that scores would be relevant both within a single yearset and across all yearsets. After the EOF analysis, yearsets were split apart and examined individually for spatial trends in scores of the dominant modes of variability – eigenfunctions, the scores of which represent strength of variability for an individual profile.

Other Variables

Results from Chapter 2 suggest that spatial variations in tidal range, wind-waves (as approximated by fetch lengths), and sediment supply (as represented by recent deposition or erosion) all contribute to spatial variation in tidal flat morphology around SSFB. To examine possible controls on temporal variations in flat morphology, we likewise looked at time-series at variables potentially related to sediment supply, tidal range, and wind-waves.

A time series of decadally averaged sediment discharge data from the Central Valley (Figure 3-5a) was taken from the work of Ganju et al. (2007) wherein discharge data from the San Joaquin and Sacramento river were hind-casted using rainfall data and sediment rating
curves. MHHW and MLLW values for the years 1900 to 2005 at the Golden Gate, Presidio station, were acquired from NOAA Tides and Currents (NOAA, 2008) in order to calculate changes in diurnal tidal range (Figure 3-5b). As a proxy for estuary-wide storminess, Pacific Decadal Oscillation (PDO) Index values were acquired from a dataset compiled and calculated by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO, 2008) (fig 3-5c). As a proxy for local sediment discharge into the inner SSFB, National Weather Service rainfall data for San Jose (Figure 3-5d) were acquired from the Western Disaster Center’s San Jose Climate site (WDC, 2008). Finally, deposition/erosion values were calculated by subtracting pre-normalized elevation data for each profile for each yearset from the yearset proceeding – i.e. the 1890s from the 1930s, etc.

3.3 Results:

Eigenfunction Analysis Results

Eigenfunction analysis of the entire temporal dataset showed there to be a single dominant eigenfunction, or component of variation, explaining 76% of morphologic change. The dominant eigenfunction captures the convexity or concavity of the overall tidal flat profile, with a positive/negative score indicating convexity/concavity (Figure 3-6a). Examination of the pattern of scores within yearsets (Figure 3-7a) reveals that spatial variation from year to year is relatively similar, and generally mirrors the results found in the in-depth spatial analysis of the 2005 bathymetry (see Chapter 2). Outer regions - those to the north of the Dumbarton Bridge “pinch” - exhibit a more concave-upward morphology, while those in the inner regions of the estuary, south of the “pinch”, trend towards convex-upward morphology.
An examination of the changes in morphologic scores of individual regions across the five yearsets reveals several discernible but somewhat inconsistent trends. Figure 3-7b shows the average score for each region across all years. The outer Regions – 1 through 4, 11 and 12 – exhibit a steady decrease in morphologic score across the time period. Regions beyond the Dumbarton pinch do not exhibit as clear a pattern. The morphologic score for Region 5, for example, fluctuates through time with no single trend evident: beginning at its highest score in 1898, it drops in 1931, rises in 1956, drops to its lowest mark in 1983 and then rises again in 2005. Tendencies in the average scores for the rest of the inner-estuary regions are somewhat more consistent than those in Region 5, with the 2005 bathymetric year always exhibiting the highest morphologic scores. With the exception of Region 8, scores for 1983 are the lowest across this set of regions.

Comparison to Physical Forcings

The patterns of morphologic score by region were compared to Central Valley sediment discharge decadal averages (from Ganju et al., 2008). Theoretical understanding of tidal flat morphology asserts that increased/decreased sediment loads translate into increased convexity/concavity of profile. Regions located down-estuary from the Dumbarton Bridge (Regions 1-4 and 11-12) are strongly and positively correlated with these sediment trends, those profiles up-estuary from the bridge are generally not (Figure 3-8). Diurnal tidal range (calculated from the Presidio gauge - #9414290 - near the Golden Gate (NOAA, 2008)) in San Francisco Bay has, with fluctuations, increased over the period examined herein. When averaged for ten years preceding each bathymetric survey, there is an increasing trend that, when compared with Regional patterns of morphologic score, shows a negative correlation with the
flats in the outer portions of SSFB (Figure 3-9). This is opposite to expectations, in that changes in tidal range have been found to correlate positively with convexity in profile shape. As with the sediment trend, a clear correlation is not generally found with the inner tidal flat regions.

The Pacific Decadal Oscillation (PDO) index has been shown to correlate with storminess in San Francisco Bay (Bromirski et al., 2003). A negative/positive value of PDO corresponds to decreased/increased storminess. Increased storminess is expected to be negatively correlated to tidal flat convexity. When averaged for ten years prior to each survey and compared to Regional patterns in morphologic score, no clear negative correlation is evident among any of the tidal flat regions (Figure 3-10). When trends in San Jose rainfall (as a proxy for inner-estuary sediment discharge) are compared to morphologic score by region, however (Figure 3-11), there is qualitative consistency in several of the inner-estuary sites, most notably in Regions 7 and 8. Recent deposition and erosion, expected to be positively correlated to convexity, also reveals qualitative consistency with temporal variability in profile shape, most clearly in Regions 6 and 10.

As a first step toward more formally identifying casual relationships between morphological change and the above described time-series, least-squares linear regressions were performed between each pair of time-series displayed in Figures 3-8 through 3-12. Table 3-1 displays the ratio of the best-fit slope determined by each of these regressions relative to the standard-error of the estimate. As a minimal requirement for further consideration of a given forcing, we require that it be associated with at least one case in Table 3-1 for which the magnitude of this ratio is greater than one and the sign of the ratio agrees with the theoretical causal relationship. The cases satisfying these two criteria are highlighted in Table 3-1.
Based on our slope/standard-error criteria, there are six potentially meaningful cases associated with Central Valley sediments, five of which are in the outer estuary. This supports the tentative conclusion that decreasing Central Valley sediment discharge has enhanced the degree of concavity among most of the outer flat regions. There are two cases that satisfy this cut-off with regards to San Jose rains, namely the two inner-most regions.

With regards to PDO, two cases have ratios with magnitudes greater than one (one in the inner estuary and one in the outer estuary). However, both of these ratios are of the wrong sign. Since PDO is positively correlated with storminess (i.e., more energetic winds and waves), the theoretical correlation with our time-series of scores should be negative. Thus with no cases satisfying our criteria, we discount the PDO time-series from further causal consideration.

The tidal range time-series exhibits six cases with ratios of magnitude greater than one, corresponding to the same regions most correlated to Central Valley sediment supply. However, the observed negative correlations are opposite to the theoretical correlation to our scores. As found through spatial correlations in Chapter 2, tidal range is expected to be positively correlated to profile convexity. Thus we also discount temporal changes in tidal range from further causal consideration.

Finally, recent deposition/erosion is positively correlated with the time-series in all 12 regions, consistent with the theoretical relationship and with the results of Chapter 2. Eight of these cases have ratios greater than 1, five in the inner estuary and three in the outer estuary (Note that deposition/erosion for the 1890’s is actually the bathymetric change between then and the next survey). Another way to demonstrate the importance of recent deposition/erosion through time is to plot scores for each yearset against the deposition/erosion that has occurred since the previous survey (Figure 3-14). It appears that profile shape is continually responding to
short-term changes in sediment supply. This relationship becomes stronger through time, presumably because of progressively improving reliability of bathymetric information.

After narrowing the field of physical forcings that meet our criteria of dependence to Central Valley sediment discharge, San Jose rainfall, and recent deposition/erosion, a stepwise multiple regression, as described in Wunsch (1996), was performed using all three variables. The criteria for keeping contributions to the multiple regression was, once more, that the magnitude of each best-fit slope exceed its associated standard error. The numerical results of this analysis are seen in Table 3-2, and modeled examples are displayed in Figure 3-13. Central Valley sediment discharge was most important to profile variability in the outer regions of SSFB, while San Jose rainfall and recent deposition/erosion both proved most important in the innermost regions. Recent deposition/erosion was most important in the central to inner-estuary.

3.4 Discussion:

There is a high degree of coherency between Central Valley sediment discharge (from Ganju et al., 2008) and morphology of those flats on the outside of the narrowing at the Dumbarton Bridge. Whether the monotonic sediment trend is directly connected to the morphology of outer tidal flats cannot be definitively stated here, but a strong consistency is present (see Tables 3-1 & 3-2). While there is a general acceptance of the role of sediment from the Central Valley as the primary source for SSFB, there is uncertainty over the role of discharge from larger inner-estuary tributaries like the Guadalupe Slough and Coyote Creek. Given their proximity to the innermost estuary and the overall north-south motion of sediments
in SSFB, it is possible that historic trends in discharge from the larger local tributaries could be largely responsible for the morphologic patterns of the inner flats.

Patterns of rainfall between 1890 and 2005 in San Jose should represent, in our estimation, at least a portion of the local inner-estuary variability in external forcing. There is a relatively strong coherency in the trends of San Jose rainfall and inner-SSFB tidal flats. This is especially true for the latter years of the study, wherein sediment discharge from the Central Valley is greatly decreased and yet profile shape in the inner SSFB suggests an accretionary environment, an anomaly that could be explained through increased local sediment discharge due to increased rainfall (see Tables 3-1 & 3-2). Regions 7 & 8 exhibit the greatest coherency with San Jose rainfall data, and are located at the mouth of Coyote Creek, which drains directly from San Jose. A more complete record of localized rainfall or stream discharge from all local tributaries might better explain changes in morphology for flats in more of the inner-estuary regions.

Local variations in deposition and erosion should, given theoretical understanding of tidal flat morphology, be closely tied to changes in tidal flat shape. In Chapter 2, spatial patterns in recent deposition/erosion were highly consistent with spatial patterns in 2005 tidal flat profile shape; within each of the other yearsets, this spatial coherency is also present (Figure 3-14). Based on our criteria, stepwise multiple regression found recent deposition and erosion to be a critical forcing in six regions of SSFB tidal flats, including all but one of the inner regions (see Table 3-2). It is important, however, to note that recent deposition/erosion need not always equate to an increase or decrease in overall convexity of concavity. A concave-up profile, for example, could continue to erode, given increased sea level, while maintaining the same near equilibrium concave shape.
There is not a clear consistency present between the temporal trends of PDO index, as a proxy for storminess, and tidal flat morphology. While wind wave activity is generally recognized to be an important forcing factor in tidal flat morphology (Friedrichs & Aubrey, 1996; Christie et al., 1999; Janssen-Stelder, 1999; Dyer, 2000; O’Brien et al., 2000; etc), and wind fetch (as a proxy for waves) was found to be an important variable in determining spatial trends in SSFB tidal flat shape (Chapter 2), there is no conclusive evidence to suggest that changes in wind or wave activity have systematically altered SSFB flat morphology over the time period studied here. Bromirksi et al. (2003) found that, while there has been a slight increase in winter storms since the 1950’s, there has been no significant change in storminess in the San Francisco Bay over the last 140 years. Based on these findings we conclude that wind and waves have likely not been significant drivers of temporal changes in convexity/concavity in the tidal flats of SSFB over decadal time-scales since the turn of the last century.

Flick et al. (2003) found that diurnal tidal range (MHHW-MLLW) in San Francisco Bay has increased at a rate of 64mm/century since 1900. An increase in tidal range has been shown in the literature to lead to increased convexity of tidal flat profile (Dyer, 1998; Roberts et al., 2000). However, there is no such correlation seen in this study. To the contrary, there is almost zero correlation between the temporal patterns of tidal flat profile change in the inner-most estuary and diurnal tidal range (Figure 3-10). Counter-intuitively, there is a relatively strange negative correlation found between tidal range and profile shape in outer-estuary flats. The case of changing tidal range highlights the potential pitfalls of spurious correlations. The trends in tidal range, Central Valley sediment supply and evolution of scores in the outer estuary are all nearly monotonic and, therefore mutually well-correlated. However, without a pre-existing theoretical understanding in relationships between trends, it would be possible to statistically link
any monotonic trend (population growth since 1850, for example) to tidal flat morphologic trends.

3.5 Conclusions

Previous studies that used eigenfunction analysis to determine morphologic trends through time (Winant et al., 1975; Aubrey 1980; Miller & Dean, 2007; etc) have usually dealt with much shorter timescales and greater frequency of sampling, and are therefore able to make dependable assertions about links among sediment motion, wave activity, and other morphodynamic processes. Even in the cases of multi-decadal studies like Short & Trembanis (2004), the focus has mainly been on open coast, sandy profiles, rather than enclosed, muddy shorelines. Given the long period covered, the important muddy estuarine environment, and its relevance to ongoing issues related to tidal wetland restoration, the tidal flat bathymetric data set available for EOF analysis in South San Francisco Bay is highly compelling. Given the large intervals between bathymetric surveys, however, upwards of three decades between certain yearsets, attempts to draw correlation between morphology and short term trends in biology or specific storm events are not realistic. Our conclusions regarding the causes and drivers of morphologic change over this 100+ year time period based on only 5 bathymetric snapshots must remain somewhat tentative. We are, however, able to point out the more clear consistencies found in analysis.

- There is a discrepancy in temporal trend between what are referred to here as the “inner” and “outer” tidal flats. The outer flats, characterized by a concave-upwards profile, trend
towards greater negativity in morphologic score, and therefore greater concavity, over the time period studied. The temporal pattern of the inner flats, characterized by a convex-upwards profile, does not follow as predictable or uniform a trend.

- The morphologic trends of SSFB agree well with findings of Krone (1979), Jaffe et al., (2006), and others who found there to be net erosion from the regions of SSFB north of the Dumbarton Bridge and a tendency toward net accretion in those regions south of the bridge.

- Reduced sediment discharge from the Central Valley, as hindcasted in Ganju et al (2007), is positively correlated to the temporal trend of increased concavity of the outer flats. This variable was also found to be meaningful in stepwise multiple regression, based on our set of statistical criteria.

- Trends in San Jose rainfall display a qualitative coherency with temporal patterns of tidal flat shape in the innermost regions of SSFB. This qualitative consistency translates into importance in single and stepwise multiple regression.

- Recent deposition/erosion was positively related to increases in convexity/concavity in all 12 regions and was found to be correlated in 6 regions after stepwise multiple regression analyses. The strongest relationships were concentrated in the middle or inner estuary.
Neither temporal changes in tidal range nor the Pacific Decadal Oscillation (as a proxy for storminess) were found to be sensibly related to temporal changes in tidal flat profile shape.

Over decadal time-scales, it appears that local and regional changes in sediment supply, rather than changes in hydrodynamics, have been most responsible for observed changes in tidal flat morphology.
Figure 3 - 1: Theoretical Response of Tidal Flat Morphology to a variety of forcings (adapted from Dyer, 1998).
Figure 3 - 2: From Foxgrover et al., 2004, South San Francisco Bay, including areas of projected salt pond restoration.
Figure 3 - 3: Cross-shore profiles drawn in ARCMAP. Of the 800+ originally drawn, 654 were used for the temporal analysis.
Figure 3-4: Example of the normalization process. (a) Tidal flat bathymetric profile, pre-normalization. Red dotted lines represent predetermined upper and lower boundaries. (b) Normalized profile. Profiles are regridded onto a unitless scale of 30 points; it is necessary for EOF analysis that all profiles have equal x-axes.
Figure 3 - 5: Raw data plots of external physical forcings. Sediment discharge is decadally averaged, all others are yearly averages.
Figure 3-6: (a) Modes of morphologic variability determined through EOF analysis. Mode 1 explains 51% of variability, and represents degree of concavity/convexity; (b) mean morphologies of SSFB tidal flat cross-shore profiles. Pictured here are the overall mean profile shape, mean shape of all positively-weighted (convex-upwards) profiles, and mean shape of all negatively-weighted (concave-upwards) profiles.
Figure 3 - 7: Spatial patterns of convex/concave eigenfunction. Positivity/negativity represents convexity/concavity. Dotted vertical lines represent region boundaries; solid vertical lines represent boundaries of inner-estuary regions; (b) Regionally averaged spatial patterns of convex/concave eigenfunction. Positivity/negativity represents convexity/concavity. Shaded box represents those regions beyond the Dumbarton “pinch.”
Figure 3 - 8: Comparison of Central Valley sediment discharge (from Ganju et al., 2007) and Regional patterns in morphologic score. Shaded regions are those within Dumbarton pinch.
Figure 3 - 9: Comparison of averaged diurnal tidal range trends (--) and Regional patterns in morphologic score (−). Shaded regions are those within Dumbarton pinch.
Figure 3 - 10: Comparison of average PDO index and Regional patterns in morphologic score. Shaded regions are those within Dumbarton pinch.
Figure 3 - 11: Comparison of averaged San Jose rainfall trends (−−) and Regional patterns in morphologic score (−). Shaded regions are those within Dumbarton pinch.
Figure 3 - 12: Comparison of averaged recent deposition/erosion trends (→) and Regional patterns in morphologic score(−). Shaded regions are those within Dumbarton pinch.
Figure 3 - 13: Modeled trends in tidal flat profile shape based upon results from multiple regression.
Figure 3-14: Relationship between recent deposition or erosion and morphologic score for the latter yearset. Note that in the case of the 1890s, the comparison is between scores from the 1890s and deposition/erosion between then and the 1930s.
### Analysis of Dependence (Slope/SE)

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Table 3 - 1: Results of analysis of indications of dependence in regression (slope/SE) between temporal trends in morphology by region and a variety of physical forcings: CV Seds = Central Valley sediment discharge, SJ Rains = San Jose rainfall, PDO = Pacific Decadal Oscillation Index, Range = Diurnal Tidal Range, Dep/Eros = Recent deposition or erosion. Highlighted examples are those that match our criteria of importance.
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</table>

Table 3 - 2: Stepwise multiple regression results using deposition/erosion, rainfall, and central valley sediment discharge: CV Seds = Central Valley sediment discharge, SJ Rains = San Jose rainfall, PDO = Pacific Decadal Oscillation Index, Range = Diurnal Tidal Range, Dep/Eros = Recent deposition or erosion.
4. Overall Conclusions/Caveats/Future Work

4.1 Major Findings:

The spatial portion of this study revealed two distinct regional patterns of equilibrium morphology in South San Francisco Bay tidal flats, responding primarily to degree of exposure to wind-wave energy – the outer regions, characterized by concave-upwards profiles – or to tidal energy – the inner regions, characterized by convex-upwards profiles. Additionally, the high degree of consistency found between tidal flat morphology and recent erosion or deposition matches theoretical understanding of equilibrium profiles: convex/concave flats are indicative of recent accretion/erosion; notably however, the amount of time used herein - roughly two decades - to determine “recent” change far exceeds that of previous studies – seasonal to yearly in scope. A mathematical model based upon results of a multiple regression was used to reproduce average spatial trends in tidal flat morphologic score with a high degree of accuracy.

Temporally, this study found long term trends in tidal flat shape to be consistent, in the outer regions of the estuary, with trends in sediment supply from the Central Valley and northern San Francisco Bay. Patterns of shape in inner region tidal flats were qualitatively consistent with trends in San Jose rainfall, although the consistency was not quantitatively significant. There was additional high coherency in the signals of mean sea level and diurnal tidal range over the time period examined. Very little consistency was found when comparing tidal flat morphologic change to patterns in the Pacific Decadal Oscillation, used as a proxy for storminess and wind energy. Recent erosion/deposition was found to be consistent with patterns of tidal flat shape. Over the studied time period, there was an overall pattern of concave tidal flats becoming
increasingly concave, and convex flats becoming more convex; however, while the patterns of the outer-estuary concave flats was monotonic and predictable, the inner-estuary convex flats were erratic in their temporal signal.

One of the original motivations of this research was to determine any possible effects that the upcoming restoration of SSFB salt ponds may have upon adjacent tidal flats. Through the course of analysis, however, it became clear that the spatial and temporal scales of the USGS bathymetric data is too coarse, and the dates of salt pond formation too vague, to capture any meaningful tidal flat response. What follows, therefore, is largely a thought experiment based upon what I have come to learn about hydrodynamic and sediment trends in SSFB and initial accounts of salt pond response to recent restoration.

Initially, there will be a large influx of sediment into a breached salt pond. Whether the adjacent tidal flat will maintain its equilibrium shape will depend largely on its geographic position within SSFB: those flats in the inner-estuary are the most likely to maintain equilibrium due to the ample supply of sediment entering from both the north and from local tributaries. There is a good chance that tidal flats in the outer estuary will become more erosive due to restoration efforts, as they are subject to higher wind wave energy as well as decreased sediment input. After the restored salt marsh achieves equilibrium, it is possible that the adjacent tidal flats will resume the morphologic character they exhibited previous to either restoration or salt pond formation.

4.2 Caveats

The process of normalizing profiles to a single horizontal scale was necessary in order to use eigenfunction analysis to characterize SSFB tidal flat morphology. However, this process
also may have served, in some cases, to truncate or elongate certain local morphologic features of the profiles. It is our opinion that any such truncations or elongations would do little to affect the larger picture of morphologic behavior, given the sheer quantity of profiles used in this study. Normalization between two set vertical boundaries also served to remove slopes of the overall tidal flat profiles; slope has been shown to be a representative factor in global typology of tidal flats (Dyer, 1998).

Tidal flat morphodynamics on daily to annual timescales is a topic that, while not entirely understood, has been examined at length and in a variety of capacities and focuses. Previous studies have focused on the response of tidal flat morphology to a variety of forcings, both external – sediment input, wind-wave activity, tidal currents, seasonal variations in climatic forcings – as well as internal – biologic influences on sediment cohesion, small scale sediment transport, bottom boundary processes. Missing from these studies is any consideration of the drivers of longer term – decadal to multi-decadal - morphologic change, as has been enacted on sandy beaches (Short & Trembanis, 2004), and estuaries (Karunarathna, 2007). This study represents a coarse examination of the processes that influence tidal flat morphology on these longer time scales.

While the apparent connections found here are seductive in their logic and coherency, it must be noted that the outer tidal flat morphology exhibited a monotonic trend towards greater concavity. When compared to the monotonic decrease in sediment supply or increases in mean sea level and diurnal tidal range, there is an inevitable statistical relationship, in some cases to a very high degree. The significance of this consistency is hard to gauge, as there are not datasets available for additional forcings (biologic activity, decadal patterns in wave heights, local
sediment input). While the connections found between morphology and sediment discharge, sea level rise, and tidal range make logical sense, there are likely other activities in play.

This fact is made abundantly clear in the inner tidal flats of SSFB, wherein coherency of trends disappears when external forcings are compared to temporal patterns of profile morphology. The conclusion was reached that, for the inner flats, there must be some additional important local forcings – input from local tributaries, sediment exchange between the inner and outer regions. Including records of San Jose rainfall (as proxy for streamflow and sediment discharge) helped to elucidate, qualitatively at least, an connection between local physical forcings and trends in tidal flat shape in the inner SSFB. If this local influence holds true for the inner flats, it is likely true for the outer flats. The difficulty then becomes locating other possible local forcings and piecing together time-series that extend back 100+ years.

Readers may note that there is scant discussion of the effects of biology on long term trends in tidal flat morphology in SSFB; there are a few reasons for this omission. Primarily, there is not a database present that charts the patterns of bioturbating and mat-forming organisms in the estuary that extends far enough into the past or with sufficient coverage of the intertidal areas from which to base any trustworthy determinations or comparisons. However, while spatial trends in biologic activity may have been useful in examination of the estuary-wide variations in tidal flat morphology, it is our opinion that semi-annual variations in biology, while important for seasonal variations in morphology, essentially cancel out when examining bathymetric “snapshots” taken over two or more decades from one another.

4.3 Future Work:
Caveats aside, this study provides a first-order examination of the major processes and forcings at work that determine tidal flat morphology in SSFB. As there is currently very little information regarding the morphologic behavior of tidal flats on any time scale spanning more than three years, an obvious suggestion for future work would be to begin a long terms study with a high temporal resolution of data-collection. LIDAR technology allows for rapid and accurate surveys of exposed topography, and could be used in a land-based setting to take bathymetric “snapshots” of intertidal zones at a set time interval – anywhere from yearly to daily, depending on the desired resolution and, of course, funding. While the amount of profiles used in this study would be nearly impossible to achieve doing in situ measurements, research could focus on the twelve regions identified here and profile a single tidal flat line in each of the twelve regions, once a month. In performing this profiling, researchers could take care to assure each profile had the same number of horizontal points, thereby negating the need for normalization before EOF analysis.

In addition to bathymetric profiles, external and internal physical forcings could be collected both from in situ measurements - grain diameter, biological activity, and wave heights – NOAA buoy records - tidal currents, suspended sediment, and wind energy – and river gauges – discharge from the Central Valley and larger South Bay tributaries. Although a massive undertaking, such a dataset would be useful in elucidating the variations in physical forcing on daily to multi-year timescales at many points in SSFB. In essence, a scaled down in size, but up in resolution, version of the work presented in this thesis.

It is also worth noting that there is a great deal of information that can still be extracted from this dataset. One specific suggestion would be an examination almost identical to this one, except looking for slope changes rather than shape changes. One could also examine individual
shoreline morphology in consideration of tidal flat shape, looking for embayed vs. lobate equilibrium, i.e. Friedrichs and Aubrey (1996).
References Cited


Bromirski, P. D., R. E. Flick, and D. R. Cayan Storminess Variability along the California Coast: 1858–2000, *Journal of Climate, 16*(6), 982-993.

Callaway, J., T. Parker, and L. Schile (June 6, 2006), Sediment Deposition in Restored South Bay Salt Marshes: Initial Results from the Island Ponds. South Bay Science Symposium, .


Conomos, T. (1979), Properties and Circulation of San Francisco Bay Waters, *As part of: SAN FRANCISCO BAY: THE URBANIZED ESTUARY Investigations into the Natural History of San Francisco Bay and Delta With Reference to the Influence of Man, , 47-84.*


Green, M. O., K. P. Black, and C. L. Amos (1997), Control of estuarine sediment dynamics by interactions between currents and waves at several scales, *Marine Geology, 144*(1), 97-116.


Phil Williams & Associates, LTD (2005), South Bay Salt Pond Restoration Project: Hydrodynamics and Sediment Dynamics Existing Conditions, .


Western Data Center - San Jose Climate Page (WDC) - [http://www.westerndisastercenter.org/sjc/climate.html](http://www.westerndisastercenter.org/sjc/climate.html), (2008).


Williams, P. B. (June 6, 2006), Physical processes and tidal marsh evolution: Cooley Landing and Warm Springs Marsh. South Bay Science Symposium, .


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