Hydrodynamic modeling of San Elijo Lagoon, California

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HYDRODYNAMIC MODELING OF SAN ELIO LAGOON, CALIFORNIA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
Requirements for the degree of
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by
Mary Bourgoyne
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ABSTRACT

Decisions on where to concentrate management efforts need to be guided by an ability to accurately simulate and predict physical and ecological changes. Many restoration projects experience difficulties due to a lack of understanding of the ecological response and evolution of wetland systems (Goodwin et al., 2001). There are several approaches that can be taken in analyzing a system. The appropriate selection should be based on the available data, the spatial scale of the wetland, and the physical processes governing the system (Goodwin and Kamman, 2001). Predictive tools are essential for good long-term management (Goodwin et al., 2001). The objective of this thesis is to determine whether San Elijo Lagoon is a morphologically stable environment and to investigate the movement of water and sediment patterns within the estuary. This will be answered through analysis of field data and numerical modeling of the hydrodynamics of the system. A field campaign was conducted to collect a suite of hydrodynamic and sediment data in the estuary. The development of a conceptual model was further applied to a numerical model. The Danish Hydraulic Institute’s (DHI) Mike21 software package was used to develop a two-dimensional flexible mesh hydrodynamic model. This is a depth-averaged finite volume commercial program. The hydrodynamic model was calibrated with the data collected in May, and then verified with observed conditions from July and August. The lagoon has a net depositional environment. The inlet of the lagoon is unstable due to the enforced unnatural location and meandering morphology of the inlet channel; the force of the tide is not large enough to keep the inlet clear. MIKE21-FlexibleMesh model simulations confirm that San Elijo Lagoon’s hydrodynamics is dominated by tidal forcing and freshwater inflow. The freshwater inflow, as well as the morphology of the lagoon causes an attenuation of the tidal signal. In the coincidence of extremely low tides and extremely high runoff in the watersheds feeding the lagoon the freshwater inflow at the man-made dike can have a significant impact, but only for a short period of time.
1 INTRODUCTION

Decisions on where to concentrate management efforts need to be guided by an ability to accurately simulate and predict physical and ecological changes. Typically, restoration is considered to be mitigation, shore protection, water quality management, or the stabilization of regional geomorphology. But many restoration projects have experienced difficulties due to a lack of understanding of the ecological response and evolution of wetland systems (Goodwin et al., 2001). There are several approaches for analyzing a system. The appropriate selection should be based on the available data, the spatial scale of the wetland, and the physical processes governing the system. These important processes will be discussed in the following sections, and include but are not limited to: the geometry of the system, inlet dynamics, mixing processes, tidal exchange, flooding and drying, and geomorphic development (Goodwin and Kamman, 2001). It is important to remember, though, that predictive tools are essential for good long-term management (Goodwin et al., 2001).

1.1 Objective

The objective of this thesis is to determine whether San Elijo Lagoon is a morphologically stable environment and to investigate the movement of water and sediment patterns within the estuary. This will be answered through analysis of field data and numerical modeling of the hydrodynamics of the system.

1.2 Literature Review

Estuaries have many definitions and many different naming conventions. The definition proposed by Cameron and Pritchard (1963) in conjunction with Dionne (1963) states that an estuary is a semi-enclosed coastal body of water which has a free connection to the open sea, within which saline water is measurably diluted with land-derived fresh water, and is subject to daily tidal action. Within an estuary, wetlands are the transitional land that exists between terrestrial and aquatic systems. The natural water table is at or near the surface of the land or covers the land with a shallow blanket of water. Estuaries occur in the coastal zone, and can have characteristics of salt marsh, brackish, or freshwater wetlands (Goodwin et al., 2001).

Estuaries are important natural resources because they serve a variety of purposes. They filter natural and man-made nutrients and contaminants; dissipate energy to reduce shoreline erosion, and replenish groundwater. They provide a holding place for floodwater and a sink for suspended sediments. Estuaries supply a habitat for many plants and animals and offer educational and recreational opportunities to the surrounding community (Goodwin et al., 2001).

1.2.1 Geometry

Coastal wetlands exist due to the interaction of large opposing forces acting in both the horizontal and vertical planes. Sediment resuspension, compaction, subsidence, and deposition as well as sea level rise all act in the vertical plane. Things that occur in the horizontal plane are the early formation of channel networks and other erosion processes. The result of these interactions
is the rapid demolition or the establishment and maintenance of the wetlands (D’Alpaos et al., 2005). The only compensation to destructive forcings is accretion.

There are three distinct morphological domains of estuaries, each one identified by different physical, hydrodynamic, and ecological characteristics. The highest elevations are typically vegetated salt marshes that can still be inundated during a significant high tide. The middling domain is the tidal flat, or sometimes called a tidal flat; it is not vegetated due to the high frequency of tidal inundation (typically every high tide). The third domain is the channel networks that contain the lowest elevations in estuaries and can be either vegetated or not, depending on the dominant ecology of the area (D’Alpaos et al., 2005).

Much of the action in estuaries occurs in the channel networks. They play a large role in redistributing the discharge of water within the tidal basin (Fagherazzi et al., 2003). A typical trait of tidal channels is a nearly exponential decrease in width in the landward direction. (D’Alpaos et al., 2005).

When considering the geometry of a system it is important to remember that small scale features can have large scale effects. The geometry is vitally important to flow characteristics (Teeter et al., 2001). For example, one of these flow characteristics is the velocity field. The predictions of salinity and sedimentation are dependent on the velocity field, which is in turn dependent on the accurate geometric representation of the system (Goodwin and Kamman, 2001).

1.2.2 Inlet Dynamics

The structure of the inlet determines the degree of tidal damping the estuary experiences as well as the amount of exchange between the ocean and the estuary. Consequently, the inlet opening governs not only the depth, duration, and frequency of inundation, but also the salinity structure and habitat distribution of the estuary and tidal wetlands. The inlet depends on a combination of three things: the tidal prism that transports sand into the estuary, longshore sediment transport and waves that carry sediment across the mouth, and freshwater inflows that scour the inlet channel. Nearshore waves, currents, and tides have critical influence on the inlet (Goodwin and Kamman, 2001).

There are certain uncertainties in determining the inlet geometry, though. There have been observations of variations of up to 50% of the cross sectional area in wetlands in California. However, given the importance of the inlet on the hydrodynamics of the system as a whole, accurate geometric representation is critical to the reliability of simulation results (Goodwin and Kamman, 2001).

1.2.3 Hydrodynamics/Mixing Processes

Water moves around in estuaries due to the conflict of natural forces; this is generally referred to as hydrodynamics. Tidal exchange is the cause of the flux of salinity and nutrients into and out of the system, but the distribution within the wetland is governed by the mixing processes within the estuary. The major contributors to mixing are wind, waves, tides, and fresh water inflow and
runoff. Groundwater can also influence the mixing, but its interaction is dependent on the local geology and what feeds it (freshwater or tidal inflow) (Goodwin and Kamman, 2001).

Mixing caused by currents generated by winds can have large fluctuations during the evolution of a shallow water marsh system. However, relatively large open water surfaces are required to generate any significant wind driven current or wave (Goodwin and Kamman, 2001). Wind generated waves are more important to sediment resuspension than mixing in systems like San Elijo Lagoon, since it has a small fetch and therefore not much room to generate waves (Teeter et al., 2001). Despite this, wind driven currents still interact with tides by causing shear stresses that introduce residual circulations or eddies (Carniello et al., 2005).

Tides have, by definition, continually varying currents that induce strong estuarine mixing. Mixing from tides is advective only, and is a result of tidal pumping and trapping. Tidal pumping is the result of water production due to residual flows, which are produced when the average flow over a tidal cycle is not equal to zero (Goodwin and Kamman, 2001). Tidal trapping is a function of the geometry of the wetland system; this type of mixing is a product of temporal variations in the tidal flow field. Another way that tides induce mixing is that the variations in flow velocity and direction that they produce. During a tidal cycle, water flows in and out of channels that have varying area, length and conveyance properties. This causes variations in flow that can have short term fluctuations of the velocity field of up to 50% of the instantaneous measurement (Goodwin and Kamman, 2001).

Another mixing mechanism in estuaries is freshwater inflow. This can be from surface runoff or upstream tributaries. This inflow of non-saline water is key in the estimation of plant-type boundaries. On top of contributing a continuous discharge to the system, freshwater mixing with the saline ocean water also adds a density gradient. If the gradient is large enough, not only is stratification of the water column possible, but a salt wedge that moves in conjunction with the tide could form. If stratification exists in the channels, it is the lighter, low salinity water that floats on top of the dense saline water. This means that the lower salinity water that is on top will enter the tidal flats and inundate the marsh plain, resulting in a less saline environment than would exist with well mixed waters (Goodwin and Kamman, 2001).

All the forces discussed above can cause different recognizable circulations and stratifications of salinity, temperature, dissolved and particulate matter (Teeter et al., 2001). This pattern was noticed, and a classification system with four general types of estuarine circulation was created by Pritchard. Type A is recognized by its highly stratified salt wedge. In an estuary that is characterized by a single fresh-water source at one end and pure sea water at the other there is usually some stratification: a dense layer below a lighter, fresher outflow (Hughes, 1958). This dense saline layer, if clearly defined with little to no mixing at its border with the less saline water on top of it, is called a salt wedge.

Another explanation for stratification, especially during the maximum tidal currents, is high runoff. This fresh water source can maintain the natural stratification throughout the entire tidal cycle. Type B is known for its moderate stratification with a deep saline flow and a fresh outflow near the surface. Type C is a vertically homogeneous flow that has a significant salinity difference across its typically wide geometry. When looking at Type C estuaries where the
salinity gradient is horizontal instead of vertical there is another, different explanation. The observation of fresher, lighter water on one side of a wide estuary is believed to be caused by Earth’s rotation, the Coriolis effect. Like C, Type D has no stratification, but it is not necessarily wide, and has salinity changes along its length. If there is no stratification, that is an indication of intense vertical turbulence (Hughes, 1958).

The main cause of turbulent mixing is tidal currents. Tidally induced vertical mixing can be complete at mid-tide, when the tidal currents are at their max. As the tidal currents slow down, horizontal velocities separate themselves into a seaward motion in the upper layer and a landward flow near the bottom, producing the above-mentioned salinity gradients (Hughes, 1958). This means that one system can go through all four (A, B, C, and D) patterns of circulation in one tidal cycle. In conclusion, the mixing power in a system results from density differences, tidal velocities, freshwater inflows, and lagoon morphology (Goodwin and Kamman, 2001).

1.2.4 Tidal Exchange

When both freshwater flow and wind magnitude is low, the currents within a lagoon are mostly the result of the tides (Fagherazzi, 2002). Tidal waves are produced in the ocean, and induce motion in estuaries when they propagate into shallow water (Li and Valle-Levinson, 1999). In a basin, the tidal motion is caused by the oscillating water surface. This motion produces a complex flow field that is dependent on two things: the basin’s shape and bathymetry (Fagherazzi, 2002). Fagherazzi et al. (2003) attempts to split tidal flow into these two components. This is important because basin boundaries develop at different time scales than the basin bathymetry. Boundaries are often determined by shape of river paleo-valleys and vary with sea level over thousands of years. Bathymetry is modified by many things – tides, sediment input, dredging for navigation, runoff, and other changes by humans, which operates on the timescale of tens to hundreds of years (Fagherazzi et al., 2003).

The tidal velocity is highly dependent on bathymetry (Li and Valle-Levinson, 1999). Because most lagoons have varying bathymetry, there is a deformation of the tidal wave, which causes an asymmetry in the current velocities (Lumborg and Windelin, 2003). The differences in depth cause a redistribution of momentum, resulting in a tidal wave speed increase in deep channels and decrease in shallow areas. Bottom friction (energy dissipation) in shallow areas also reduces the tidal wave speed, causing a time lag in the tidal peak (Fagherazzi, 2002). When tidal currents are peaking, the max bottom shear stress in deep channels occurs during flood and ebb conditions (Carniello et al., 2005). This is one of the reasons that tidal flow creates and changes the channels that often dissect tidal flats and salt marshes (Fagherazzi et al., 2003). These asymmetries are a consequence of drainage basin morphology and storage characteristics, and can change depending on the current tidal range and stage (Boon 1975). One last thing to remember about tidal exchange is that it is a determinant for the sediment budget in shallow lagoons (Fagherazzi et al., 2003).

1.2.5 Flooding and Drying

As was already discussed, tidal wetlands typically have a network of channels and open water bodies that are subject to tidal forcing, and undergo some degree of wetting (or flooding) and
drying during a tidal cycle. This cyclical rising and falling of the water surface within the wetland system results in the wetting and drying of not just the secondary, but often the primary channel network as well. This process as well as the flooding and draining of mudflats and marsh plains impacts and shapes the unique habitats in the system (Goodwin and Kamman, 2001).

The ecological health and filtering capacity of an estuary is dependent on the flushing time (the average length of time it takes fresh water to pass through part of an estuary (Hughes, 1958); Li and Valle-Levinson, 1999). If tidal hydrodynamics and salinity distribution are to be accurately simulated, flooding and drying should be accounted for in the model. Failure to do so can result in too short or too long of a hydroperiod, the outcome being a system that cannot support marsh vegetation and therefore wildlife. Early restoration approaches had this problem, where the marsh was flooded too long, or it was unable to drain. These failed attempts confirmed the need to understand tidal processes in wetland systems (Goodwin and Kamman, 2001).

1.2.6 Geomorphic Development

Morphodynamics is how the existing morphology shapes the future of the system (Friedrichs and Perry, 2001). It is the rate of change of the morphology of a system, and is important to the study of any site as it gives insight into the relative stability of the system (Goodwin and Kamman, 2001). According to Friedrichs and Perry (2001), the period of time between 1990 and 2000 was marked by major advances in the observation of sedimentation and accretion patterns in tidal salt marshes. Those observations brought to light that many systems in the coastal zone are highly dynamic and are constantly changing due to local forcings. In sheltered environments, though, some tidal wetlands show little to no change over time (Goodwin and Kamman, 2001).

Systems have the potential to change rapidly if the forcings drastically change. Large storms in the winter can deposit significant amounts of sediment in a single event or there could be a slowing of sea level rise, causing abrupt accretion. Loss of sediment supply or an acceleration of sea level can cause an equally devastating loss of wetland (Friedrichs and Perry, 2001).

“The classical model of a salt marsh very slowly accreting upward and outward and as it fills a lagoon is applicable only to restricted circumstances where the lagoon boundaries and sea level remain fixed, and where sediment input gradually and continually fills the lagoon. Even under these circumstances, the vertical and horizontal extent of the marsh grass is continually near dynamic equilibrium with the slowly changing boundary conditions imposed by the adjacent depth of the lagoon (Friedrichs and Perry, 2001).”

Systems such as the one this study is focused on are unique. Tidal salt marshes only occur in specific latitudes, and then only if the wave environment is conducive to the establishment of salt tolerant grasses. In the field of coastal morphodynamics, these tidal salt marshes set themselves apart due to the combined presence of vegetative growth and sedimentary features (Friedrichs and Perry, 2001). The evolution of the system is dependent on many factors, such as the layout of channel networks and intertidal tidal flats, the presence and type of vegetation, the embayment length and depth, and sediment availability (van Leeumen et al., 2000; Friedrichs and Perry,
All these factors are interdependent and largely impacted by the natural hydrodynamics of the system as well as man-made forcings.

1.2.6.1 Vegetation

For salt marsh vegetation to grow it needs to not only be protected from wave energy, it also has specific needs when it comes to inundation. Marsh grasses generally grow above mean tide level and below spring high tides. If they are not submerged long enough, other terrestrial plants will take over and if they are submerged too frequently or for too long, they can get water logged. Water logging usually occurs on the inner portion of the marsh, usually a result of inadequate drainage. As the vegetation dies, the water evaporates; if it was salt water, it creates a hyper-saline environment which further encourages plant death and reduces the likelihood that plants will repopulate. Water logging is a serious problem, and can be caused by sea level rise, subsidence or simply reduced sediment supply. It prevents oxygen from reaching the roots, resulting in plant death. Plant death can also be caused by salt intrusion, but either way can lead to elevation loss on the order of 10-15 cm or a complete shift in species, which destroys plant and animal habitats (Friedrichs and Perry, 2001).

The presence of salt marsh grasses dramatically changes deposition rates due to the fact that the grasses slow flow velocity and trap sediments. These tendencies of increasing deposition and reducing resuspension increase with increased stem density. The reduction in velocity is related to the distance from the main channel: the further away from the channel, the slower the flow. It is generally accepted that sedimentation in marsh grasses occurs continuously during inundation due to this reduction in flow velocity. Because of this, there is a seasonal correlation. Deposition rates are larger in the summer, and this is attributed to the fact that the vegetation is at a maximum at that time (Friedrichs and Perry, 2001).

1.2.6.2 Channel Geometry

The location of main channels is usually inherited; this can be due to the underlying bedrock, tidal channels from pre-existing lagoons or tidal flats, or from the natural drainage pattern of the land before it became tidally influenced. Main channels of established salt marshes do not migrate overmuch due to the vegetation stabilizing the banks. Slumping and undercutting is the common mode of meander migration, and the vegetation works hard to resist even that. The more thickly vegetated, the more stable and tight the bends can be (Friedrichs and Perry, 2001). This stabilization encourages the tidal channel network in the marsh to be narrower and deeper than the channels on the tidal flats. The smaller creeks or channels on the tidal flats are the most vulnerable to change.

1.2.6.3 Dredging

Dredging is a common practice to increase circulation or maintain an open waterway. When channels fill in or slump, they sometimes need help to open the channel up again. However, dredging has distinct side-effects. It decreases the velocity in the channel, which encourages deposition. This deposition reduces the suspended sediment load, thereby reducing the amount of sediment delivered either to the upland marsh, the nearby banks, or the ocean. Depending on the
dredging practices being used, the spoil is sometimes left on the adjacent banks, which prevents sediment laden water from flowing onto the marsh surface. These are all examples of detrimental effects of dredging, but if the dredging is done in such a way as to mimic the natural cross section of the tidal creeks, it can have a restorative effect on the system. Also, if the spoil is disposed of in such a way as to be a thin layer on the marsh, it acts as a net accretion of the marsh elevation (Friedrichs and Perry, 2001).

1.2.6.4 Sediment Trapping/ Deposition Patterns

Flow velocity is the most important thing when considering sediment deposition in the channel network. There exists a threshold velocity where above this velocity, sediment is eroded, and below it, sediment is deposited. Since channels are usually inundated, the frequency and duration are considered to be secondary, unlike on the salt marsh, where these variables are primary (Friedrichs and Perry, 2001).

For sedimentation to occur on the salt marsh there needs to be sediment suspended in the water source (marsh creek, freshwater creek, tidal inflow). The amount to sediment supplied to the marsh is proportional to the concentration of suspended sediment in the source water. An increase in this concentration increases the accretion rate of the marsh. Since sedimentation occurs continuously throughout a flooding event over marsh grass, the accretion rate also increases with increased duration of inundation, even though sedimentation slows as time goes by (Friedrichs and Perry, 2001).

However, there are many factors that contribute to the accretion rate, so it is hard to isolate just one variable like the length of inundation. Another possible factor that can be correlated to accretion rate is marsh elevation. Higher marsh will be inundated for a shorter amount of time during a specific event, thereby receiving less sediment. It has been observed in several marshes that there is an inverse relationship between accretion rate and marsh elevation. So there is a pattern in the sedimentation that follows the shape of the channel and the topographical lows within the system (Friedrichs and Perry, 2001). However, when tide overtops the marsh and the channels no longer direct the flow through the system (during storms or very high tides), there is a different pattern of deposition. When this occurs, bands of sediment radiate out from the source of the surge.

If the water is so deep that none of the vegetation affects the flow, then there may not be any sedimentation until the water reaches the edges of the marsh, in which case the deposition pattern will outline the marsh. This pattern also occurs with storm water runoff. When there is a large storm or high tide, runoff does not follow the channels of the marsh, causing an interesting reversal of the grain size pattern found near channels. The coarser material will be found closer to the source, no matter what. So for normal channel overwash, the largest sediments are immediately deposited (causing the creation of topographic highs and levees), and the sediment fines the further into the marsh and the further away from the channel. For stormwater runoff, the pattern is opposite, with coarser material closer to the edges of the marsh and finer material found closer to the channels (Friedrichs and Perry, 2001).
The patterns discussed above apply to inorganic sediment and sediment originating from outside the system. Material that originates from within the system (organic sediments), can follow a different pattern. These sediments are a combination of phytoplankton, animal fecal pellets, the remains of microbes or other dead things, and plant detritus as well as partially preserved in situ roots and rhizomes (Friedrichs and Perry, 2001). The proportion of organics to inorganics increases with distance into the marsh and sometimes with elevation.

1.2.6.5 Erosion

Friedrichs and Perry (2001) agree that long term net erosion is unlikely in flow through healthy marsh grass due to the damping effect that grass has on flow velocity. They argue that even erosion due to extreme storm surges where waves directly impact the surface of the marsh will be replenished easily and quickly. The only place that erosion will likely occur is on the channel banks where undercutting causes slumps (Friedrichs and Perry, 2001).

1.2.6.6 Tide Range

Tidal embayments are divided into three distinct domains: macro tidal, mesotidal, and microtidal environments. Macrotidal systems have a spring tide range of greater than four meters, mesotidal systems range between two and four meters, and microtidal systems have a spring tide range smaller than two meters. Due to their larger tide range, macro- and mesotidal coasts tend to develop tidal salt marshes more so than microtidal coasts. Intense storms are more likely to be erosional in macrotidal systems. In meso- and microtidal systems, though, storms are depositional events, and the water depth is too small for waves to develop. Although there is no clear correlation between tide range and accretion rate in macrotidal systems, one has been observed in microtidal environments. It has also been observed that with increased tidal range, there is an increase in tidal creek velocity. Macrotidal and mesotidal systems are much more likely to survive in the event of an increase in sea level, whereas microtidal systems are much more sensitive. A small change in sediment supply, accretion rate, or sea level can easily drown a microtidal environment, killing the marsh grass and opening the system up to drastic changes (Friedrichs and Perry, 2001).

1.2.6.7 Hydroperiod

The hydroperiod of a marsh defines the duration and frequency of inundation typical of that location. The greater the hydroperiod, the more often the system is inundated, the greater the deposition rate, as well as the greater the stress on the marsh’s vegetation. There is a significant stabilizing morphodynamic feedback loop between hydroperiod, inorganic deposition, and sea level rise:

“If future sea level rises faster than the present rate of vertical marsh accretion, the elevation of the marsh will fall, increasing the hydroperiod which favors an increase in rate of inorganic sedimentation. This, in turn, has the potential of increasing the rate of accretion sufficiently to match the enhanced rate of sea level rise (assuming the additional sediment is available). Conversely, if future sea level rise is less than the present rate of vertical accretion, the marsh will rise, decreasing the hydroperiod,
decreasing inorganic sedimentation, and reducing the rate of accretion (Friedrichs and Perry, 2001).”

This means that a system dominated by inorganic or foreign sediment uses the hydroperiod as a way of staying in dynamic equilibrium with sea level (Figure 1) (Friedrichs and Perry, 2001).

Figure 1: The interaction of tides, storms, hydroperiod, deposition, vegetative growth, sea level, marsh elevation and net vertical accretion. If the correlation between two components is positive, the arrow connecting the two boxes displays a “+”, if the correlation is negative, the arrow displays a “-”.

Source: Friedrichs and Perry 2001

In systems dominated by land runoff and/or organic material, there is a destabilizing feedback loop:

“In contrast to the stabilizing morphodynamic feedback of hydroperiod on accretion of allochthonous sediment, decreased hydroperiod favors increased vegetative growth, enhanced accretion of organic matter, and a further shortening of hydroperiod. If future sea level rise is greater than the present rate of accretion in tidal marshes dominated by organic matter (hydroperiod increases), such marshes may have a harder time keeping up with accelerated sea level rise that will marshes dominated by inorganic sediment. This conclusion follows logically from the observation that increased inundation and associated salt stress tent to reduce grass productivity and resulting organic matter accumulation. Thus increased hydroperiod favors decreased accretion or organic matter, and a further lengthening of the hydroperiod (Friedrichs and Perry, 2001).”

It is acknowledged that these statements are slightly simplistic and that other factors need to be considered as well. Things such as the fact that plants grow better in soil with greater mineral content, encouraging accretion, and organic soils are more prone to compact, reducing accretion (Friedrichs and Perry, 2001).
1.2.6.8 Tidal Asymmetry

Several types of tidal asymmetries exist, but they affect lagoons similarly by producing flows that are either flood dominant or ebb dominant. Flood dominance is defined as a rising tidal flow whose peak currents are stronger than the corresponding falling tidal flow. It also has a longer slack between flood and ebb tide. Conversely, ebb dominance is defined as a falling tide whose peak currents are stronger than the corresponding rising tide’s with a shorter slack between the flood and the ebb tide. Due to the fact that sediment erosion and deposition in the channels are primarily dependent on flow velocity, flood dominant tides tend to move sediment inland. This happens because the sediment is eroded on the incoming tide and deposited during the longer slack after high tide. Ebb dominant tides tend to move sediment toward the ocean due to the stronger currents in the falling tide eroding and then carrying the sediment out to the ocean (Friedrichs and Perry, 2001). Other characteristics of flood and ebb dominance are summarized in the following table.

<table>
<thead>
<tr>
<th><strong>Table 1: Comparison of Flood and Ebb Dominance</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flood Dominance</strong></td>
</tr>
<tr>
<td>Longer high water slack</td>
</tr>
<tr>
<td>Sediment transport inland</td>
</tr>
<tr>
<td>Increase in marine sediment supply to marsh</td>
</tr>
<tr>
<td>Higher marsh</td>
</tr>
<tr>
<td>Higher suspended sediment concentrations</td>
</tr>
<tr>
<td>Shorter Duration of Rising Tide</td>
</tr>
<tr>
<td>Shallower Channels</td>
</tr>
</tbody>
</table>

Other types of asymmetry that play a role in flood or ebb dominance are offshore tidal asymmetry and scour/settling lag. Offshore tidal asymmetry is a local condition that can only be determined by looking at how the tides interact with the shape and bathymetry of the coastline in a geographic region. Scour or settling lag is something experienced by the suspended sediment particles. With changes in geometry of the channel, there are adjustments in the rate of change of the current speed between high water slack and low water slack. For example, if the rate of change of current speed and high water slack is slower than the rate of change of current speed at low water slack, then more sediment will fall out after high water slack than low water slack. This means that landward accretion will occur, encouraging flood dominance (Friedrichs and Perry, 2001). The opposite is true of ebb dominance.

Typically systems are much more complex than being simply flood or ebb dominant. As discussed before, channel geometry changes throughout a system (usually shallower the further inland), which means that flood and ebb dominance can vary in space. If a portion of a lagoon is shallow and a portion deep, these two sections could behave flood and ebb dominant, respectively, at the same time. On an even smaller scale, if one side of a channel is shallow and
the other deep, the shallow may behave flood dominant while the deep behaves ebb dominantly. With tidal fluctuations (monthly, annual, 4.4, 18.6 year highs), a system can switch between dominance type on the basis of time as well. Interestingly, human interference can also change the regime of a system. Dredging the seaward channels of a lagoon can cause a shift to ebb dominance (Friedrichs and Perry, 2001).

![Diagram](image)

Figure 2: Morphodynamic Relationships
Between tidal range, inlet spacing, marsh size, tidal prism, channel depth, flood- or ebb-dominance, marsh sediment supply, and equilibrium marsh height.

*Source: Friedrichs and Perry, 2001*

Interestingly, in some lagoons a morphodynamic balance has been observed between flood/ebb dominance and scour/settling lag (Figure 2). These two conditions can act “preferentially” on sediment grain sizes. Flood and ebb dominance have to do with flow velocity, which affects coarser sediment, while scour/settling lag has more to do with gradients in tidal velocity amplitude, which affects smaller gain sizes. This combination can result in the seaward transport of sand and the landward transport of fines (Friedrichs and Perry, 2001).
2 SITE DESCRIPTION

2.1 Geographic Setting

San Elijo Lagoon (SEL) is a coastal wetland dominated by salt water. It is located at Cardiff by the Sea in the City of Encinitas 20 miles north of the city of San Diego, CA (Figure 3). The lagoon is composed of coastal wetland habitat, including over 1000 acres of mudflat and salt marsh (Wu et al., 2006). It varies in width from 0.25 to 0.75 miles and extends inland (east) for about 2.5 miles (Soil Conservation Service, 1993, Sedimentation Study Report, 2006).

In the past, San Elijo Lagoon was a fully tidal estuary with multiple inlet channels that connected it directly to the Pacific Ocean and was populated by low-lying salt marsh plants. The inlet of the main channel migrated freely up and down the coast and cut through the beach dunes at the lowest point. This inlet configuration allowed for a constant saltwater exchange, regardless of season (Byrd, 2008). In today’s environment, the Pacific Ocean is the western border, bluffs restrict the lagoon to the south, and Manchester Avenue winds along the northern edge.

Most southern California lagoons have been altered over the last century, with the construction of roads, railways, parks, airports, and sewage treatment facilities; some were even completely dredged and made into marinas, leaving nothing natural behind (Flick 2008). In San Elijo Lagoon, there are four main man-made structures (and their embankments) that restrict flow throughout the lagoon (Figure 4). From the Pacific inland these are US Highway 101 (Coast Highway), the North County Transit District Railroad (or the Santa Fe Railroad), Interstate 5, and a dike located upstream (east) of the I-5 embankment. These structures divide the lagoon into three distinct basins, the West, Central, and East Basins (Figure 4), which are connected by small channels. The inlet is a narrow channel restricted by the Coast Hwy Bridge to the Northwest corner of the lagoon, and extends east approximately 1700m before it meets the
railroad bridge. From there the inlet splits; part of it feeds the West Basin, but almost all of the tide enters the Central Basin.

![Figure 4: San Elijo Lagoon Basins, Restrictions, and Main Tributaries](image)

*Note: Boxes outline man-made restrictions.*

*Source: Image from Google Earth*

The West Basin is formed by the parallel embankments of the Coast Highway and the Santa Fe Railroad, and contains several ponds that usually do not receive circulating flows of any kind. The Central Basin lies between the railroad and Interstate 5 and is composed of salt marsh, mudflat, and shallow open water. The I-5 bridge on the northern side of the lagoon (at Manchester Ave) allows a short, narrow channel to connect the Central to the East Basin. The East Basin is further subdivided by the man made dike east of the I-5; it contains a spillway with two pipe floodgates built into it. The area between the I-5 and the dike is fresh water to brackish marsh habitat while the area east of the dike is composed of a mixture of natural and artificial habitats, mainly artificial freshwater duck ponds. The dike traps freshwater in the duck ponds and allows for seasonal freshwater inflow to the lagoon through the pipes. The distinct difference in habitat between the Central (salt water influenced) and East (nearly all freshwater influenced) Basins is what makes San Elijo so unique (Soil Conservation Service, 1993).

The cities of Escondido, Encinitas, Carlsbad, San Marcos, and Solana Beach are located in the watersheds that feed San Elijo Lagoon. Land uses vary within the watershed, but generally fall into the categories of residential, commercial, industrial, agricultural, vacant, undeveloped,
parks, etc (Soil Conservation Service 1993). The Escondido Creek Watershed (Figure 5) covers approximately 77 square miles (200 km²; 50,000 acres; San Diego County Report, 2006), begins above Lake Wohlford to the east, and flows over 26 miles to empty into San Elijo Lagoon. It is the largest watershed of the seven in the Carlsbad Hydrologic Unit (CHU; Figure 5).

![Figure 5: The Carlsbad Hydrologic Unit (CHU) The highlighted portion is the Escondido Creek Watershed
Source: www.sanelijo.org](image)

Damages to wetlands are sometimes regulated by the Clean Water Act, Endangered Species Act, or the Coastal Zone Management Act, but there is no specific legislature in the US to protect them (Goodwin et al., 2001). The recognition of the loss and the continued value of wetlands made the community aware that restoration was needed. However, there is an inherent problem with the word restoration as it implies an unrealistic goal of recreating historic conditions. Some things cannot be undone, and certain regional hydrologic and geomorphic changes cannot be reversed. Even though there is increasing awareness by government agencies and the general public, intensive land use, low water quality, and alien species still threaten the wetland systems that remain (Goodwin et al., 2001).

### 2.2 Hydrodynamic Setting

Small and shallow Southern California lagoons like San Elijo are dynamic, and the inlet channels can change rapidly. These changes occur by a shift in the bottom morphology in response to flow conditions and suspended sediment concentrations (City of Encinitas, 2001). The main forcing function that dictates the flow conditions in San Elijo Lagoon is the tide. Sea water affects the lagoon in two ways: tidal inundation on the surface and upwelling through the ground water (USACE, 2002). Although tidal flushing is the principal method of tidal circulation, storm water flows are not to be discredited. Freshwater inundation has changed so drastically since the 1970s due to urbanization (despite the construction of dams) that storm water can now cause large scale mixing in the lagoon, albeit on a much smaller time scale of only a few days or weeks. Studies
have found, though, that whether freshwater is presently flowing into the lagoon or not, the tidal signal is always felt past the I-5 bridge (USACE, 2002).

This variable mix of fresh and salt water provides a constantly changing salinity in the lagoon. Typical salinities flowing into the lagoon from the ocean range between 33 and 34 parts per thousand (ppt). This mixes with the fresh and brackish water in the lagoon to provide salinity gradients that are highly beneficial to the lagoon. Salinities between 15 and 30 ppt have been shown to increase oxygen levels in the water, reducing the chance for eutrophic conditions to exist, increase salt marsh, fisheries, and benthos, diversify the species and habitats, improve human health conditions, and reduce the impacts of future contamination.

The degree that the tide affects the lagoon is determined by the stability of the inlet (USACE, 2002). The inlet is also the mechanism for tide to enter the lagoon; the tide induces circulation in San Elijo by way of a single meandering channel. The channel narrows as it travels inland and has abrupt changes in bottom morphology (City of Encinitas, 2001). It does a good job of distributing flow throughout the lagoon even though the meander bends slows the tidal signal, causing a dampening effect.

The ease of movement of the tide is vital to the effective mixing and circulation of water in the lagoon. There are areas where the flood tide is impeded in all three of the basins of San Elijo. The main channel shallows rapidly near the railroad bridge, impeding inflow to the Western Basin. Flow is further obstructed by the berms for the sewage outfalls and pipelines, diminishing the tidal signal so that part of the West Basin is rarely if ever under the influence of any circulation. In the Central Basin there are three specific areas that are isolated from the main channel and infrequently catch the tidal signal, experiencing circulation only from high flows that overtop the channel system and flow across the tidal flats. The three cut off areas are: the southeastern corner of the Central Basin next to the I-5 berm, the middle of the mudflat filling the basin, and next to the railroad berm south of the old sewage treatment ponds (USACE, 2002). In the East Basin, it is the presence of cattails and bulrushes that restricts flow, encourages deposition, and is shrinking the size of the channels (City of Encinitas, 2001).

Most southern California lagoons like San Elijo take a shorter time to fill in than to drain. This means that velocities are higher when the tide comes in, and sediment has a tendency to move further into the lagoon. This asymmetry is what causes the instability of lagoon inlets in southern California (City of Encinitas, 2001). Now, if the tidal prisms (volume of water contained in the lagoon at high tide) of the lagoons were large enough, they could enable the scouring of all sediment deposited by the flood tide with the ebb tide, allowing the inlet to stay open (USACE, 2002). However, San Elijo Lagoon as well as the surrounding lagoons has a small tidal prism due to the last century of sediment accumulation, making this a moot point.

The Conservancy has been up-keeping the inlet for almost 10 years now, and they have increase the time the lagoon stays open by 40%, but the present configuration still requires maintenance operations two to three times per year. Other forms of maintenance of the lagoon have been suggested repeatedly over the last decade. Analysis of long term observations has lead to multiple restoration plans that include the removal of vegetation in specific areas as well as dredging throughout the lagoon removing old structures or creating sediment traps, new
channels, and alternate inlets to improve circulation in the lagoon (City of Encinitas, 2001). Many alternatives have been presented, and for the most part, all of them predict an improvement in the lagoon’s health. However, they also bring up many concerns about the inlet, its capacity, location and dimensions. The full impact of this type of extensive alteration is still hazy, and needs further investigation.

As discussed above, significant dampening (up to 85% attenuation; Wu et al., 2006) reduces the effect of the tide in the lagoon. This results in lower velocities within the lagoon, making deposition likely and erosion improbable. Selective dredging could reduce this dampening, improving circulation, creating deep water environments, expanding the tidal prism, and improving water quality in general. The growth of the tidal prism would help to maintain an open inlet for longer. This is because the larger the prism, the larger the outflow and the stronger the ebb currents. Strong ebb currents would take the responsibility of flushing the system of any deposited sediment. To naturally maintain an open inlet, the tidal prism in 1991 needed an estimated 600,000 m³ increase. To show the magnitude of this number, the sludge available for removal in 2001 (Appendix A) came to a total of less than 32,000 m³. If no dredging occurs in the next 30 years, the present sedimentation rate of 0.8 mm/year will fill the lagoon, and the basins will no longer function as an estuarine environment (City of Encinitas, 2001).

2.2.1 Tide

The water level changes that make up the tide are caused by a combination of forces exerted on the earth by the moon and sun. The resulting patterns correlate with the position of the sun and moon with respect to each other and the earth (Flick, 2008). The elevation difference between the low and high tide is referred to as the tidal range; the tidal range for San Elijo Lagoon and the surrounding area is between one and three meters. In southern California, the tides are a mix of diurnal (once per day) and semi-diurnal (twice per day) tides. This means that there are usually two tidal cycles a day (tidal day is 24 hours and 50 minutes long), two (unequal) high tides and two (unequal) low tides. The pattern is typically a higher high tide followed by a lower low tide, and then a lower high tide followed by a higher low tide (Figure 6).

![Figure 6: Typical Daily Tidal Pattern for San Elijo Lagoon](image-url)
Fluctuations in the tidal record occur twice every day, month, year, 4.4 years, and 18.6 years (which is a tidal epoch) (Flick, 2008). These fluctuations are important because they affect the seasonally varying vegetative habitat, as well as the benthos that rely on the tide to transport them into and out of the lagoon. During each month, there are two episodes of higher and lower tides, which are referred to as “spring” and “neap” tides, correspondingly, regardless of season. Figure 7 shows the tides affecting the lagoon when velocity measurements and total suspended solids samples were taken. The Spring/Neap tide phenomenon can be observed in these plots. The spring (higher) tides occur due to full or new moon phases, while the times in between are the (lower) neap tides (Flick, 2008).

Figure 7a: Tide During May Sampling

Figure 7b: Tide During July Sampling
Seasonally, higher tide ranges occur in the summer and winter while lower ranges happen in the spring and autumn; this annual cycle is due to the declination of the sun (Figure 8) (Flick, 2008). When comparing the averaged tidal record for the last century to Mean Sea Level (MSL), researchers have found that the tidal range has been increasing. High tides have been getting higher faster than MSL, and low tides have been increasing at a slower rate than MSL. In addition, sea level has risen approximately 0.7 feet in the last century. Evidence suggests that the global MSL is rising at an accelerated rate in the last decade when compared to the 20th century (Flick, 2008). Sea level now seems to be rising around one foot per century.

### 2.2.2 Precipitation

Annual precipitation for Southern California is typically between 10” and 15” and occurs primarily in the winter season. Winter is also considered the growing season. In the spring,
dense fogs occur, and summer is known for its haze and smog. The Santa Ana winds (blown from the Mojave Desert to the Pacific Ocean) blow any moisture in the air out to sea, causing extreme dryness and flash fires.

Precipitation was also analyzed (Table 2; Figure 9). November and December of 2007 were two unusually wet months for the time of year; normal rainfall for November and December is less than an inch for each month. January was also a little wetter than normal. March and April were odd for the opposite reason. There was barely any precipitation when there would usually be at least 0.5 to 1.0 inch. This will be important later during the analysis and discussion of the results.

Table 2: Precipitation During Sampling

<table>
<thead>
<tr>
<th></th>
<th>Oct-07</th>
<th>Nov-07</th>
<th>Dec-07</th>
<th>Jan-08</th>
<th>Feb-08</th>
<th>Mar-08</th>
<th>Apr-08</th>
<th>May-08</th>
<th>Jun-08</th>
<th>Jul-08</th>
<th>Aug-08</th>
<th>Sep-08</th>
<th>Oct-08</th>
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<tbody>
<tr>
<td>mm Rain</td>
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<td>64</td>
<td>27</td>
<td>90</td>
<td>79</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>cm Rain</td>
<td>0.4</td>
<td>6.4</td>
<td>2.7</td>
<td>9</td>
<td>7.9</td>
<td>0</td>
<td>0.1</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>in of Rain</td>
<td>0.16</td>
<td>2.52</td>
<td>1.06</td>
<td>3.54</td>
<td>3.11</td>
<td>0</td>
<td>0.04</td>
<td>0.16</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
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<td># of days</td>
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<td>9</td>
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<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 9: Precipitation During Sampling

Source: SELC

2.3 Construction Setting

During sampling several projects were under construction in the area surrounding San Elijo Lagoon. Two residential areas were under construction that would add to the local runoff into the lagoon. Also the San Elijo Lagoon Conservancy’s Nature Center was under construction. The Nature Center is located directly adjacent to the lagoon, and could easily contribute to local runoff into the lagoon.
3 FIELD METHODS

A field campaign was conducted to collect a suite of hydrodynamic, sediment, and water quality data in the estuary (Figure 10). In addition to the data collected by the LSU group, other research groups and stakeholders collected background (ancillary) data. The collected data was then analyzed according to the procedures described below.

![Figure 10: San Elijo Lagoon Sampling Sites](source: Image from GoogleEarth 2007)

To make this document more cohesive, the sondes were re-named. The following table is for clarity:

<table>
<thead>
<tr>
<th>Thesis Name</th>
<th>Research Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Sonde</td>
<td>Inlet Sonde</td>
</tr>
<tr>
<td>Central Sonde</td>
<td>Segment 2 Sonde</td>
</tr>
<tr>
<td>East Sonde</td>
<td>Segment 1 Sonde</td>
</tr>
</tbody>
</table>
Ancillary data (Table 4) was collected and tabulated for use in development of the conceptual model of the estuarine hydrodynamics and for direct use in model calibration and verification.

<table>
<thead>
<tr>
<th>Table 4: Ancillary Data for San Elijo Lagoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Data</td>
</tr>
<tr>
<td>Bathymetry, Topography</td>
</tr>
<tr>
<td>Rain Gauge and flow data</td>
</tr>
<tr>
<td>Sonde Data: Date (M/D/Y), Time (hh:mm:ss), Temp (°C), Depth (m), Water Depth (m), pH, Turbidity (NTU) (15 minute intervals)</td>
</tr>
<tr>
<td>Weather Data (Daily)</td>
</tr>
<tr>
<td>Wet Weight &amp; Dry Weight for each segment of core</td>
</tr>
<tr>
<td>Wet Weight, Dry Weight, %Fines, %Organic Carbon, %Total Nitrogen, %Total Phosphorus for each segment of core</td>
</tr>
</tbody>
</table>

3.1 Hydrodynamic Data

Over a one-year period current velocities were collected three times at cross-sections of the main channels. These collections occurred at multiple stations in the lagoon (Figure 10). The channel network was accessed via kayak at a range of tidal stages. Current velocity and direction (two-dimensions in horizontal plane) were measured using a SonTek Flow Tracker handheld acoustic Doppler velocimeter (ADV) at three stations (10%, 50%, and 90%) across the channel and at two depths (20% and 80%). From these velocities, discharges were calculated and vector maps showing the magnitude and direction of the current velocity were created (with the help of Dr. Gregg Snedden, Louisiana State University). The discharge values and velocity maps were used to develop a conceptual model of the estuarine hydrodynamics and for calibration of the hydrodynamic model. These procedures are described below.

3.1.1 Water Velocity Collection and Processing

The procedure to collect and process water velocities within San Elijo Lagoon entailed taking six measurements at each cross-section. The six measurements were taken at three points across the channel (10%, 50%, and 90%) and at two depths for each of these three points (20% and 80%). If the water was shallow, only one depth measurement was taken at that station. In the very deep cross sections the center (50%) bottom (80%) measurement was taken as far as could be reached. The data were processed via Microsoft Excel into a usable format and used to create vector maps.

MATLAB® by The MathWorks™ and Google Earth by Google™ were used in conjunction to create a map of the lagoon with velocity flow vectors. The latitude and longitude of the locations where measurements were taken had to be determined by marking them in Google Earth using the field map as a reference. In the field, the measurements were taken in reference to the
centerline of the channel and the output from the ADV was in x and y components. True angle of the measurements to North and South had to be found. The resultant angles calculated were put into MATLAB® with the Google Earth Toolbox. The resulting vector maps are shown in the results section.

3.1.2 Discharge

When the velocities were measured, the depth and width of the channel was taken, making it possible to later calculate the discharge. Using the methods shown in Chow et al. (1988), discharge was calculated using the following equation:

$$ Q = \int_A V \cdot dA $$

(1)

This is approximated by Figure 11 and the following equation:

$$ Q = \Sigma_{i=1}^{n} V_i d_i \Delta \omega_i $$

(2)

where

$$ V_i = \frac{\nu_{0.2} + \nu_{0.8}}{2} $$

(3)

![Figure 11: Approximation for the Computation of Discharge](image)

3.2 Sediment Data

Sediment cores were collected every four to six weeks at two locations within the estuary, the locations staggered with each collection (Blue dots in Figure 12). The sediment cores were analyzed for grain size, bulk density, porosity, and Beryllium 7 (7Be) activities. Short term deposition and re-suspension events were determined using 7Be as a proxy for the relative age of the sediment. Using the bulk density, sediment inventories were calculated (Cable and Bourgoine, in prep). In August of 2008, ten grab samples of water were collected and then analyzed for total suspended solids (TSS). These spatial and temporal sediment data were used to identify erosional and depositional patterns within the estuary.
3.2.1 Sediment Core Collection and Processing

To collect and process sediment cores one 20-cm sediment push core was taken in the upper subtidal zones with 4”-ID polycarbonate tubing at each site. To do this, the sediment corer was pushed into the sediments as vertically as possible. The core was then pulled up, making sure that the bottom of the core remained under water. The clear insert was placed into the bottom of the core and pushed up about 1-2 mm so that the insert was flush with the bottom of the core tube, and then a cap was placed on the bottom. Once the bottom cap was secure, a cap was placed on the top. The core was carried vertically to the extruding location.

The core extruder was then set up on a stable surface. The bottom cap was loosened from the core and removed. The core tube containing the sediment was immediately placed on the extruder and held firm while the top cap was removed. The core was slowly pushed down so that the sediment interface became even with the top of the core. The overlying water poured down the sides. Using spatulas, each vertical section was comprehensively sampled. The site, date, and interval were recorded on the sample bag. Out of the 20 centimeters collected only the top 12 centimeters were sampled, the first six centimeters in one-centimeter intervals, the second six centimeters in two-centimeter intervals.

3.2.2 Beryllium 7 Processing

Following the protocol of Collis (2006), sediment physical characteristics of grain size, porosity, and bulk density were measured. Sediments were prepared and counted via gamma spectrometry on an intrinsic germanium well detector at 477.1 keV for $^7$Be. These data were used to calculate mass accumulation or removal rates (Collis, 2006). In short, activities (dpm/g) of $^7$Be were converted to inventories using the wet sediment bulk density (g/cm$^3$). Then total inventories
(dpm/cm²) were corrected for residual ⁷Be and decay through time. Finally, these new inventories (dpm/cm²) were divided by new activities (dpm/g) to yield mass accumulation or removal rates (g/cm²).

3.2.3 Grab Sample Collection and Total Suspended Solids

Ten water grab samples were collected in August of 2008. They were collected twice at five different locations, once on the incoming tide and once on the outgoing tide. The 400mL sample bottle was opened and rinsed three times. With the opening of the bottle facing the flow direction (so that water flows into the bottle), it was held under the surface of the water until completely full and the lid was secured.

To calculate the total suspended solids in the water samples, sample numbers were scraped into aluminum tins and one filter (TCLP Glass Fiber filter, 0.7 microns) was placed into each tin. Each filter weight was recorded to keep track of which sample it would be used for. The filter apparatus (Figure 13) was turned on without the vacuum enabled. A single filter was placed over each opening and wetted with distilled water. A vessel was placed over the filter and clamped into place. The bottled samples were well shaken and 200mL measured into a beaker. The vacuum was turned on and the measured sample was poured into the apparatus through the vessel. The 200mL beaker was rinsed with distilled water and poured into the vessel as well. Once the entire sample ran through the apparatus, the vessel and the apparatus were rinsed with distilled water. The purpose of these extra rinses was to capture any stray sediment. The clamp and vessel were carefully removed from on top of the filter and the vacuum turned off. The filter was carefully placed back into its original aluminum tin. This process was repeated for each sample. The filters were dried in their tins in an oven for at least 24 hours. Once the filters were dry, each was weighed again.

The TSS analysis consisted of subtracting the dried weight of each filter from its original weight. The result of this computation is the weight of sediment per 200mL of sample water. Multiplying by five and dividing by 1000 gives the result of the total suspended solids in units of mg/L.
4 MODELING METHODS

The second approach to this research was the development of a conceptual model that was further applied to a numerical model. The Danish Hydraulic Institute’s (DHI) Mike21 software package was used to develop a two-dimensional flexible mesh hydrodynamic model. This is a depth-averaged finite volume commercial program. Building and calibrating the model required the previously collected and analyzed data. The hydrodynamic model was calibrated with the May data, and then verified with the observed conditions in July and August.

4.1 Conceptual Model

The physical boundaries of the conceptual model are based on elevations. The water surface elevation in the lagoon never goes above 1.5 m NAVD88. Therefore, the cutoff for elevation was conservatively set at 2.0 m NAVD88. There is constant circulation in San Elijo Lagoon; it is never dry. There are three distinct wet regions within the lagoon: the main channel network that always has water in it, a network of smaller channels that dry out at low tide, and mudflats that also dry out at low tide. The main channel is lined on both sides with low marsh vegetation that is inundated when the tide overtops the channel network. The smaller channels break up this vegetation bank and give the water easier access to the mudflats.

Typical forcings on any coastal environment include tide, wind, precipitation, groundwater, direct surface runoff, and freshwater discharge. Water flows into the lagoon from both ends. The tide enters San Elijo at the inlet while freshwater enters the lagoon at the man-made dike in the East Basin. This freshwater discharge is the sum of the runoff from the watersheds of Escondido, La Orilla, and Lux (or Canyon) Creeks. Tide and freshwater discharge from upstream had the most impact on the hydrodynamics of the lagoon. The available fetch for wind-wave development was so small that wind as a forcing was neglected. Also, there was such a minimal amount of precipitation during the velocity collection times (May, July, and August) that the rain was neglected as well. For the other two parameters, groundwater and direct surface runoff, no data was available and were therefore excluded from the calculation.

The resulting conceptual model gave an outline of the limits of the project. The man-made dike in the East Basin was assumed as the eastern limit of the model, while Manchester Avenue was taken as the northern limit, the elevated walking path and bluffs the southern boundary, and the Pacific Ocean the western margin. The berms of the Coast Highway (101), the Santa Fe Rail Road, and Interstate 5 separated the lagoon into its basins. It was assumed that the wind, rain, direct surface runoff, and groundwater had no significant effect on the hydrodynamics of the lagoon, and therefore the only active boundaries were at the inlet in the west and the man-made dike in the east (Figure 23). The rest of the boundaries were closed, meaning that nothing entered or exited.

Based on the data available, the Mike21-FlexibleMesh (FM) suite of programs by the Danish Hydraulic Institute (DHI) was decided upon to be used for the numerical modeling. This module uses a finite volume approach; it combines the numerical stability of the Finite Difference method (regular rectangular mesh) with the ability of the Finite Element method to create
complex geometry (flexible triangular or rectangular grids). The following section reviews modeling theory, methods, and Mike21-FM’s approach.

4.2 Modeling Background

Modeling is done on three levels, related to resolution: macroscopic, intermediate, and microscopic. In a macroscopic model, the overall flow regime is shown, but flow is left unresolved in the channels and across the vegetated areas. At the intermediate scale, the main features of the marsh are identified in the model, and the uneven bathymetry is described, but local channels and small scale features are lost in averaging. On the microscopic scale the physical details of the system are included in the model; even the small channels that only emerge at low water levels are shown (King, 2001). When modeling, domains typically have irregular bathymetry and boundary features; they are most accurately represented by using unstructured grids or meshes (Teeter et al., 2001).

Modeling in marshes and wetlands brings up a number of obstacles that are not present when modeling open water bodies (King 2001). A detailed knowledge of boundary forcing, marsh topography and bathymetry, and the morphological variation of channels and inlets in response to tidal and freshwater flows is essential to produce an accurate model based simulation. It is necessary not only to understand the physical processes at work in the system, but also to account for them in the model (Goodwin and Kamman, 2001).

The biggest difference between the flow regimes of marshes and open water systems is the depth. Marshes are much shallower than typical open water systems. Also, with the oscillations of tides, depth changes can be on the order of the overall depth (King, 2001). In open water, this depth change is neglected.

4.2.1 Governing Equations

The Mike21 model uses the two-dimensional shallow water equations. These are based on the solution of the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure (MIKE21-FM Scientific Documentation Manual). This comprises of the continuity equation (4) and the x-component (5) and y-component (6) of the momentum equation, shown below. When using the continuity equation, it is assumed that the tidal prism can be calculated as the volume of water contained between the tidal maximum and minimum horizontal planes. The flow in ebb is assumed to be equal to the flow in flood (Fagherazzi, 2002).

Shallow Water Equations: By integrating the continuity equation and the horizontal momentum equations over depth, the following two-dimensional shallow water equations are obtained.

\[
\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = hS
\]  

(4)
\[
\frac{\partial h\overline{u}}{\partial t} + \frac{\partial h\overline{u}^2}{\partial x} + \frac{\partial h\overline{v}u}{\partial y} = f\nu h - gh \frac{\partial \eta}{\partial x} - \frac{h}{\rho_o} \frac{\partial p_a}{\partial x} - \frac{gh^2}{2\rho_o} \frac{\partial \rho}{\partial x} + \frac{\tau_{sx}}{\rho_o} - \tau_{bx} - \frac{1}{\rho_o} \left( \frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right) + \frac{\partial}{\partial x} \left( hT_{xx} \right) + \frac{\partial}{\partial y} \left( hT_{xy} \right) + hu_sS
\]

\[
\frac{\partial h\overline{v}}{\partial t} + \frac{\partial h\overline{v}v}{\partial x} + \frac{\partial h\overline{u}v}{\partial y} = -f\nu h - gh \frac{\partial \eta}{\partial y} - \frac{h}{\rho_o} \frac{\partial p_a}{\partial y} - \frac{gh^2}{2\rho_o} \frac{\partial \rho}{\partial y} + \frac{\tau_{sy}}{\rho_o} - \tau_{by} - \frac{1}{\rho_o} \left( \frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y} \right) + \frac{\partial}{\partial x} \left( hT_{xy} \right) + \frac{\partial}{\partial y} \left( hT_{yy} \right) + hv_sS
\]

Any variable with an overbar (i.e. \(\overline{u}\)) indicates that it is depth averaged \((h = \eta + d)\). The definitions of the variables are listed in Table 5.

<table>
<thead>
<tr>
<th>Variable/Symbol</th>
<th>Definition</th>
<th>Variable/Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t)</td>
<td>Time</td>
<td>(h)</td>
<td>Water depth</td>
</tr>
<tr>
<td>(x, y)</td>
<td>Cartesian coordinates</td>
<td>(g)</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>(S)</td>
<td>Discharge</td>
<td>(\overline{u}, \overline{v})</td>
<td>Depth averaged velocity in the (x) and (y) directions</td>
</tr>
<tr>
<td>(\rho_o)</td>
<td>Reference density of water</td>
<td>(\eta)</td>
<td>Water surface elevation</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density of water</td>
<td>(\tau_{bx}, \tau_{by})</td>
<td>Components of Bottom Stress</td>
</tr>
<tr>
<td>(p_a)</td>
<td>Atmospheric pressure</td>
<td>(\tau_{sx}, \tau_{sy})</td>
<td>Components of Surface Wind Stress</td>
</tr>
<tr>
<td>(s_{xx}, s_{xy}, s_{yx}, s_{yy})</td>
<td>Components of radiation stress</td>
<td>(u_s, v_s)</td>
<td>Velocity by which water is discharged into ambient water</td>
</tr>
<tr>
<td>(T_{xx}, T_{xy}, T_{yx}, T_{yy})</td>
<td>Components of lateral stress</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Definitions of Variables in the 2D Shallow Water Equations

Source: MikeZero User Manual

The key to understanding the estuarine system lies in the determination of tidal fluxes. Numerical resolution of the shallow water equations is considered to be a powerful technique, and is widely used (Fagherazzi et al., 2003). The shallow water equations, when utilized to propagate tides through an estuary, are dependent on embayment geometry, bottom friction, length of embayment, and the presence of tidal flats (Fagherazzi et al., 2003; van Leeumen et al., 2000). There are several methods to simplify the shallow water equations; they include assuming the water to be an incompressible fluid, elimination of the inertial and diffusion terms, neglecting the friction at the bottom, and integrating over the depth to get a vertical average (Fagherazzi, 2002; Fagherazzi et al., 2003). It is customary to do depth averaging for most two dimensional models. This approach is easily justified and very useful for shallow, near homogeneous estuaries (Teeter et al., 2001).
4.2.2 Solution Technique

For simplified solutions to be effective, they have three requirements. They must have a strong site-specific physical basis, have an origin from general principle (conservation of mass, momentum, or energy), and if a full set of equations has already been described in the problem, the solution has to satisfy these equations (Fagherazzi, 2002). If a setup is not site-specific, results can be meaningless or wrong. A site-specific model is based in fieldwork which is required to calibrate and validate the model; the combination of fieldwork and modeling can be highly effective (Lumborg and Windelin, 2003).

In Mike21 there are two parts of the numerical calculation that can be controlled: the time integration and the space discretization. There are two options for both of these aspects of the solution technique: a lower order scheme (first order) or a higher order scheme. The lower-order scheme is less accurate than the higher, but it is computationally much faster. As a general rule, the higher-order space discretization should be chosen when the important processes are dominated by convection (flow), and the lower-order space discretization should be chosen if those processes are dominated by diffusion. The time integration method should be chosen to match the space discretization method. It should be kept in mind that choosing both to be higher-order will increase the running time by an order of magnitude of 3-4, but the higher-order scheme will produce results that are more accurate than the lower-order scheme (Mike21-FM User Manual).

A measure of the stability of the numerical scheme is the Courant-Friedrich-Lévy, or CFL number. If the CFL number is below one, then the stability of the numerical scheme should be secure. For the shallow water equations in Cartesian coordinates, the CFL number is defined as

\[
CFL_{HD} = \left( \sqrt{gh} + |u| \right) \frac{\Delta t}{\Delta x} + \left( \sqrt{gh} + |v| \right) \frac{\Delta t}{\Delta y}
\]  

(7)

where \( h \) is the total water depth, \( u \) and \( v \) are the velocity components in the x- and y-direction, \( g \) is the gravitational acceleration, \( \Delta x \) and \( \Delta y \) are a characteristic length scale in the x- and y-direction for an element and \( \Delta t \) is the time step interval. The characteristic length scale, \( \Delta x \) and \( \Delta y \), is approximated by the minimum edge length for each element and the water depth, and the velocity component is evaluated at the element’s center.

The CFL number is an estimate, and therefore stability problems can occur. If this happens, the critical CFL value can be reduced (default value is 0.8). Also, the calculation of the shallow water equations uses a variable time step interval so that the CFL number stays below that critical level. The user can define a minimum and maximum time step to help control the interval the model uses. Reduction of the maximum time step can also help to control the stability of the numerical calculation (Mike21-FM User Manual).

4.2.3 Flooding and Drying

To accurately describe the way a system floods, drains, and re-floods, a numerical model must be microscopic and use a high resolution grid capable of modeling the minute processes in the
channels. Over a tidal cycle, the marsh will alternate between being wet and dry. In open water systems, this condition is negligible and mostly ignored, but in estuarine environments the process of wetting and drying presents the unique difficulty of representing a moving boundary. As the surface elevation changes, so does the shape of the exposed marsh (King, 2001). This is an extremely difficult problem to resolve, especially in a two dimensional model (Goodwin and Kamman, 2001). The model must be capable of defining a moving boundary at the point where water depth equals zero (King, 2001).

One option is to create a method that automatically moves all boundaries to the zero depth location. This method determines the location where the depth equals zero within each element. The elements are divided into three groups: fully inundated, partially inundated with a zero-depth boundary passing through it, and fully dry and therefore ignored (taken out of the computation). The movement of boundaries is extremely complex and can require automatic mesh generation algorithms. This method also requires a degree of precision to match boundaries that many finite difference models are not capable of. The second option is to drop an element when it becomes dry and return it when the element is inundated again. This method has had problems with premature removal of elements and leads to inaccuracies within the mass balance equation. As a direct consequence, the tidal prism can be underestimated and there are errors in the simulation of current magnitude and depth in the inland reaches of the marsh area. The third option was introduced to solve some of these problems by leaving the element in the system until the entire area is dry. This does help, but because the zero depth boundary is taken at the edges of the partially wet elements, it is not accurately represented. The fourth and final option is to not drop any elements, but manipulate the governing equations to make the velocities near zero where the zero depth line is located (King, 2001).

Most of the methods just reviewed use a minimum depth threshold in a computational cell to signify the drying of a region to avoid numerical instability. This minimum depth is based on the effective roughness length, $k_s$, or the measure of flow resistance in a wetland. During the simulation, if the water surface drops below this critical elevation, the cell is considered to be dry, and no water is allowed to enter it until the water surface rises in neighboring cells. Where this occurs is called the wetting and drying front, and it is performed in the two horizontal dimensions so that flow is unrestricted in the domain (Goodwin and Kamman, 2001). Most modern numerical models calculate flows using a horizontal two dimensional formulation so that when the marsh is fully inundated, overland flow occurs, and as the water level drops, marsh topography emerges and flow confines itself to defined channels. The model moves from two dimensional overland flow to one dimensional channel flow as the tide falls (King, 2001).

Mike21-FM uses a moving boundary approach that utilizes three parameters to define the wetting and drying scheme, the drying water depth, the flooding water depth and the wetting water depth. By setting the momentum fluxes to zero and only considering the mass fluxes, the problem can be reformulated. The depth in each element or cell is monitored continuously, and the problem is reformulated when the depths of water become small. The boundary moves when depths are very small and those cells are removed from the calculation (Mike21-FM User Manual).
The elements are classified as dry, partially dry, and wet. These classifications are based on three tolerance depths, $h_{\text{dry}}$, $h_{\text{flood}}$, and $h_{\text{wet}}$. The wetting depth, $h_{\text{wet}}$, must be larger than the drying depth, $h_{\text{dry}}$, and flooding depth, $h_{\text{flood}}$, and they must satisfy the following relationship.

$$h_{\text{dry}} < h_{\text{flood}} < h_{\text{wet}}$$  \(\text{(8)}\)

The faces of each element are also monitored, and help to define whether or not the element is considered dry, partially dry or wet. There are two criteria that an element face has to meet to be considered flooded, and the manual defines these best,

“Firstly, the water depth at one side of face must be less than a tolerance depth, $h_{\text{dry}}$, and the water depth at the other side of the face larger than a tolerance depth, $h_{\text{flood}}$. Secondly, the sum of the still water depth at the side for which the water depth is less than $h_{\text{dry}}$ and the surface elevation at the other side must be larger than zero (Mike21-FM User Manual).”

An element is considered dry if there are no flooded faces and the water depth in the element is less than $h_{\text{dry}}$. An element is partially dry in one of two cases, when one element face is flooded and the water depth in the element is less than $h_{\text{dry}}$, or when the water depth in the element is greater than $h_{\text{dry}}$ but less than $h_{\text{wet}}$. An element is wet if the water depth is greater than $h_{\text{wet}}$. When the element is wet, both the mass and momentum fluxes are calculated. When an element is dry, and removed from the calculation, the small amount of water that remains in the cell is removed from the computational domain. This water depth is saved and reused when the element is put back into the calculation for conservation of mass (Mike21-FM User Manual).

4.2.4 Horizontal Eddy Viscosity

The concept of eddy viscosity is used to counteract the additional stress terms in the governing equations that result from turbulent fluctuations and some non-resolved processes in both space and time. Eddy viscosity allows the effective shear stresses in the momentum equations to contain the laminar stresses and the Reynolds stresses (turbulence). There are three ways of dealing with the horizontal eddy viscosity in Mike21-FM, adopting no eddy viscosity, constant eddy viscosity, or using the Smagorinsky eddy viscosity formulation. An eddy viscosity coefficient must be specified if the constant eddy viscosity formulation is chosen, and a Smagorinsky coefficient can be specified as constant or varying in domain if the Smagorinsky eddy viscosity formulation is chosen. It should be noted that using the Smagorinsky eddy viscosity formulation increases the CPU usage time (Mike21-FM User Manual).

4.2.5 Bed Resistance/Roughness

The bed resistance is calculated using the bottom stress, and can be defined either by the Chezy number or the Manning number. The bottom stress is determined by the quadratic friction law:

$$\frac{\tau_{b}}{\rho_{o}} = c_{f} \frac{\left| u_{b} \right|}{|u_{b}|}$$  \(\text{(9)}\)
where $|\tau_b|$ is the bottom stress, $c_f$ is the drag coefficient, $|\mathbf{u}_b|$ is the depth averaged velocity above the bottom and $\rho_o$ is the density of the water. The drag coefficient can be determined from the Chezy number, $C$, or Manning number, $M$

$$
c_f = g/C^2
$$

$$
c_f = \frac{g}{(Mh^{1/6})^2}
$$

where $h$ is the total water depth and $g$ is the gravitational acceleration. The units of Chezy numbers and Manning numbers are $(m^{1/2}/s)$ and $(m^{1/3}/s)$, respectively. Please note that the relation between the Manning number and the bed roughness length, $k_s$, can be estimated using the following. The bed roughness length, $k_s$, comes from the local grain size.

$$
M = 25.4/k_s^{1/6}
$$

Also note that the Manning number used here is the reciprocal value of the Manning’s $n$.

### 4.2.6 Coriolis Forcing

There are three options in Mike21-FM for calculation of the Coriolis force: one, there is no coriolis force; two, the coriolis force is constant in the domain; and three, the coriolis force varies throughout the domain. If the ‘constant in domain’ option is chosen, then a reference latitude (in degrees) must be specified. The Coriolis force will be calculated using this reference latitude. The geographic information given in the mesh file is used when the ‘varying in domain’ option is selected (Mike21-FM User Manual).

### 4.2.7 Initial Conditions

Initial conditions that can be specified in a model are usually the water surface elevation and the direction and velocity of water movement in the domain. Mike21-FM allows for the user to specify these variables as constant, spatially varying surface elevation with zero velocity, or spatially varying water depths and velocities. For the last case, the input can be the result of a previous simulation. An initial surface elevation should be chosen to closely match to the boundary conditions at the start of the simulation. This will reduce the probability of shock waves forming (Mike21-FM User Manual).

### 4.2.8 Boundary Conditions

There are several assumptions when developing the boundary condition for numerical models. For example, the water surface can be initially taken as flat in small basins with tidal wavelengths that are long compared to the basin’s dimensions. This flat water surface is considered to oscillate synchronously with the tide levels at the inlet (Fagherazzi et al., 2003). Another assumption is to take a zero flux at the land water boundary (Fagherazzi, 2002). This will factor out surface runoff, and it will drastically simplify the model. This, combined with
other fixed boundaries (especially no sea level rise) make it possible to show that morphodynamic equilibrium does exist (van Leeumen et al., 2000).

In Mike21 FM’s Hydrodynamic model, there are six boundary conditions. For stationary solid boundaries (land boundaries) there are two options. The "Land (normal velocity)" is where the full slip boundary condition is assumed to hold and the normal velocity component is zero. The "Land (zero velocity)" is where the no slip condition is assumed to hold and both the normal and tangential velocity components are zero. The other four boundaries are specified by the velocities, fluxes, water levels, or discharges along the boundary. When the velocity or flux boundary is selected, the velocities or fluxes (flux is the depth integrated velocity) in the x- and y-direction can be specified in three different ways: constant (in time and along boundary), variable in time and constant along boundary, and variable in time and along boundary. If a level boundary is selected the format of the water level (surface elevation, in m) can be specified as constant in time and along boundary, variable in time and constant along boundary, and variable in time and along boundary. The discharge boundary, however, can only be specified as constant in time and variable in time. The discharge will always be distributed along the boundary as it would have been in a uniform flow field with the Manning resistance law applied.

4.3 Hydrodynamic Modeling: Mike21-FM

4.3.1 Bathymetry and Mesh Generation

The physical basis of the model is topography and bathymetry that was collected in 2000 by researchers at SCRIPPs in San Diego. The topography and bathymetry was provided in a grid with 20 m spacing (Figure 14). The main channel varies from 5 to 40 meters wide. This meant that the grid of elevation data was large enough to miss significant physical attributes in San Elijo, such as the smaller channel networks.

Figure 14a: Topography and Bathymetry Grid for San Elijo Lagoon
Aerial overlaid with data grid
Source: Images from GoogleEarth 2007
Mike21-FM provides a platform or Graphical User Interface (GUI) called MikeZero, with which a mesh can be generated. Using MikeZero, a mesh was generated based on the provided elevation data (Figure 15). To try and minimize computation time, most of the lagoon uses a larger triangular mesh (52.4 m$^2$; 564 ft$^2$), while the main channel uses a finer mesh (22.4 m$^2$; 241 ft$^2$). The size of the mesh was also based on what was needed to capture the activity in that area. The mesh was smoothed to reduce sharp angles that would cause a place where the program generates smaller and smaller triangles that increase computation time.

Figure 14b: Topography and Bathymetry Grid for San Elijo Lagoon
Zoom in of Aerial overlaid with data grid
Source: Images from GoogleEarth 2007

Figure 15a: Mesh for Bathymetry of San Elijo Lagoon
Aerial overlaid with data grid and flexible mesh
Source: Images from GoogleEarth 2007
The resulting bathymetry (Figure 16) was then truth-checked against historical conditions, documented marsh habitat conditions, and recent aerial photography (Figures 17-18). As stated previously, the topography/bathymetry data had several drawbacks. It appeared to have been collected at a time when the inlet needed to be dredged, shown by the high elevations in the Inlet Channel. Also, the lagoon was only open to tidal influence roughly 50% of the time in the years leading up to the data collection (Appendix B). In addition, the grid of elevation data was large enough to miss significant physical attributes in San Elijo, such as the smaller channel networks.
Figure 17: Altered for 2008 Bathymetry of San Elijo Lagoon

Figure 18: Aerial Photography Overlain by Altered Bathymetry

Source: Images from GoogleEarth 2007
4.3.2 Input Data

A variety of data were collected and used as input into the model. Table 6 contains a summary of the input, and the following text expands on it.

<table>
<thead>
<tr>
<th>Table 6: Model Input for the Hydrodynamic Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Technique</td>
</tr>
<tr>
<td>Flood and Dry (h)</td>
</tr>
<tr>
<td>Density (ρ)</td>
</tr>
<tr>
<td>Eddy Viscosity</td>
</tr>
<tr>
<td>(Txx, Txy, Tyx, Tyy)</td>
</tr>
<tr>
<td>Bed Resistance</td>
</tr>
<tr>
<td>(τbx, τby)</td>
</tr>
<tr>
<td>Initial Conditions</td>
</tr>
<tr>
<td>(η, u, v)</td>
</tr>
<tr>
<td>Boundary Conditions</td>
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<tr>
<td>Ocean Inlet (η)</td>
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<tr>
<td>Dike</td>
</tr>
<tr>
<td>Dike Culverts (S)</td>
</tr>
<tr>
<td>Land Boundary</td>
</tr>
<tr>
<td>Outputs</td>
</tr>
</tbody>
</table>

4.3.2.1 Water Level Data

Tide data was collected from the National Oceanic and Atmospheric Association (NOAA) website. The gauge nearest to San Elijo Lagoon was located at the SCRIPPs pier in La Jolla, CA (Station 9410230), which began recording data in 1925 (Flick, 2008). During the project, three data sondes were deployed within the estuary, one near the inlet at the railroad bridge (Inlet Sonde), one in the central basin closer to the ocean (Central Sonde) and one at the I-5 bridge where the Central and East Basins are separated (East Sonde; Figure 10). The East Sonde was near a column of the I-5 Bridge and the Central Sonde was stationed near the reserve’s walking path. Due to its mooring elevation, the Central Sonde has gaps in its record when the tide was so low that it left the sonde dry (Figure 19).

4.3.2.2 Discharge Data

At the upland end of the lagoon, the man-made dike collects and distributes fresh water into San Elijo Lagoon from the three creeks upstream (Escondido, La Orilla, and Lux Creeks). The San Elijo Lagoon Conservancy (SELC) monitors the flow from the dike, and has developed a stage/discharge relationship for the freshwater input into the lagoon (Figure 20). The gate at the north end of the dike was broken in a closed position in the mid 20th century and the south gate was closed from November 21, 2007 to March 26, 2008 and open during the rest of the sampling period.
Figure 19: Measured Water Levels
The equations given below are used to calculate the discharge into the lagoon from the water level observed at the dike. In the two locations along the dike where water is allowed to flow into the East Basin, the resulting discharge was converted to metric and input into the model as varying discharge, constant along the boundary (Figure 23). The equations for one gate open and one gate closed are as follows:

\[ Q = 0 \]  \hspace{1cm} (13)

Where: \( x = x < 2.62 \text{ ft} \)

\[ Q = ax + b \]  \hspace{1cm} (14)

Where: \( 2.62 \leq x \leq 2.71 \text{ ft} \)
\[
\begin{align*}
    a &= 0.406975 \\
    b &= -1.06627
\end{align*}
\]

\[ Q = ax^4 + bx^3 + cx^2 + dx + e \]  \hspace{1cm} (15)

Where: \( 2.71 < x \leq 6.69 \text{ ft} \)
\[
\begin{align*}
    a &= 0.15925405 \\
    b &= -1.8980236 \\
    c &= 9.2690047 \\
    d &= -14.343968 \\
    e &= 0.022223789
\end{align*}
\]

where \( Q \) is discharge in cubic feet per second and \( x \) is the water surface elevation above mean sea level in feet. The resulting input is shown in Figure 21.
4.3.2.3 Coefficients

As discussed in section 4.2 (Modeling Background), there are two coefficients of concern in this model: the drag coefficient (roughness) and the eddy viscosity. The Mannings Number (M) (equivalent to the reciprocal of the manning coefficient, n) was used for the roughness coefficient. This roughness varied in the domain (Figure 22), but was kept constant over time. The values of M ranged from 4 to 60 (MikeZero User Manual). The justification for the different reaches is based on grain size. The largest grains (cobbles, gravel, coarse sand) are found in the Inlet, coarse to medium sands are found in Reach 1, and the sediment further into the lagoon have a larger mix of fines. There is also a mix of fines moving laterally away from the main channel. This is where the vegetation slows water down, causing sediments to drop out of suspension. The largest grains would drop out first, closest to the channel and fine further away from the source (main channel).
For eddy viscosity, the Smagorinsky coefficient was used. The default value was 0.28, but upon further research, it was found that 0.28 is more common for open water conditions and a value of 0.1 is more appropriate for channelized systems (Thomas and Williams, 1995). This value was taken as constant in domain and constant through time.

4.3.2.4 Boundary Conditions

There were three different boundary conditions: one at the inlet, which was the ocean, two, at the land/water interface, and three, at the dike, where the two weirs allow the upstream freshwater runoff through (Figure 23). The ocean boundary was set to ‘varying in time’, ‘constant along boundary’, and the input file consisted of the tide data gathered from NOAA (Station 9410230; Section 2.2.1 on page 16). Since there was no measured information on surface runoff discharged from the area directly adjacent to the lagoon, the land boundary was set to ‘zero normal flux’. Some error in the model can be accounted for because of this. At the dike, the discharge calculated from the stage relationship was input as ‘varying with time’, ‘constant along boundary’.

![Figure 23: Boundaries](image)

4.3.3 Output Data

A variety of options exist for output of the MIKE21-FM modeling system. For example, the post-processor allows for the selection of any x-y data point in the mesh, resulting in a depth-averaged output of the u-velocity, v-velocity, current speed, current direction, etc (Figure 24). Also available is a mass budget output, which uses the entire mesh, and a discharge output where the user selects a line (for example, across a channel) where the discharge value is wanted.
Figure 24: Example of Output of Mike21-FM
5 FIELD RESULTS

5.1 Hydrodynamic Data

5.1.1 Vector Maps

The following figures show the magnitude and direction of velocity near the top and bottom (0.2d and 0.8d, respectively) of the water column (d = height of water column). Figures 25(a) – (d) show that the top and bottom velocities are similar in magnitude and direction in SEL. This means that the assumption of a well-mixed environment is a good one, and that using a 2D depth-averaged model is ok. Figure 25(e) shows the top values for Augusts’ incoming and outgoing tide. It shows that the velocities in the lagoon are nearly opposite in direction, which is to be expected. The magnitudes are nearly equal, though at certain locations the outgoing tide has a higher velocity. This suggests a stronger outgoing tide, which is supported by the tidal asymmetry of the region (Flick et al., 2008). However, the higher velocity may simply be due to sampling at different parts of the tidal cycle.

Figure 25a: Vector Maps, May Outgoing Tide (Blue = Top)
Source: Image from GoogleEarth 2007
Figure 25b: Vector Maps, July Outgoing Tide (Blue = Top)
*Source: Image from GoogleEarth 2007*

Figure 25c: Vector Maps, August Incoming Tide (Blue = Top)
*Source: Image from GoogleEarth 2007*
Figure 25d: Vector Maps, August Outgoing Tide (Blue = Top)
Source: Image from GoogleEarth 2007

Figure 25e: Vector Maps, August In vs. Out Top (Green = In)
Source: Image from GoogleEarth 2007
5.1.2 Discharge

The discharge was calculated from the collected velocities. These calculations show the lagoon’s significant attenuation of the tidal signal. Figure 26 shows this particularly well. All four sets of data have a similar trend. The August data is especially interesting, as it shows the discharge getting smaller further into the lagoon and larger traveling out of the lagoon. This means that the water slows as it enters the lagoon, resulting in a smaller amount entering the upper reaches.

Figure 26: Discharges Calculated from Velocity Measurements
5.2 Sediment Data

5.2.1 Core Samples

The grain sizes for the study were based on soil borings collected from two locations in the central basin of the lagoon (Figure 10). Previous studies did not indicate a specific pattern of sediment grain size distribution along the lagoon, but did have some general characteristics: fine sand generally constitutes a large fraction of the sediment within the lagoon ranging from 43% to 93% of the total sediment, less than 1% of the sediment is larger than medium sand, and silt and clay (cohesive bed materials) still made up a significant fraction of sediment in the lagoon (San Diego County Report, 2006). Based on these findings, this study concentrated on two classifications: percent sand (>0.063 mm) and percent fines (<0.063 mm; Figure 27).

Figure 27: San Elijo Lagoon Core Samples

<table>
<thead>
<tr>
<th></th>
<th>January Station 1</th>
<th>January Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>18.7</td>
<td>0.0</td>
</tr>
<tr>
<td>4-5</td>
<td>28.0</td>
<td>36.4</td>
</tr>
<tr>
<td>6-8</td>
<td>32.5</td>
<td>35.9</td>
</tr>
<tr>
<td>10-12</td>
<td>49.9</td>
<td>46.0</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>April Station 1</th>
<th>April Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>17.7</td>
<td>28.9</td>
</tr>
<tr>
<td>4-5</td>
<td>23.2</td>
<td>38.4</td>
</tr>
<tr>
<td>6-8</td>
<td>44.3</td>
<td>41.5</td>
</tr>
<tr>
<td>10-12</td>
<td>64.3</td>
<td>59.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>July Station 1</th>
<th>July Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>5.4</td>
<td>15.8</td>
</tr>
<tr>
<td>2-3</td>
<td>8.3</td>
<td>28.8</td>
</tr>
<tr>
<td>4-5</td>
<td>9.1</td>
<td>42.1</td>
</tr>
<tr>
<td>6-8</td>
<td>5.8</td>
<td>58.8</td>
</tr>
<tr>
<td>10-12</td>
<td>9.8</td>
<td>71.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>September Station 1</th>
<th>September Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>12.0</td>
<td>28.0</td>
</tr>
<tr>
<td>2-3</td>
<td>9.9</td>
<td>42.7</td>
</tr>
<tr>
<td>4-5</td>
<td>14.1</td>
<td>57.3</td>
</tr>
<tr>
<td>6-8</td>
<td>14.3</td>
<td>67.0</td>
</tr>
<tr>
<td>10-12</td>
<td>10.9</td>
<td>72.0</td>
</tr>
</tbody>
</table>

Source: SCCWRP
There is a distinct seasonal influence to the grain size fractions (Figure 27). In January, both stations are more evenly divided between sands and fines. By April the top 4 to 6 cm of sediments start to show a preference of more fines or more sands that is more apparent through July and September. The figure from April on shows that Station 1 of the lagoon (closer to the ocean) is dominated by sands while Station 2 (further inland; Figure 10) has more fines.

5.2.2 Beryllium 7

Beryllium is a particle reactive element with a half life of 53.12 days; it can therefore be a good indicator of recent sediment behavior in finer sediments. It is produced in the atmosphere by cosmic ray spallation of oxygen and nitrogen, and may fall out as dry deposition or be washed out by precipitation. Dry deposition may be especially important for San Elijo Lagoon and all of Southern California due to the seasonal flash forest fires. The Santa Ana winds are generated in the desert to the east, and carry dust and fine sediments west over the coastal mountains to the Pacific Ocean. As shown in Figure 28, the flash fires generate copious amounts of smoke and ash, which could scavenge beryllium in the atmosphere. The Santa Ana winds then disperse the ash and dust with the beryllium attached large distances, depositing it in coastal areas.

![Figure 28: California Flash Fires in the Fall of 2007](earthobservatory.nasa.gov/NaturalHazards/view.php?id=19219)

Sediment cores were collected, sectioned in the field, and returned to Louisiana State University for analysis of beryllium activities for nine sampling events (from November 2007 to October 2008). Results from the $^7$Be activities were then used to calculate inventories in the sediment (e.g. Collis, 2006). Inventories can be converted to mass accumulation and removal rates for a given new $^7$Be activity. Monthly mass accumulation (positive) or removal (negative) trends are shown in Figure 29.
(a) Station 1 correlates to the core sampling site 1 in Figure 15

(b) Station 2 correlates to core sampling site 2 in Figure 15

Figure 29: Mass Accumulation and Removal (Results of $^7$Be Analysis)
When the annual sediment movement is quantified as the sum of monthly mass accumulation and removal for each station, net deposition is found at each site (Table 7). The main sources for $^7$Be and sediments are the atmosphere, ocean, and both upstream and direct runoff.

### Table 7: Mass Accumulation/Removal Rates (g/cm²)

<table>
<thead>
<tr>
<th>Sampling Period</th>
<th>Station 1</th>
<th>Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-November-07</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>13-December-07</td>
<td>1.5619</td>
<td>-0.7392</td>
</tr>
<tr>
<td>21-January-08</td>
<td>-1.5258</td>
<td>4.2852</td>
</tr>
<tr>
<td>28-February-08</td>
<td>1.9381</td>
<td>-3.7329</td>
</tr>
<tr>
<td>3-April-08</td>
<td>-10.4750</td>
<td>0.6503</td>
</tr>
<tr>
<td>14-May-08</td>
<td>0.3980</td>
<td>-0.2900</td>
</tr>
<tr>
<td>24-July-08</td>
<td>3.2311</td>
<td>3.8198</td>
</tr>
<tr>
<td>20-August-08</td>
<td>2.2579</td>
<td>0.5661</td>
</tr>
<tr>
<td>30-September-08</td>
<td>7.3095</td>
<td>1.2016</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>4.6957</strong></td>
<td><strong>5.7610</strong></td>
</tr>
</tbody>
</table>

For the months of December 2007 through May 2008 the two stations show an inverse relationship. When one station is seeing an accumulation event, the other is experiencing a removal event. The seemingly inverse relationship between the two areas of the lagoon could mean several things. One area of the lagoon could serve as a $^7$Be source for the other, the tidally induced circulation redistributing the $^7$Be rich sediments to other areas of the lagoon. The source of the $^7$Be could be the ocean, the discharge from upstream, or some combination of the two.

Part of the inverse relationship could be explained by how precipitation affects the different areas of the lagoon. At Station 1 rain produces runoff that likely carries $^7$Be rich sediment directly into the lagoon, causing an apparent accumulation event. The rain produces a stronger outflow at Station 2 with the additional flow from the runoff in the upstream watersheds, producing a removal event. However, the gate in the dike was closed from late November of 2007 to late March of 2008. The rain event in November likely overtopped the dike, producing a large flow that may have caused the removal at Station 2 in December. The combined rains in January and February of 2008 could also have overtopped the dike, producing a removal event at Station 2, but this is speculation.

In March of 2008, the inlet closed and the lagoon was not open to tidal flushing. At the end of March/ beginning of April, two things happened simultaneously: the inlet was dredged allowing for tidal flushing, and the gate in the dike was opened allowing for freshwater to flow in and help flush out the lagoon. As a result, for April 2008 Station 1 has a large removal event because of the inlet being dredged. Station 2 is not as strongly affected as Station 1. It could have
accumulated sediment while both the inlet and gate were closed, and when they were opened, this large accumulation was removed, leaving a smaller accumulation event.

In May of 2008, there was a small rain event that produced direct runoff into the lagoon from the surrounding roads and residences. This runoff likely carried $^7$Be rich sediments that would immediately be mixed into the system. This accounts for the small accumulation event at Station 1. This rain event was also the first rain event since the opening of the gate in the dike, resulting in a stronger discharge and a small removal event at Station 2.

From July 2008 to the end of sampling in September 2008, both stations experienced high accumulation events. This could be explained by dry fallout, but that is purely speculation. The source of the $^7$Be would have been from the flash fires that began in late June. The smoke carried by the Santa Ana winds could have brought the extra $^7$Be into the system as ash fallout, causing a false-positive effect for the months of July through September of 2008.

5.2.3 Total Suspended Solids

At the same time that velocity measurements were taken in August, water samples were taken for further analysis of total suspended solids (TSS). It is important to look at the trend of the data, not the numbers, since this was one isolated data gathering and there is no extensive data to support the actual numbers (Figure 30). The overall trend is that the flow carries less sediment the further into the lagoon it goes on the incoming tide, and the flow picks up more sediment as it leaves on the outgoing tide. This agrees with the results from the velocity measurements and the consequent discharge calculations. In August the flow velocity and discharge decrease as the rising tide goes further into the lagoon, so the sediment would drop out; the outgoing tide’s flow velocity increases as it travels out of the lagoon, possibly picking up sediment as it speeds up.

![Figure 30: August Total Suspended Solids Results](image-url)

Error bars calculated using Standard Error
6 MODELING RESULTS

6.1 Calibration

It was important to match up May’s observed conditions to the model results. These are listed below.

- a lag of 36 minutes between the ocean (boundary) and the Inlet Sonde,
- no lag between the Inlet Sonde and the Central Sonde,
- a lag of 15 minutes between the Central Sonde and the East Sonde,

The model was calibrated by adjusting the Manning’s Number (M) (the reciprocal of the Manning’s Coefficient, n). The effect of the roughness changes on the water surface elevations (WSEL) had distinct impacts. When the roughness was the same for both the Inlet and Reach 1, the lag between the Inlet and Central Sondes was not long enough. Also, if Reach 1’s roughness value was too high (smoother), the time lag between the Central and East Sondes became insufficient. When the Manning’s Roughness, M was set too low (rougher), the tidal signal deformed and became too elongated.

Two and a half days of the WSELS resulting from the chosen roughness combination are shown in Figure 31. Only the last 12 hours should be considered. The first two days of the simulation are the model coming to steady state. Because the inputs at the boundaries are changing over time, the model is by definition unsteady, so it was run for those two extra days to equilibrate. Table 8 tabulates the difference between the measured/observed conditions and Mike21-FM’s simulated results.

<table>
<thead>
<tr>
<th>Table 8: Timing and WSEL Results of Calibration (May data)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Min WSEL</strong></td>
</tr>
<tr>
<td><strong>Measure</strong></td>
</tr>
<tr>
<td>Midi</td>
</tr>
<tr>
<td>m NAVD88</td>
</tr>
<tr>
<td>Max WSEL</td>
</tr>
<tr>
<td>m NAVD88</td>
</tr>
</tbody>
</table>

¹ Tide Measured timing is in 6 minute intervals; Sonde Measured timing is in 15 minute intervals; Model timing is in 5 minute intervals
² These Measured times and WSELS are not available since the water level dropped below the sonde.
Figure 31: May Calibration Results
Gray box is the results to be looked at; the first two days of simulation are equilibration time.
After the model was calibrated, a sensitivity analysis was done to finalize the roughness coefficients. This was done by running the model with different combinations of roughnesses for the three divisions of the lagoon (Inlet, Reach 1, and the rest of the lagoon; Figure 22). Firstly, the water surface elevations were matched up and then the velocities were looked at. Twelve different scenarios were run, the six best matching velocities shown below (Figure 32). A root mean squared deviation analysis was done (Table 9), and the scenario where the Inlet M = 4, Reach 1 M = 5, All Else M = 60 was the best fit when looking at both WSELs and velocities.

**Table 9: Root Mean Squared Deviation**

<table>
<thead>
<tr>
<th>Combination of Roughness</th>
<th>RMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet M=6 All Else M=60</td>
<td>3.95E-02</td>
</tr>
<tr>
<td>Inlet M=7 All Else M=60</td>
<td>4.55E-02</td>
</tr>
<tr>
<td>Inlet M=10 Reach 1 M=10 All Else M=60</td>
<td>4.42E-02</td>
</tr>
<tr>
<td>Inlet M=10 All Else M=60</td>
<td>4.05E-02</td>
</tr>
<tr>
<td>Inlet M=4 Reach 1 M=5 All Else M=60</td>
<td>1.71E-02</td>
</tr>
</tbody>
</table>

**Figure 32: Sensitivity Analysis for Calibration of Model**

Error bars calculated using Standard Error
6.2 Verification

Once the model was calibrated with the May data, verification runs were conducted (Figures 33 and 34; Tables 10 and 11).

Table 10: Timing and WSEL Results of July Verification

<table>
<thead>
<tr>
<th></th>
<th>Tide (boundary)</th>
<th>Inlet Sonde</th>
<th>Central Sonde</th>
<th>East Sonde</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measure</td>
<td>Model</td>
<td>Measure</td>
<td>Model</td>
</tr>
<tr>
<td>Min WSEL</td>
<td>Timing¹</td>
<td>6:24am</td>
<td>6:40am</td>
<td>---²</td>
</tr>
<tr>
<td></td>
<td>m NAVD88</td>
<td>0.255</td>
<td>0.259</td>
<td>---²</td>
</tr>
<tr>
<td>Max WSEL</td>
<td>Timing¹</td>
<td>1:12pm</td>
<td>1:30pm</td>
<td>1:45pm</td>
</tr>
<tr>
<td></td>
<td>m NAVD88</td>
<td>1.480</td>
<td>1.480</td>
<td>1.398</td>
</tr>
</tbody>
</table>

¹ Tide Measured timing is in 6 minute intervals; Sonde Measured timing is in 15 minute intervals; Model timing is in 5 minute intervals
² These Measured times and WSELs are not available since the water level dropped below the sonde.

Figure 33a: July Verification Results, Inlet Sonde
Gray box is the results to be looked at; the first two days of simulation are equilibration time.
Figure 33b: July Verification Results, Central Sonde
Gray box is the results to be looked at; the first two days of simulation are equilibration time.

Figure 33c: July Verification Results, East Sonde
Gray box is the results to be looked at; the first two days of simulation are equilibration time.

Table 11: Timing and WSEL Results of August Verification

<table>
<thead>
<tr>
<th></th>
<th>Tide (boundary)</th>
<th>Inlet Sonde</th>
<th>Central Sonde</th>
<th>East Sonde</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measure</td>
<td>Model</td>
<td>Measure</td>
<td>Model</td>
</tr>
<tr>
<td>Min</td>
<td>Timing(^1)</td>
<td>Timing(^1)</td>
<td>Measure</td>
<td>Model</td>
</tr>
<tr>
<td>WSEL</td>
<td>4:12am</td>
<td>4:30am</td>
<td>---(^2)</td>
<td>6:30am</td>
</tr>
<tr>
<td>m NAVD88</td>
<td>0.190</td>
<td>0.190</td>
<td>---(^2)</td>
<td>0.582</td>
</tr>
<tr>
<td>Max</td>
<td>Timing(^1)</td>
<td>Timing(^1)</td>
<td>Measure</td>
<td>Model</td>
</tr>
<tr>
<td>WSEL</td>
<td>10:36am</td>
<td>10:35am</td>
<td>12:15pm</td>
<td>12:10pm</td>
</tr>
<tr>
<td>m NAVD88</td>
<td>1.588</td>
<td>1.591</td>
<td>1.467</td>
<td>1.455</td>
</tr>
</tbody>
</table>

\(^1\) Tide Measured timing is in 6 minute intervals; Sonde Measured timing is in 15 minute intervals; Model timing is in 5 minute intervals

\(^2\) These Measured times and WSELs are not available since the water level dropped below the sonde.
Figure 34: August Verification Results
Gray box is the results to be looked at; the first two days of simulation are equilibration time.
The model results show that the tidal signal is felt throughout the lagoon, reinforcing that the tide is a mainforcing on the lagoon’s hydrodynamics. However, the model consistently underestimates the velocities throughout the lagoon (Figures 35 and 36).

Figure 35: July Velocity Comparison

Figure 36: August Velocity Comparison
The model was run with and without the discharge at the dike to verify that the freshwater inflow through the man-made dike was also a significant forcing (Figure 37). It resulted in an attenuation of the tide throughout the lagoon, but the tidal signal is still apparent through the lagoon.

Figure 37: Verification that Discharge at Man-Made Dike is a Significant Forcing
6.3 Model Projections

There was a large rain event in November of 2007 (Figure 9; Table 2). This event was simulated in the lagoon to investigate the impact of a large freshwater inflow on the lagoon hydrodynamics. The results are an estimate at best, not an example of what actually happened in November of 2007. This is because the gate in the dike had already been closed, and the freshwater runoff from upstream built up behind the dike until overtopping it. Since there is no way to measure the actual discharge into the lagoon, the equations for the one-gate-open scenario were used to estimate a discharge into the lagoon (Figure 38). These estimates are conservative and the actual event likely generated a larger discharge over the man-made dike and through the lagoon; however, the simulated event has a peak flow of four times the flow in May, so it is still significant.

![Discharge at Man-Made Dike](image)

At the peak of the discharge, there is significant dampening of the tidal signal (Figure 39), but the tidal signal can still be seen. The high discharge event’s effects are felt only temporarily; its effect on the lagoon waning in a matter of hours. The second chart in Figure 39 shows the same time period with the mean discharge from the dike (1 cms). When comparing the two charts, it is apparent that the large freshwater discharge’s effects are felt past the Inlet Sonde.
Figure 39: November High Rain Event Results

Graph 1: November With High Rain Event
- Water Surface Elevation (m NAVD88)
- Date/Time: 11/28/2007 0:00 to 12/4/2007 0:00
- Graph shows the tide variation with Inlet Sonde, Central Sonde, and East Sonde.

Graph 2: November Without High Rain Event
- Water Surface Elevation (m NAVD88)
- Date/Time: 11/28/2007 0:00 to 12/4/2007 0:00
- Graph shows the tide variation with Inlet Sonde, Central Sonde, and East Sonde.

Figure 39: November High Rain Event Results
7 DISCUSSION

7.1 Forcings

Three forcings control the ecological dynamics and productivity as well as the hydrodynamics of San Elijo Lagoon: tidal flushing, freshwater inflow, and sediment transport (USACE, 2002). Anything that affects the way water and sediment move around inside a body of water is considered a ‘forcing’. Identifying these forcings is important due to the insight they give on the hydrodynamics of a system. The existing physical conditions of San Elijo Lagoon play a part in how the forcings affect the lagoon. For example, if the tide is low, then the channel network in SEL contains the water, and the impact of tidal flushing is minimized. Therefore the conditions within the lagoon modify the impact of the forcings on the lagoon.

During the mild weather conditions that are typical for Southern California, tidal flushing plays a large role in inducing circulation within the lagoon (Wu et al., 2006). However, the tide effects reach only about halfway up the 2.5 mile span of the lagoon, through surface waters as well as groundwater (Soil Conservation Service, 1993, EIS/EIR, 2002). The Southern California coastal tides are of the mixed semi-diurnal type, having two low tides and two high tides per lunar day, which is about 24 hours (USACE, 2002). The tides are of different magnitude each time, usually a higher high tide followed by a lower low tide then a lower high tide followed by a higher low tide, and usually have a range between one and three meters (Figure 6; USACE, 2002).

San Elijo Lagoon’s hydrodynamics are mainly controlled by tides, but there is also a freshwater input. There are three main tributaries that feed the lagoon, La Orilla Creek to the southeast, Escondido Creek directly east, and another small tributary that feeds into the lagoon on the northeastern edge called Lux Creek (or Canyon Creek). Escondido Creek is considerably larger than both La Orilla and Lux Creeks and has a gauging station set up several miles upstream to capture its discharge. It also runs year round now, when historically it seasonally went dry. Although neither Lux Creek nor La Orilla Creek are gauged, the Conservancy takes measurements at the man-made dike in the East Basin that captures the combined discharges of all three creeks. Any other freshwater that enters the lagoon comes in the form of local surface water runoff. This may also have an impact in San Elijo’s hydrodynamics; however, it was not within the scope of this study.

Sediment transport is also a forcing within SEL because when sediment is deposited, it alters the conditions within the lagoon, therefore altering the hydrodynamics. Example: the inlet closes approximately twice a year due to sediment deposition. Also, the channel in the East Basin that distributes the freshwater input is full of cattails and other vegetation that are slowing the flow, causing sediment to drop out and filling the channel in. There is an interdependent relationship between the hydrodynamics and sediment deposition, the water is the means by which the sediment moves (erosion or deposition). There are four ways in which sediment enters the water in the lagoon: coming in with the tide, the creeks or the local runoff, and through erosion within the lagoon. The runoff carries not only fine sediments that cause siltation in the lagoon, but also surface contaminants. Surface runoff carrying contaminants (and sediment) is not isolated to the local area surrounding San Elijo, but occurs throughout its watersheds.
7.2 Stability

7.2.1 Erosion/Deposition

The Shields Parameter was used to assess the stability of the lagoon. The Shields Parameter ($\theta$) shows the balance between disturbing and destabilizing forces (Nielsen, 1992). It is useful because it is based on velocity and depth, which are easy to measure. When the Shields Parameter of a flow is compared to the Critical Shields Parameter ($\theta_c$) for a specific grain size, it can be concluded whether or not those grains have a tendency to move or not. The following equations were used. The Shields Parameter is defined by

$$\theta = \frac{u^2}{(S-1)gd_{50}}$$  \hspace{1cm} (16)

Where $u_*$ = $\frac{\frac{\kappa}{\ln(z/z_0)}}{\ln(0.4h/z_0)}$, $z_0 = \frac{2.5d_{50}}{30}$, $\bar{u}$ is the average velocity, $z$ is the depth of water, and $\kappa$ is the Von Karman Constant (0.4). The average velocity is calculated from observed conditions (average of 0.2d and 0.8d) and obtained as output of model simulations. The Critical Shields Parameter (Table 12) is defined by

$$\theta_c = \frac{0.24}{D_*} + 0.055[1 - e^{-0.02D_*}]$$  \hspace{1cm} (17)

where $D_* = d_{50}^{[(g(S-1))/v^2]}^{1/3}$, $d_{50}$ is the mean grain size, $g$ is acceleration due to gravity (9.81 m/sec$^2$), $S$ is the specific gravity of the sediment (2.65 kg/m$^3$; sand has a range of 2.63-2.67 and silt has a range of 2.65-2.70), and $v$ is the kinematic viscosity of water ($1.0 \times 10^{-6}$ m$^2$/sec). The mean grain sizes ($d_{50}$) were chosen to be 0.03 mm, 0.063 mm, 0.25 mm, 0.5 mm based on 0.063 mm being the cut off for the %sand and %fines in the sediment analysis. One smaller and two larger grain sizes were also selected to be analyzed.

<table>
<thead>
<tr>
<th>$d_{50}$ (mm)</th>
<th>0.03</th>
<th>0.063</th>
<th>0.25</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_c$</td>
<td>0.317085</td>
<td>0.152324</td>
<td>0.044485</td>
<td>0.031268</td>
</tr>
</tbody>
</table>

These result in the following relationship:

if $\theta > \theta_c$, erosion occurs  \hspace{1cm} (18)

Figures 40-42 show that there was no erosion at Segment 1, which makes sense since Segment 1 was characterized by the largest sediments. The Shields Parameter peaked at the inflection points, which is when the tidal flow is at its strongest; the numbers were low and went to zero at the max and min tide WSELS. At Segment 2 erosion was observed intermittently for all grain sizes. The Shields Parameters peaked for longer periods of time, from the falling limb inflection point of the tide WSEL to the rising limb inflection point. This is due to the stronger outflow in this region of the lagoon, since the tide combines with the upstream discharge. The numbers are low and go to zero only at the tidal peak.
The following condition was true at Segment 1 for the entire time period, therefore there was no Erosion for Segment 1 $\theta < \theta_c$.

Figure 40: May Shields Parameters
The following condition was true at Segment 1 for the entire time period, therefore there was no erosion for Segment 1. 
\[ \theta < \theta_c \]
The following condition was true at Segment 1 for the entire time period, therefore there was no Erosion for Segment 1.

\[ \theta < \theta_c \]
To get an idea of the likelihood that sediment would fall out of suspension the settling velocity \( w_s \) and the Rouse number \( R_o \) were calculated. Settling dominance versus entrainment can be determined when the settling velocity (Table 13) is compared to the Rouse number.

\[
w_s = \frac{\sqrt{4(5-1)gd_{50}}}{3C_D}
\]

(19)

where \( C_D = 1.4 + \frac{36}{\mathcal{R}} \), and \( \mathcal{R} = \frac{w_s d_{50}}{v} \).

<table>
<thead>
<tr>
<th>Table 13: Settling Velocity Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_s ) (mm)</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.25</td>
</tr>
<tr>
<td>0.063</td>
</tr>
<tr>
<td>0.03</td>
</tr>
</tbody>
</table>

The calculation of the settling velocity requires a circular reference in a computing program like MATLAB™ or Microsoft Office Excel, but when compared to the Rouse Parameter, it can be very useful in showing whether sediments will stay entrained or are settling dominant.

\[
R_o = \frac{w_s}{\kappa u_*} \begin{cases} 
> 1 & \text{settling dominant} \\
< 1 & \text{stays entrained} 
\end{cases}
\]

(20)

Tables 14 through 17 provide the data upon which all the calculations were based.

<table>
<thead>
<tr>
<th>Table 14: May Outgoing Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Meter</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>875</td>
</tr>
<tr>
<td>1652</td>
</tr>
<tr>
<td>2718</td>
</tr>
<tr>
<td>2969</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 15: July Outgoing Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Meter</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>875</td>
</tr>
<tr>
<td>1652</td>
</tr>
<tr>
<td>2718</td>
</tr>
<tr>
<td>2849</td>
</tr>
<tr>
<td>3002.5</td>
</tr>
</tbody>
</table>
Table 16: August Incoming Tide Data

<table>
<thead>
<tr>
<th>Channel Meter</th>
<th>( V_{\text{Bottom}} ) (m/s)</th>
<th>( V_{\text{Top}} ) (m/s)</th>
<th>( V_{\text{Average}} ) (m/s)</th>
<th>( h ) (m)</th>
<th>Range of ( U^* ) (m/s) for all 4 D50s</th>
</tr>
</thead>
<tbody>
<tr>
<td>875</td>
<td>0.370</td>
<td>0.390</td>
<td>0.380</td>
<td>1.68</td>
<td>0.0122-0.0157</td>
</tr>
<tr>
<td>1081</td>
<td>0.416</td>
<td>0.387</td>
<td>0.402</td>
<td>1.37</td>
<td>0.0131-0.0169</td>
</tr>
<tr>
<td>1409</td>
<td>0.331</td>
<td>0.288</td>
<td>0.309</td>
<td>0.61</td>
<td>0.0108-0.0143</td>
</tr>
<tr>
<td>2022</td>
<td>0.365</td>
<td>0.236</td>
<td>0.301</td>
<td>1.19</td>
<td>0.0099-0.0129</td>
</tr>
<tr>
<td>2369</td>
<td>0.340</td>
<td>0.208</td>
<td>0.274</td>
<td>1.09</td>
<td>0.0091-0.0118</td>
</tr>
<tr>
<td>2538</td>
<td>0.332</td>
<td>0.241</td>
<td>0.287</td>
<td>0.89</td>
<td>0.0097-0.0127</td>
</tr>
<tr>
<td>2673</td>
<td>0.210</td>
<td>0.215</td>
<td>0.213</td>
<td>0.97</td>
<td>0.0071-0.0093</td>
</tr>
<tr>
<td>2944</td>
<td>0.212</td>
<td>0.195</td>
<td>0.203</td>
<td>1.19</td>
<td>0.0067-0.0087</td>
</tr>
</tbody>
</table>

Table 17: August Outgoing Tide Data

<table>
<thead>
<tr>
<th>Channel Meter</th>
<th>( V_{\text{Bottom}} ) (m/s)</th>
<th>( V_{\text{Top}} ) (m/s)</th>
<th>( V_{\text{Average}} ) (m/s)</th>
<th>( h ) (m)</th>
<th>Range of ( U^* ) (m/s) for all 4 D50s</th>
</tr>
</thead>
<tbody>
<tr>
<td>875</td>
<td>0.432</td>
<td>0.389</td>
<td>0.411</td>
<td>1.42</td>
<td>0.0133-0.0172</td>
</tr>
<tr>
<td>1081</td>
<td>0.552</td>
<td>0.451</td>
<td>0.501</td>
<td>1.22</td>
<td>0.0165-0.0214</td>
</tr>
<tr>
<td>1409</td>
<td>0.235</td>
<td>0.228</td>
<td>0.231</td>
<td>0.53</td>
<td>0.0082-0.0108</td>
</tr>
<tr>
<td>2022</td>
<td>0.224</td>
<td>0.139</td>
<td>0.181</td>
<td>0.76</td>
<td>0.0062-0.0081</td>
</tr>
<tr>
<td>2369</td>
<td>0.359</td>
<td>0.344</td>
<td>0.351</td>
<td>1.02</td>
<td>0.0117-0.0153</td>
</tr>
<tr>
<td>2538</td>
<td>0.282</td>
<td>0.248</td>
<td>0.265</td>
<td>0.91</td>
<td>0.0089-0.0117</td>
</tr>
<tr>
<td>2673</td>
<td>0.207</td>
<td>0.172</td>
<td>0.190</td>
<td>1.02</td>
<td>0.0063-0.0083</td>
</tr>
<tr>
<td>2944</td>
<td>0.187</td>
<td>0.158</td>
<td>0.173</td>
<td>1.22</td>
<td>0.0057-0.0074</td>
</tr>
</tbody>
</table>

The difference in measured and modeled Rouse Parameters for each of the grain sizes is similar in trend, just on a different order of magnitude (Figures 43-46). May’s results from the measured numbers’ calculations agree well with the results of the modeled numbers’ calculations. July Model’s second point is consistently high, while its other points agree well with the Rouse Parameters from the measured conditions. August In and Out Model are also generally high, but are within a reasonable range.

\[ d_{50} = 0.03 \text{ mm} \]

**Figure 43: Rouse Numbers for \( d_{50} = 0.03 \text{ mm} \)**

If \( R>1 \), sediments are settling dominant; if \( R<1 \), sediments stay entrained.

Rouse numbers based on measured and modeled velocities.
Figure 44: Rouse Numbers for $d_{50} = 0.063$ mm
If $R>1$, sediments are settling dominant; if $R<1$, sediments stay entrained.
Rouse numbers based on measured and modeled velocities.

Figure 45: Rouse Numbers for $d_{50} = 0.25$ mm
If $R>1$, sediments are settling dominant; if $R<1$, sediments stay entrained.
Rouse numbers based on measured and modeled velocities.
The model output was used to look at the two locations in the lagoon where cores were taken. The likelihood of sediments to fall out of suspension or stay entrained was calculated at these two locations over a period of two days using the settling velocity and the Rouse Parameter. Each grain size has a trend over time (Figures 47-49). The largest grain sizes ($D_{50} \geq 0.25\text{mm}$) were settling dominant over all time periods. Station 1 was also settling dominant for $D_{50} = 0.063\text{mm}$. At Station 2, though, $D_{50} = 0.063\text{mm}$ showed a trend of becoming gradually more settling dominant over time. This means that at Segment 2, more fines were deposited, making the percentages shift. For the finest sediment grain size, $D_{50} = 0.03\text{mm}$, Station 1 became gradually less settling dominant over time. So from May to July to August, there would be less fines deposited at Station 1. Station 2 consistently was settling dominant about half the time for $D_{50} = 0.03\text{mm}$.
Figure 47: Rouse Numbers for May

May Segment 1 Rouse Numbers and Tide

May Segment 2 Rouse Numbers and Tide

Figure 47: Rouse Numbers for May
Figure 48: Rouse Numbers for July
August Segment 1 Rouse Numbers and Tide

August Segment 2 Rouse Numbers and Tide

Figure 49: Rouse Numbers for August
7.2.2 Stability

The natural pattern of San Elijo lagoon has been to adjust to current sea level conditions, varying from an open bay to a salt marsh. The inlet of the main channel would migrate freely up and down the coast and cut through the beach dunes at the lowest point. This allowed for a constant saltwater exchange, regardless of season (Byrd, 2008). This natural pattern has been interfered within the last two centuries due to human intervention. The construction of roads, railways, and their embankments has restricted the inlet to the northwest corner of the lagoon. The tide study done in 2008 (Flick, 2008) shows that the morphology of the southern California coast creates a tidal asymmetry resulting in an ebb dominant tide, however dredging of inlets can reverse tidal asymmetry effects (Friedrichs and Perry, 2001; Flick, 2008).

An ebb dominant tide is characterized by a short, strong outflow, which would allow for erosion and a clear, open inlet. A flood dominant tide is identified by a quick rise in tide and a slower ebb. The sediment transport equations that were used to calculate the Shields and Rouse Parameters suggest that the back half of the lagoon (from the middle of the Central Basin east) is ebb dominant while the front half of the lagoon (from the middle of the Central Basin west) is Flood dominant, which was observed by the author in the lagoon while collecting data. This helps in understanding why the lagoon is having siltation problems; flood dominance favors accretion, not erosion, therefore sediment would stay in the lagoon, causing infilling. The $^7$Be data supports this. It shows that in both areas of the lagoon, there is a net depositional environment (sum of columns in Table 7). The fact that the lagoon inlet needs mechanical dredging and widening operations nearly twice a year also supports this.

7.3 Sources/Sinks

7.3.1 Water

Sources of water are the tide, direct precipitation into the lagoon, runoff (stormwater, roads, residences, farms), and freshwater inflow from Escondido, La Orilla, and Lux Creeks. Sinks for water are the ponding areas within the lagoon (West, Central, and East Basins), the duck ponds east of the man-made dike, and the ocean.

7.3.2 Sediment

Sources for sediments can be a little more complicated. Sediments are carried by wind and water. Therefore, sediment enters the lagoon by particulates falling out of the atmosphere and being washed out of the atmosphere by rain. They are carried in by the tides, direct local runoff, and stream discharge (which is made up of stream flow and runoff from upstream). Lastly, sediments can simply be moved around within lagoon, so the lagoon itself is a source of sediments. The lagoon also serves as a sink for sediments. Most of the sediments from upstream are trapped behind the man-made dike in the East Basin, only the fines make it over the dike (Figure 50), and they fall out of suspension wherever water ponds or is impeded by vegetation. Three obvious locations for sediments sinks are the inlet, the point bars for the channel curves, and the ocean.
Whether the water level is high enough to discharge into the lagoon or not, water ponds on the east side of the dike, slowing the runoff from upstream and allowing the largest sediments to fall out. Only the fine sediment that stay entrained in the water column actually enter the lagoon.

Figure 50: Stored Water and Sediments
8 SUMMARY AND CONCLUSIONS

San Elijo Lagoon is influenced by tides, freshwater input from natural tributaries and surface water runoff, sediment transport, and by human activities such as construction projects. The lagoon was a typical tidal salt marsh that’s inlet drifted north to south according to season until human intervention in the late 1880s. Its mouth restricted by bridges, the lagoon’s inlet channel began to periodically fill in due to long shore sediment transport. The stagnant waters became an issue, so the estuary garnered public attention. It became a protected conservancy and annual dredging began, walking paths were constructed, and the dike that restricted freshwater inflow from the lagoon’s natural tributaries was built. With the residential buildup of the area, more and more runoff enters the lagoon, and more fine silts and pollutants with it. The current dredging plan funded through the San Elijo Lagoon Conservancy keeps the lagoon open more than 90% of the year, on average.

The field campaign (November of 2007 through September of 2008) resulted in the creation of vector maps that confirmed the assumption of a well mixed environment and the use of a two dimensional depth integrated model. Also confirmed was the attenuation of the tidal signal through discharges calculated from the measured velocities. Cores were taken at two locations within the lagoon, in two distinctly different sediment compositional areas. From these sediment samples it was found that there is a pattern of composition according to space and season. Sediments within the channel appeared to fine inland, with coarser sediment near the mouth and finer sediments inland where the main channel network spreads out into more of a braided channel system. The seasonal pattern is due to the combination of seasonal tidal patterns, seasonal precipitation patterns, as well as when the gate in the man-made dike and the inlet are open. The $^{7}$Be analysis done on the collected sediments showed that the lagoon is a net depositional environment. This is supported by the Rouse Parameter calculations, but it is important to note that the $^{7}$Be numbers could be skewed due to dry fallout.

The model formulated from the collected data was calibrated by adjusting the bottom roughness (Manning’s M), which was based on the sediment grain sizes within the lagoon. Calibration was done using the data collected in May of 2008; the model was considered calibrated when the simulated water surface elevations (WSEls) and peak timings were matched to observed conditions. A sensitivity analysis was then run, and velocities were used to confirm the chosen Manning Roughness layout. A root mean squared deviation (RMSD) was calculated for this confirmation. Data collected in July and August of 2008 were used to verify the model. Simulations were run with and without the discharge at the man-made dike to verify that the discharge at the man-made dike was significant. To further investigate the impact of freshwater discharge, a high rain event equal to four times the normal discharge was simulated. The effect of the high discharge was seen all the way to the ocean boundary. The conclusion was that the discharge from a large rain event would have a significant impact on the water circulation and therefore the sediment transport in the lagoon; however, these effects would be seen only for a short period of time.

Using the Shields and Rouse Parameters (calculated from model velocity and depth output) trends were observed at the two locations where sediment cores were taken. The Shields Parameter indicates whether or not a sediment grain size will erode in a given flow field. This
Analysis showed that there was no erosion at Segment 1, which makes sense since Segment 1 was characterized by the largest sediments. The Shields Parameter peaked at the inflection points, which is when the tidal flow is at its strongest; the numbers were low and went to zero at the max and min tide WSELs. At Segment 2 erosion was observed intermittently for all grain sizes. The Shields Parameters peaked for longer periods of time, from the falling limb inflection point of the tide WSEL to the rising limb inflection point. This is due to the stronger outflow in this region of the lagoon, since the tide combines with the upstream discharge. The numbers are low and go to zero only at the tidal peak.

The Rouse Parameter indicates if a grain size is settling dominant or if it will stay entrained in the water column. It was shown that sands would fall out of suspensions wherever they were carried – Station 1 or Station 2. The grain size of 0.063 mm (the cutoff between %fines and %sands in the sediment analysis), the trend was similarly uniform in time, but not space. It was settling dominant at Segment 1 for the three months calculated (May, July, and August 2008), while at Station 2 it became more settling dominant over time, suggesting that flow rates became weaker in the late summer – the vector maps confirm this. In May, the 0.063 mm sediments would stay entrained nearly one fourth of the two days calculated; in July this time of entrainment was reduced by half; and in August it was nearly always settling dominant. The finest sediment calculated, 0.03 mm diameter, showed the exact opposite trend at Station 1, suggesting that flow became stronger there over time. The amount of time that fines fell out of suspension reduced over the three months, so that less fines would fall out at Station 1 over the months. These fines (0.03 mm) had a consistent trend of being settling dominant about half the time at Station 2. These Rouse calculations are supported by the grain size analysis that was conducted on the collected sediments.

An ebb dominant tide is characterized by a short, strong outflow, which would allow for erosion and a clear, open inlet. A flood dominant tide is identified by a quick rise in tide and slower ebb, which creates a pattern of accretion and infilling. The sediment transport equations that were used to calculate the Shields and Rouse Parameters suggest that the back half of the lagoon (from the middle of the Central Basin east) is ebb dominant while the front half of the lagoon (from the middle of the Central Basin west) is Flood dominant.

The lagoon has a net depositional environment; this means that the main forcings on the lagoon encourage accretion, which accounts for the problems the lagoon is having with siltation. Due to the required location and morphology of the inlet channel, the force of the tide is not large enough to keep the inlet clear. The freshwater inflow, as well as the morphology of the lagoon causes an attenuation of the tidal signal. This attenuation can be amplified by a larger freshwater inflow, in the case of large storms or if a dam breaks upstream.
REFERENCES


California Wetlands Information System (CWIS) (http://ceres.ca.gov/wetlands/geo_info/so_cal/san_elijo.html)

Carlsbad Watershed Network Conservancy (http://www.carlsbadwatershednetwork.org)


Escondido Creek Conservancy (http://www.escondidocreek.org)


*Potential Mitigation Opportunities for the I-5 North Coast Project*


San Elijo Lagoon Conservancy ([http://www.sanelijo.org](http://www.sanelijo.org))


United States Department of Agriculture, Soil Conservation Service, Davis, California Water Resources Planning Staff *San Elijo Lagoon and Escondido Creek Watershed: Non-Point Source Pollution Management Plan* Draft San Diego County, California (June 1993).


A Historical Overview

Over 50% of the world’s wetlands have been lost, and California has lost even more. Ninety percent of its historic wetland area is gone today (Goodwin et al., 2001). One of the California coastline’s more prominent features is the coastal lagoons, and the remaining ones in San Diego County are important due to their unique condition of not yet being drastically developed and altered (USACE 2002). There are many reasons for wetland loss. Development, agriculture, changes to the tributary watershed, altered tidal inlet conditions, and the invasion of alien species are all things that have affected San Elijo Lagoon (Goodwin et al., 2001). San Elijo Lagoon has a long and rich history, and much of the changes that have occurred in the last 150 years have been well documented.

A1: Pre-19th Century

Remnant Native American Indian sites show that during most of the last 6,000 years California lagoons have been open to the sea. The local geologic record shows that San Elijo Lagoon is a drowned river valley that has a pattern of switching between the open bay and shallow lagoon according to ocean sea level condition. San Elijo Lagoon shows evidence that 800 years ago it was a deep open bay that slowly evolved into the shallow estuary it is today with a barrier sand spit that has been heavily documented only for the last 150 years. The inlet was free to range north to south and vice versa to find the lowest point in the sand spit barrier, keeping the lagoon healthy by naturally maintaining an open connection to the ocean, allowing for tidal flushing (USACE 2002). This continuous open connection kept the lagoon from infilling with silt by always passing the fine material out to the ocean.

A2: 19th Century

In the 1840s things changed. The Spanish Portola Expedition had come and gone (1769), naming the area San Elijo, and in 1848, the Gold Rush began. Permanent settlements became established and people started altering the lagoon’s natural condition. In 1887 a basic narrow-gauge railroad was built across the lagoon, and its continuous link to the ocean was destroyed. When berms for roads and railways restricted the inlet to one location it restricted tidal flushing, while the construction of dikes, water impoundments and diversions changed the natural hydrology of the lagoon (Soil Conservation Service 1993). In 1895 the Lake Wohlford (the source of Escondido Creek) Dam was constructed, and reduced the flow of water through Escondido Creek, further reducing the ability of water to flush the lagoon and keep the inlet open. Due to alterations like these, most California lagoons have been closed to tidal circulation for some time (USACE 2002).

A3: 20th Century:

A3.1: 1900-1940

The modification of the lagoon continued into the 20th century, beginning in 1912 with the construction of the Pacific Coast Highway across the sand dunes and continuing in 1925 when the present Santa Fe Railroad was built. With the construction of these two main thoroughfares, the mouth of the lagoon was permanently fixed, causing the seasonal closure of the lagoon and
allowing for the trapping and build up of fine materials (Soil Conservation Service 1993). In 1937 the shallow area in the east basin was modified to create ponds for duck hunting. This included the construction of a concrete dike containing two floodgates to control the water level in the East Basin (City of Encinitas 2001). This dike was rebuilt in the 1980s to improve its purpose, and it still exists today (Soil Conservation Service 1993).

**A3.2: 1940-1979**

In 1940 the practice of discharging treated sewage into the lagoon became prevalent, including influxes from the cities of Encinitas, Escondido, and Solana Beach. This unfortunate and detrimental practice continued into the early to mid 1970s. The effluent processed at the Solana Beach and Cardiff Sanitation Districts’ sewage treatment plants were discharged directly into the lagoon. There were several pipelines in the lagoon, and the treatment facilities were adjacent to the lagoon (Figure A1). It was recognized in 1962, when the San Diego Regional Water Quality Control Board notified the two districts that the practice needed to end. In response, they created the San Elijo Water Pollution Control Facility, which combines the two districts’ effluent and began discharging it directly into the ocean through an outfall 8,000 feet offshore in 120 feet of water (Soil Conservation Service 1993). This effectively stopped the direct discharge into the lagoon in 1966, but the City of Escondido still put their treated effluent into Escondido Creek, and therefore into San Elijo Lagoon. This discharge contributed a huge amount of nutrients (approximately 68,000 pounds per year) into the lagoon (causing problems discussed below). This stopped in 1976 with the installation of a pipeline along the creek, carrying Escondido’s wastewater to another deep ocean outfall.

![Pipeline Locations at San Elijo Lagoon](image)

**Figure A1: Pipeline Locations at San Elijo Lagoon**

*Source: City of Encinitas (2001)*
The last major physical adjustment to the San Elijo Lagoon was made in 1965 with the construction of Interstate 5 across the middle of the lagoon, effectively cutting the lagoon into the East and Central Basins. Even though there were no longer deliberate treated wastewater discharges into the lagoon, those past actions caused problems that continued to exist (Soil Conservation Service 1993). The influx of effluent caused the lagoon to stagnate; combining this with the excess nutrients produced algal blooms and serious problems with insects, sludge and odors (USACE 2002). With reliable transportation established in the area, developers began building up the housing market, solidifying the problem of urbanization by increasing the erosion and input of non-point source pollution into the lagoon. With the increase in pollution and reduced access to tidal circulation, the water quality in the lagoon was further injured, raising concerns and complaints from the new community.

Problems with water quality continued into the 1970s with the construction of the Lake Dixon Dam, further reducing the freshwater inflow to the lagoon. These continued problems caused the formation of the San Elijo Alliance in 1970 to protect the lagoon and convince the county and state governments of the value of San Elijo Lagoon as a cultural and natural resource.

Many positive management changes occurred in the 1970s: the Endangered Species Act designated the habitats in and around the lagoon as protected, the Coastal Act of California began to protect the coastline, and an agreement between the County of San Diego and the State of California solidified a management plan for the new reserve. Urbanization also continued in the 1970s, increasing the problems with pollution in the lagoon, typically from non-point sources. Concerning non-point source pollution, the United States Department of Agriculture estimates that “up to 99% of suspended solids, and 50% to 90% of the other pollutants in our national waters come from non-point sources of pollution”. They also state that the overall effect of urbanization is an order of magnitude growth in the pollutant runoff loads, an increase in peak discharge and the velocity of runoff during storms, as well as changing the type and nature of the pollutants (Soil Conservation Service 1993).

**A3.3: 1980-2000**
A regular water quality monitoring program was not established until the late 1980s, though there are records as far back as 1960 (USACE 2002). These records show that conditions in the western end of the lagoon improved after the 1960s, but problems like eutrophication and the odor of rotting vegetables still persisted. There are three main indicators that eutrophication is underway: an increase in total plant biomass, a species shift in the vegetation of the area from plants that require large amounts of dissolved oxygen to those that need less dissolved oxygen, and lastly the water clarity or transparency is reduced. The continued problem of eutrophication that exists still is blamed mainly on the residual effects of the discharges of treated wastewater effluent and non-point source pollution from the watersheds of Escondido Creek and San Elijo’s other tributaries. It is important to note here that it is the suspended sediment carried by these discharges that is the main problem. Pollutants attach themselves to the sediment grains and maintain this contact for many years (Soil Conservation Service 1993). Sedimentation in the lagoon has had many causes: construction activity, erosion of roads and stream banks, along with urban and agricultural runoff.
In 1980, the failure of the Lake Val Sereno dam added a considerable amount of sediment loading to the system (USACE 2002). The added sediment was detrimental to the health of the lagoon. The sediments carried excess nutrients from fertilizers, manure and byproducts of animal facilities, and irrigation water containing nitrogen, phosphorus, ammonium, bacteria, salts, and other oxygen demanding materials. Inside the lagoon, this stimulated plant growth and resulted in algal blooms which lead to further eutrophication; the lack of oxygen in this type of environment has been known to result in fish and benthic invertebrate kills. Sedimentation rates were now nearly five times what they were in the late 19th century (Soil Conservation Service 1993).

Besides the sediment carrying nutrients and pollutants, it had physical side effects as well. It was unhealthy for the organisms living in the lagoon. It muddied the waters, and “cover(ed) the growing, spawning, and feeding areas of water life, clog(ged) fish gills, and reduc(ed) the filtering capacity of filter feeders” (Soil Conservation Service 1993). It filled in the lagoon, raising the elevation and reducing the depth of water in the lagoon; effectively reducing the tidal circulation and flushing capacity of the lagoon. This reduced the habitat diversity by eliminating a place for open and/or deep water dependent species to exist.

The restriction of the inlet prevented the fine sediment from flushing directly out of the system, allowing it to build up the often closed system. In the 1990s, a study of the lagoon showed that the lagoon had a 10-24 foot thick layer (in some areas) of organics on top of 140 feet of coarser material (Soil Conservation Service 1993). The organic layer was first noticed in 1967 and was determined to be a black silty-clay. The sludge was easily redistributed by the storm water runoff and occasional tidal circulation. Much of the sludge was attributed to the influx of secondary treated effluent from the Solana Beach and Cardiff Waste Treatment plants. The nutrient rich waters from the waste water plants encouraged the growth of algal blooms that died, decayed, and settled out to form the sludge. However, a study done in 1976 found that the input of sediments, pollutants, and nutrients was due more to the increased urbanization in the area, and that urbanization was a much more significant impact on the system than the input from the treated sewage. This study also found nine significant sources of input into the system in addition to the two main tributaries of Escondido and La Orilla Creeks (Figure A2) (USACE 2002).
The area was formally dedicated as the San Elijo Lagoon Ecological Reserve in 1983. In 1987 the San Elijo Lagoon Conservancy (SELC) was born, and was followed by the construction of San Elijo’s first Nature Center in 1988. The SELC then began experimentally opening the lagoon inlet, and once the method and benefits of dredging were established, they received a grant from the California Coastal Conservancy to establish the Tidal Circulation Endowment to maintain an open inlet (in 2000).

In the early 1990s, surfers and beachgoers once again raised concerns about the effect of bacteria in the lagoon on human health. At this time, the lagoon was a shallow water (only 18 inches deep in most areas) brackish environment that only rarely was open to tidal influence. When the mouth did open (from a couple days to a few weeks), the stagnant putrefied contents flushed into the nearshore beach environment and alarmed people. Complaints included odorous vegetation and pesky insects. The water was again tested and found to contain high counts of coliform bacteria, especially near La Orilla Creek, the mouth of the lagoon, and around the restaurants bordering the West Basin near the inlet on the Pacific Coast Highway (Soil Conservation Service 1993).
In 1990 the San Diego Regional Water Quality Control Board identified that nearly half of San Elijo’s waters as impaired (Soil Conservation Service 1993). In 1997 the State Water Resources Control Board found the benthos of San Elijo Lagoon to be degraded after doing a thorough investigation (USACE 2002). The problems identified are familiar ones: accelerated erosion and sedimentation, high levels of coliform bacteria, high levels of nutrients, and excess fresh water inflows. The only thing not discussed previously is the excess freshwater. Excess freshwater is a problem because it alters habitats from salt to fresh water, causing the loss of salt marsh, salt water and precious salt panne habitat. Fresher water also increases the numbers of mosquitoes, gnats, and other insect pests (Soil Conservation Service 1993). This freshwater was a problem due to the fact that the inlet was closed so often; if the influence of tides had been present, the freshwater’s effects would not have been felt so close to the inlet.

The sediment accumulating in the lagoon was from “fast activities,” such as construction activity as well as agricultural land uses. Since the 1960s and 1970s, however, land uses had changed and conservation practices had been installed, slowing the rate of erosion. Even with this slower rate, the sediment still accumulated and would continue to do so unless (drastic) measures were taken to increase the natural “flushing effect” of the lagoon (Soil Conservation Service 1993). It was estimated that of the average 40,000 tons/year of sediment transported to the lagoon, 30,000 tons/year were deposited in the lagoon while only 10,000 tons/yr were flushed out to the ocean (USACE 2002). Even with conservation practices reducing the nutrient and sediment flux, San Elijo Lagoon would still be impaired from the presence of sludge and a lack of tidal circulation flushing it out (Soil Conservation Service 1993).

Until 1994 the inlet of San Elijo Lagoon was predominantly closed. From 1986 to 1993, the inlet was occasionally open for the purpose of reducing mosquito habitats and odor issues (dredging records can be found in Appendix B). Then the SELC began experimentally opening the inlet to see the effect on the water quality of the lagoon (1994-1999). These efforts showed significant benefits from the increased tidal circulation including diversification of species of plants and animals as well as a reduction in eutrophication, insect pests, and odor problems. This success lead to the endowment being established in 2000, ensuring a continual opening to tidal flows (USACE 2002).

A3.4: 2001 to Present
In 2002 the Army Corps of Engineers drafted an Environmental Impact Statement/Environmental Impact Report (EIS/EIR) summarizing the current conditions in the San Elijo Lagoon. Their official finding was that since the report in 1970, the lagoon had continued to deteriorate (USACE 2002). A study done the previous year (2001) reported the same thing, with the qualifier that conditions in the lagoon were good for fish and benthos, but only when the inlet was open to tidal flows. There were two possibilities for the lagoon when the inlet was closed, and both were negative. The first scenario is when freshwater was flowing into the lagoon; the salinity was greatly reduced, as were the oxygen levels, resulting in quick fish and invertebrate kills. The other scenario is a dry condition and there freshwater inflows were not present; the brackish/saline water evaporated, decreasing the water level and increasing the salinity, which lead to slow fish and invertebrate kills (City of Encinitas 2001). Either way, inlet closure was bad for all those interested, be it the creatures whose survival depended on the health of the lagoon or the people who lived around it.
Even with the SELC attempting to maintain an open inlet, there were still problems and the lagoon still filled in. As recently as 2001, the inlet was still frequently closed (City of Encinitas 2001). The capacity of the lagoon to maintain itself was in question because the effects of the past and the continuously increasing urbanization of the watershed; the Escondido Creek watershed is projected grow another 25% in the next 20 years (USACE 2002). Also, Escondido Creek now flowed year round (no seasonal dry period), and that excess freshwater had an effect. Cattails and bulrushes (freshwater invasive species) began spreading from the East Basin to the Central Basin, replacing and reducing the salt marsh and severely impairing circulation (USACE 2002). Another reason for the species shift was the continuing shallowing of the lagoon; most of San Elijo is above -0.64 m North American Vertical Datum of 1988 (NAVD88). In other words, the lagoon had a minimum elevation of -2.11 feet NAVD88 in 2001 (City of Encinitas 2001).

The following two figures show the change in habitat from 2002 to 2005 due to the changing conditions in tidal circulation. The SELC documented an estimated 35% loss of mudflats over those 3.5 years. At that rate (a little over an acre a month) most of the remaining mudflats will be gone in 8 years (Potential Mitigation Opportunities).

![Figure A3: 2002 Habitat Conditions](source: Potential Mitigation Opportunities)
Figure A4: 2005 Habitat Conditions

Source: Potential Mitigation Opportunities
APPENDIX B: DREDGING HISTORY
Table B1: Opening of Lagoon for Public Health (mosquitos) and California Least Tern nesting

<table>
<thead>
<tr>
<th>Date Open</th>
<th>Date Closed</th>
<th># Days Open</th>
<th>Natural/Artificial</th>
<th>% Open</th>
<th>Days Open/Year</th>
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Table B2: Opening of Lagoon for Lagoon Health (Experimental)

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<th>Natural/Artificial</th>
<th>% Open</th>
<th>Days Open/Year</th>
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APPENDIX C: BACKGROUND DATA

- Cross sections
- Tides during sampling
- Hysteresis (clock-wise)
Tides During Sampling
D1: Central Sonde from walking path, looking southwest (taken at high tide)

D2: East Sonde from kayak looking northeast (taken at high tide)
D3(a) – (g) Inlet from beach, looking north-northeast at the Coast Highway (101) bridge
D4(a) – (e): Inlet Channel between Cost Highway (101) Bridge and Railroad bridge. (a) and (b) simply show filling in of channel; (c) through (e) show the Inlet Channel during dredging operations.
The rest of the photos are all taken from the south side of the lagoon, on the ridge. The idea was to get a panoramic view of the lagoon from east to west and back again. (taken at low tide)
VITA

Mary “Molly” Bourgoyne nee Friedmann grew up in Metairie, Louisiana, a suburb of New Orleans, with her parents and her older sister. She received her bachelor’s degree in civil engineering with minors in structures and geology from Louisiana State University in the spring of 2007. During the summer of 2009 she married Brad Bourgoyne. They live together with their dog, cat, hamster, and two geckos in Baton Rouge, Louisiana.