Appendix G – Goleta Slough Inlet Modeling Study

This Appendix presents the results of the study conducted by Environmental Science Associates (ESA) to model how various management practices and sea level rise scenarios affect the dynamics of the Goleta Slough lagoon mouth[1]. The study provides an improved understanding of how changing the management of the lagoon inlet may impact water levels within the Slough and patterns of breaching and closing of the lagoon mouth, with implications for local flood risk and habitat. This study was conducted for the City of Santa Barbara to inform ongoing efforts to develop a sustainable inlet management plan that addresses both flood control and ecological uses of the Slough.

This study was made possible thanks to the Santa Barbara Coastal Resource Enhancement Fund (CREF), US Fish and Wildlife Service, the City of Santa Barbara, Coastal Conservancy and the Goleta Slough Management Committee (GSMC).

We would also like to acknowledge the contributions of Dr. Lisa Stratton and others at the Cheadle Center for Biodiversity and Ecological Restoration, who contributed to field data collection and site observation in support of this study.

KEY FINDINGS

The following are the key findings of the Goleta Slough Inlet Modeling Study based on simulations conducted by ESA using the Coastal Lagoon Quantified Conceptual Model (QCM). Details related to the QCM set-up and specific scenarios modeled are described in more detail in the "Model Development" and "Scenario Modeling" sections later in this memorandum.

Storage Volume Adjustments:

ESA has evaluated a set of model scenarios which test the sensitivity the lagoon mouth to adjustments to the storage volume of the Slough. This sensitivity analysis evaluates the expected impact of large changes to the Goleta Slough landscape on the dynamics of the lagoon. These scenarios are representative of landscape-scale changes to the Goleta Slough topography, such as large scale habitat restoration projects and major flood protection projects. The following are the key findings of this study related to storage volume adjustments:

- Alterations to the Goleta Slough landscape which increase the volume of the Slough are predicted to have two main effects on the lagoon inlet:
    1. An increased lagoon volume delays natural mouth breaches that are caused by watershed inflows due to the larger storage capacity below the breaching water level; and

[1] The lagoon mouth is also called the lagoon "inlet" due to the tidal inflows which enter Goleta Slough through the lagoon mouth under open conditions.

2. An increased lagoon volume delays the closure of the lagoon mouth due to increased tidal scour associated with the increased intertidal volume, also called "tidal prism".

- Specific projects can be designed to emphasize open conditions or closed conditions by adding or removing storage volume within certain elevation ranges. Storage volume added in the intertidal range enhances tidal scour, which encourages open conditions. Storage volume added between the high tide elevation and the elevation of the beach berm encourages closed conditions by increasing the potential for ponding during rain events.

- Decreasing the Slough volume is predicted to cause a small decrease in the percent of time that the lagoon mouth is closed since the lagoon will breach more quickly during rain events, but it will also reduce tidal exchange and increase the likelihood of closure during dry conditions.

- Sensitivity analysis suggests that increasing the tidal prism of the lagoon by ~600-800 ac-ft would result in an almost-always open system. Such an increase in lagoon tidal prism may greatly reduce the frequency of mechanical breaches required in order to achieve flood protection and habitat goals. There does not appear to sufficient open space available near Goleta Slough to achieve this level of tidal prism enhancement through the creation of inter-tidal habitat without significant land use changes.

- Smaller increases in lagoon volume, on the order of ~200-400 acre feet may increase the frequency of natural open conditions, but may require intermittent lagoon mouth management to avoid flooding. This result suggests the potential for multi-benefit projects through the creation of new tidal wetlands in areas of the Slough that are currently diked off from tidal action.

Sea Level Rise:
ESA has evaluated several scenarios which represent existing conditions and expected future conditions at the Slough based on projected rates of sea level rise. The following are the key findings of this study related to sea level rise:

- Rising sea levels are predicted to increase the elevation of the beach berm, which will in turn increase the storage volume of the lagoon and decrease the likelihood of the lagoon breaching naturally during small and medium sized rain events.

- For small amounts of sea level rise (up to +1 foot) the model results indicate an increased likelihood of extended periods of mouth closure, especially during dry years (assuming no managed breaches occur).

- If the lagoon mouth is not managed, model results predict an increase in the duration of ponded conditions at the lagoon for sea level rise up to +1 foot. The increased occurrence of ponding causes predicted average water levels within the lagoon to rise faster than the rate of sea level rise under unmanaged conditions for up to +1 foot of sea level rise.

- As sea levels continue to rise, eventually the tidal prism of the lagoon will grow large enough that the lagoon channel will become self-scouring. At this point the lagoon will transition to an almost always open system, with water levels controlled primarily by the tide elevation. Model results indicate that the lagoon mouth will almost always be open once sea levels rise +3 feet above existing conditions, with or without inlet management.

Inlet Management:

ESA has evaluated several scenarios representing potential future inlet management strategies where the lagoon mouth is mechanically breached whenever water levels within the lagoon exceed a pre-determined threshold elevation. The following are the key findings of this study related to these management strategies:

- Existing infrastructure near the Slough is at risk of flooding when water levels in the Slough reach approximately El. 9.0' NAVD. Model results indicate that the managed breaching threshold elevations of 1.25 and 2.25 feet above MHHW (El.6.5' and 7.5' NAVD) greatly reduces the frequency of occurrence of water levels above El. 9.0' NAVD in the Slough for scenarios with +0 and +1 feet of sea level rise.

- Model results for breaching at 3.75' above MHHW (El. 9.0' NAVD) and for unmanaged conditions showed the regular occurrence of water levels greater that El. 9.0' in the Slough, indicating a significant risk of inundation of nearby infrastructure for these scenarios.

- Model results indicate that managed breaching at any elevation cannot prevent the occurrence of water levels in the Slough above El. 9.0' NAVD for scenarios with +3 and +5 feet of sea level rise. The predicted frequency of occurrence of elevated water levels within the Slough continues to increase as sea levels rise.

- Sensitive pickleweed marsh habitat in the Slough may become degraded if inundated (water levels >7.0' NAVD) for an extended duration. Model results indicate that managed breaching with threshold elevations at 1.25 and 2.25 feet above MHHW (El.6.5' and 7.5' NAVD) can greatly reduce the frequency of occurrence of water levels above El. 7.0' NAVD relative to unmanaged conditions, both for existing sea levels and for scenarios with +1 feet of sea level rise.

- Based on these results, we conclude that inlet management is likely to be a viable strategy for achieving flood protection and habitat goals at Goleta Slough during the short- to medium-term for conditions on the order of +1 foot of sea level rise. The model results indicate that inlet management will become less effective at achieving flood protection and habitat goals under conditions with 3 or more feet of sea level rise.

- The model results indicate that the selection of a lower threshold elevation results in an increase in the number of predicted managed breaches, and a corresponding increase in the frequency of open lagoon conditions.

Key Study Limitations

- Due to the limited availability of water level and beach elevation observations at Goleta Slough, the analysis presented herein has only evaluated the expected patterns in breaching and closing of the lagoon mouth and lagoon water levels under "typical conditions" similar to those observed at Goleta Slough between 2010 and 2014. While this time period includes a range of wet and dry conditions, we recommend additional study to better characterize the potential for elevated water levels, flooding and prolonged mouth closures due to extreme events such as El Nino, major floods and prolonged drought.

- The modeling conducted for this study simulates spatially averaged water levels within the Slough and is not intended to resolve small scale variations caused by local hydraulic features. This study has not evaluated the suitability of the modeled lagoon management strategies for achieving flood protection or ecological benefits or impacts at any specific parcel or location within the Slough.

- The modeling of coastal lagoon systems is an area of active research. This study attempts to apply the best available analytical methods to improve our understanding of the Goleta Slough system but several areas of uncertainty remain; see the “Model Limitations and Uncertainty” section bellow.

BACKGROUND

Goleta Slough is a coastal estuary in Santa Barbara County with more than 300 acres of tidal wetland habitat, a key resource for several threatened and endangered species including Tidewater Goby and southern Steelhead. Goleta Slough has experienced several large flood events over the past century; including major floods which forced the closure of the Santa Barbara Airport in 1969 and 1995. As the climate changes and sea levels rise, the risk of flooding and other adverse impacts to both infrastructure and habitats due to elevated water levels within Goleta Slough will increase. Figure G-1 shows the Goleta Slough study area, which is located at the downstream end of the 45 square mile Goleta Slough watershed.

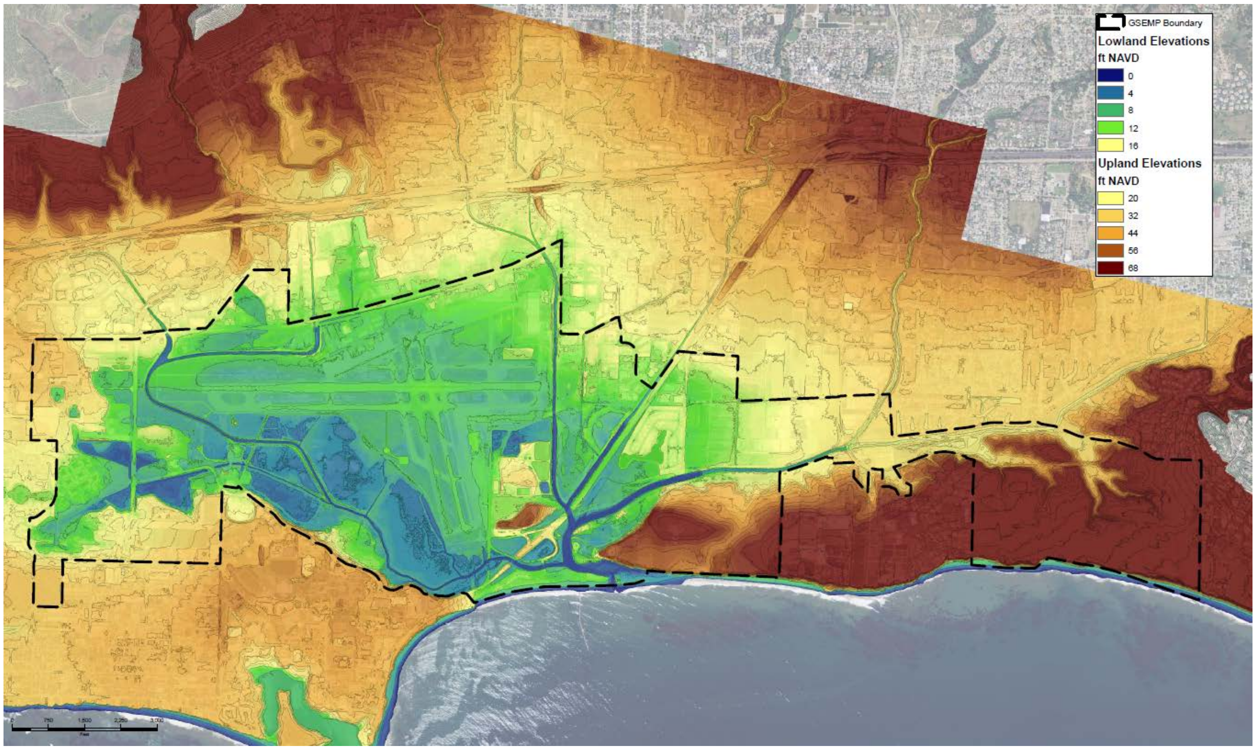

Figure G-1 – Goleta Slough Study Area with NOAA Lidar (NOAA, 2012)

Historic maps show that Goleta Slough once contained an extensive open-water area at the location of the present-day Santa Barbara airport. The large tidal prism associated with this open-water area suggests that under pre-development historic conditions Goleta Slough was most often a tidal coastal lagoon with internal water levels closely matching ocean water levels. Over the last century extensive infill and sediment deposition within the lagoon has led to a massive reduction of tidal prism which has resulted in a lagoon that, when unmanaged, naturally tends towards closed inlet conditions. Under closed inlet conditions water levels within the lagoon are controlled primarily by watershed inflows and the beach elevation.

Goleta Slough is located in Central California approximately 8 miles west of Santa Barbara. This region experiences mixed semi-diurnal tides, with a great diurnal tide range of 5.4 feet. Table G-1 lists several key tidal datums measured at the nearby Santa Barbara Tide gage (NOAA #9411340).

Datum	Elevation (ft NAVD)
Mean Higher High Water (MHHW)	5.27
Mean High Water (MHW)	4.51
Mean Sea Level (MSL)	2.66
Mean Low Water (MLW)	0.85
Mean Lower Low Water (MLLW)	-0.17

Table G-1 – Goleta Slough Study Area

For purposes of this study it is assumed that all tidal datums will shift upwards equally with rising sea levels.

In recent years the lagoon has often been mechanically breached by excavating through the beach berm in order to open the lagoon mouth during extended periods of closure. Following these mechanical breaches, the lagoon eventually returns to closed conditions. This most often occurs during the following dry season, with the timing of mouth closure varying depending on wave conditions and the amount of streamflow entering the lagoon from the watershed. Managed breaches had historically been conducted by the Santa Barbara Flood Control District with the presumptive goal of reducing flood risk and improving water quality, however it is not clear what if any analysis was conducted to support these goals and there are few records documenting the frequency and manner in which these breaches occurred.

In 2013, the Flood Control District decided not to continue managed breaching of the lagoon. This decision was attributed to the high expected costs of the biological studies that would be necessary to renew the permits. A limited number of managed breaches have occurred since 2013 under emergency permits strictly to prevent flooding during major rain events; meanwhile the City of Santa Barbara has commissioned studies to evaluate the impact of managed breaches on the local ecology and to plan for the long term management of the Goleta Slough estuary.

STUDY OBJECTIVE

This study is intended to inform an ongoing effort among local stakeholders to plan for the long-term management of Goleta Slough by providing an improved understanding of how various management strategies are likely to affect lagoon hydrodynamics. ESA has developed a Quantified Conceptual Model (QCM) which represents the key physical processes that control water levels and breaching dynamics for coastal estuaries and lagoons. ESA has calibrated this model for Goleta Slough based on available historical water level data and then applied this model to study the expected conditions at the lagoon under several potential future conditions scenarios.

The goal of the Goleta Slough Inlet Modeling Study is to apply a quantified conceptual model (“QCM”) of lagoon hydrodynamics to evaluate and compare several potential lagoon management strategies under existing conditions and for future sea level rise scenarios. This study has evaluated three sets of scenarios addressing the following topics:

- Adjustments to Lagoon Storage Volume
- Sea Level Rise
- Lagoon Mouth Management

These scenarios were evaluated based on wave, tide, precipitation and watershed conditions observed during a period spanning from October 2010 to July 2014. This period was selected based on the availability of observed calibration data, and includes a "wet" year, WY[2] 2011; a "dry" year, WY 2013; and an "intermediate" year, WY 2012.

THE INLET QUANTIFIED CONCEPTUAL MODEL

A Quantified Conceptual Model ("QCM") is a numerical model that attempts to simulate the evolution and interaction of complex physical systems through the use of numerical representations of each of the key processes which control how that system behaves. The QCM used for the Inlet Modeling Study represents the key processes which control water levels within Goleta Slough. These include the growth and erosion of the lagoon inlet bed ("sill") and beach berm due to waves, inlet bed scouring from tides and stream flows; inflows to the lagoon due to precipitation and watershed inputs; and outflows from the lagoon due to evaporation, groundwater seepage, and flow through the lagoon channel. By tracking these several processes over time, the QCM can be used to predict water levels within the lagoon and to evaluate the periodic opening and closure of the lagoon mouth.

The QCM uses observed historic data to represent the influence of coastal and watershed processes on the lagoon. Key input parameters include:

- Topography and bathymetry of Goleta Slough, derived from 2010 Coastal LiDAR (NOAA, 2012) and surveyed cross sections (CCBER, 2015)
- Nearshore wave data derived from prior ESA studies at Goleta Beach
- Synthetic stream flow time series based on hydrologic analysis of the Goleta Slough watershed (see Attachment A)
- Evaporation and rainfall data from CIMIS Station #94 (Goleta Foothills)
- Seepage rate estimates based on basic beach geometry, observations of beach sediment size, and nearby seepage studies.
- Beach growth rate parameters estimated from local observations of beach elevation

The following sections contain detailed descriptions of the model setup, the input parameters, and the limitations and uncertainties of the model results.

The evaluation of changes in watershed hydrology due to climate change was outside of the scope of this study. Changes in watershed runoff may affect the dynamics of the lagoon inlet, including the frequency of breach and closure events and therefore future investigation in this area may prove informative for lagoon management.

Modeling Approach

At its core, the QCM is a water balance model which accounts for the different flows of water entering and leaving the lagoon. This water balance is coupled with a dynamically-varying beach

[2] WY – "Water Year", a 12-month period commonly used in hydrologic analysis which begins on October 1 and ends on September 30. Water year 2011 began on October 1, 2010 and ended September 30, 2011.

and inlet system, accounting for the fact that bar-built estuaries, such as Goleta Slough, are often defined by a morphologically unstable mouth (inlet) that influences the lagoon stage, volume, and flowrates.

The model dynamically simulates time series of inlet, beach, and lagoon state based on external forcing from waves, tides, and stream input (Battalio et al. 2006; Behrens et al. 2013; Rich and Keller 2013). The model is based on two core concepts:

- All water flows entering and leaving the system should balance.
- The net erosion/sedimentation of the inlet channel results from a balance of erosive (fluvial and tidal) and constructive (wave) processes.

Rules enforcing beach berm growth, equilibrium inlet geometry, beach seepage, and inlet closure and breaching, are drawn from the research literature and approaches derived from prior project experience.

The model provides the following outputs:

- Time series of inlet state (open or closed to the ocean) and geometry (depth and cross sectional area)
- Time series of lagoon stage and volume (which can be used to assess inundation frequency and flood risk)
- Estimated hydrologic inputs and outputs, including wave overwash, berm seepage, evapotranspiration, and inlet flows.

When a range of external conditions (beach management, climate change) vary with time, these outputs can be used to predict potential changes in short-term and seasonal behavior at the inlet, and to inform future management for habitat and flood risk. The model has been verified extensively using field data. The most recent work on the Russian River, Mission Creek, San Lorenzo, and Devereux Slough lagoons has shown that the model performs well under a wide range of hydrologic and oceanic conditions. Preliminary results discussed below also suggest a high level of model competence for Goleta Slough.

MODEL DEVELOPEMENT

This section outlines the process of applying the inlet QCM to a coastal lagoon system. We list the steps needed to initialize the model and also discuss the methods the model applies to characterize the key lagoon and coastal processes which shape the system response to external forcing. Figure G-2 provides a flow chart schematic of the model procedures described in this section.

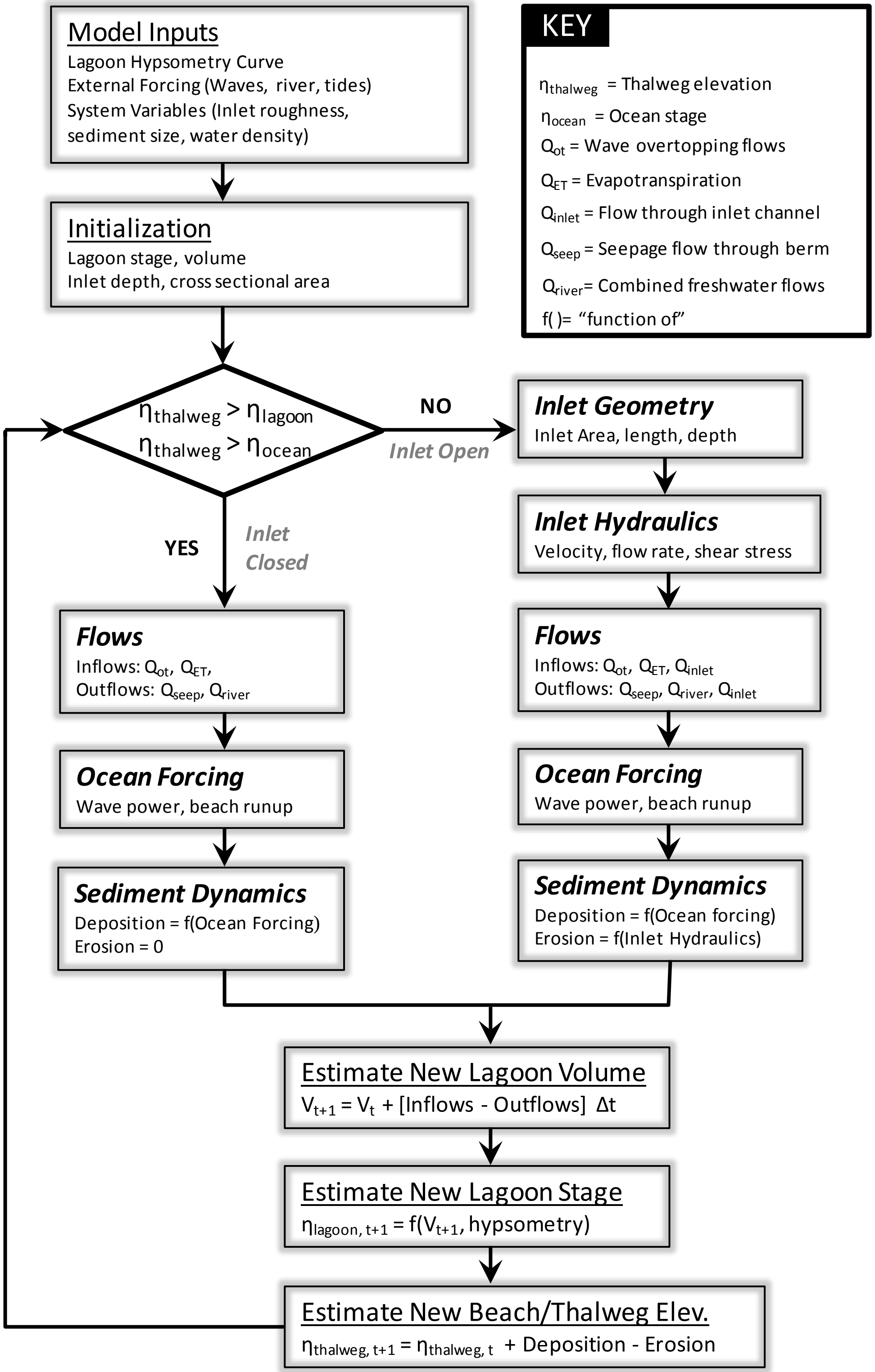

Figure G-2 – Inlet QCM Schematic

Lagoon Representation

The lagoon is modeled as a basin with a known hypsometry (stage-storage relationship). Lagoon characteristics, including surface area, stage, and volume, are derived from the hypsometry. Figure G-3 shows the hypsometry curve for Goleta Slough.

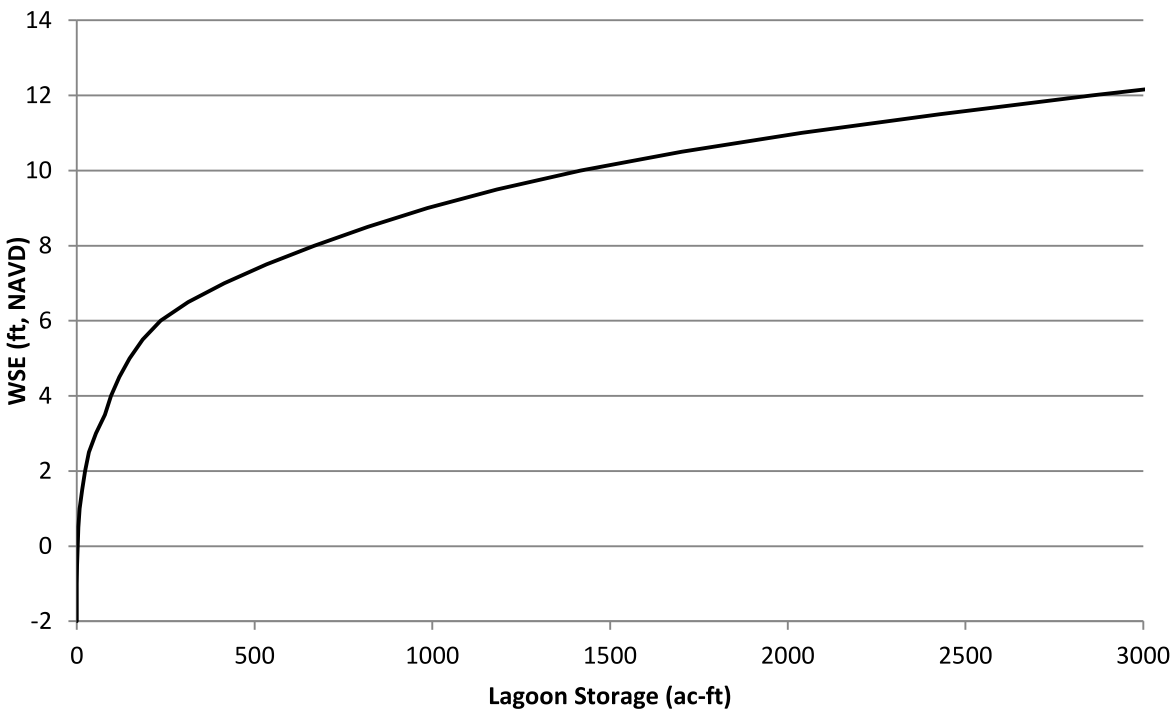

Figure G-3 – Goleta Slough Hypsometry

The beach is characterized by a known length (shore-parallel length), width (cross-shore length), beach face slope, median sediment grain size, and permeability (used to estimate seepage flows). When the inlet is open to the ocean, it is treated as a channel having variable width, length, depth, cross sectional area, and channel roughness. The depth of flow through the inlet is calculated as the difference between the lagoon stage and the mean elevation of the channel bottom.

Boundary Conditions

Boundary conditions are applied to the lagoon representation as inputs/outputs and sources/sinks. A source term is used to represent inflows to the lagoon from the upland watershed. Wave overwash and inlet flows, which can be directed either into or out of the lagoon, connect the lagoon to the ocean. Water is also allowed to leave the lagoon via berm seepage and evapotranspiration. The beach is treated as a barrier between the lagoon and the ocean. Coastal processes (waves and tides) are allowed to shape the beach, a process that occurs simultaneous with the balance of lagoon water inflows and outflows. Table G-2 lists the sources of data used to populate boundary condition time series.

Parameter	Source/Location	Position	Measurement Period
Offshore Waves	NDBC Buoy 46216: Goleta Point	34.333 N 119.803 W	2004-present
Nearshore Waves	ESA PWA transformation matrix from NDBC Harvest Buoy (46218)		2004-present
River Flow	USGS: Atascadero Cr Near Goleta USGS: San Jose Cr Near Goleta	34.425 N 119.811 W 34.459 N 119.808 W	2007-present 2007-present
Ocean Stage (water level)	NOAA: Santa Barbara (9411340)	34.405 N 119.692 W	2005-present
Inlet Condition (Open/Closed)	Anecdotal Reports from GSMC and local stakeholders	(various)	(various)
Inlet Shape	Photos provided by GSMC and City of Santa Barbara	(various)	(various)

Table G-2 - Summary of sources of data used for modeling

Model Initialization

The QCM was applied to Goleta Slough by first defining the following:

- Coastal and fluvial boundary conditions for the site (see Table G-2),
- Lagoon hypsometry,
- Beach roughness, sediment size, and shape,
- Time step, and
- Initial conditions.

LiDAR and cross section survey data were processed in ArcGIS to provide stage-storage and stage-area relations for the lagoon. The median beach sediment size was taken as 1 mm, following Behrens et al. (2013), and we applied a Chezy roughness value corresponding to coarse sand for the inlet. Aerial Photography described in the Goleta Slough Ecosystem Management Report were used in ArcGIS to characterize the beach length, width. A typical beach face slope of 1:10 (vertical: horizontal) was identified based on surveyed beach profiles (CCBER, 2015).

The model advances in time using a constant time step chosen by the user. The choice of the time step influences model stability and level of accuracy in resolving the lagoon water level time series, especially during high river flows. Testing of the Goleta Slough QCM indicated that a model time step of 20 seconds met these modeling criteria and was used for the preliminary results discussed below. All of the time series boundary condition data sets are interpolated to match the chosen time step.

Lastly, the model is initialized by assuming initial inlet channel dimensions, and the initial lagoon stage and volume. The inlet is typically assumed to be open at the first time step and is allowed to adjust to the boundary conditions over several time steps. We found that model results were typically independent of the initial condition within several days after the first time step.

Water Balance Components

When the inlet is closed, the water balance is calculated as a sum of wave overwash, evapotranspiration, berm seepage, and river inflows. Wave overwash is estimated using the coastal engineering approaches described in the Existing Conditions Report (ESA PWA 2012). We estimate evapotranspiration using the nearest node of the California Irrigation Management Information System (CIMIS) database. Berm seepage is estimated using a D'Arcy approach based on the work of Rich and Keller (2013) in Carmel Lagoon.

When the inlet is open, inlet flows represent additional terms in the water balance. Estimating these terms requires knowledge of the inlet geometry and hydraulics. The inlet geometry is calculated based on flows in the prior time steps. A daily-average cross sectional area is estimated from Hughes (2002) based on flows through the inlet during the previous 24 hours and beach parameters. This mean is amplified or decreased according to the level of the tide by applying a multiplier based on the deviation of the ocean tide from its 24.5-hour lunar mean. The inlet depth is represented using the knowledge of the lagoon stage and the shape of the inlet cross sectional area, as described above. The inlet length is taken as the beach width (length in the cross-shore direction). Inlet velocity, flow rate, and shear stress are then estimated using the Van de Kreeke (1967) approach, which is based on a solution for inlet momentum in the along-channel dimension.

The change in lagoon stage is evaluated using the flows described above. The sum of the inflow and outflow terms is multiplied by the time step to give the change in lagoon volume. This is used in conjunction with the known stage-storage curve to arrive at the new lagoon stage for each time step.

Inlet Morphology Components

Inlet morphology in the QCM is treated as a balance of beach/inlet erosion and deposition. Ocean waves are assumed to deposit sediment on the beach, raising the inlet thalweg, while currents in the inlet remove (erode) sediments, lowering the inlet thalweg. Closures result in the model when deposition is greater than erosion for a long enough period of time to allow the inlet thalweg to rise above both the lagoon and ocean stages.

Inlet erosion is evaluated using the inlet velocities and flow rates described in Section 2.4. We use the Bagnold (1966) energetics approach, which accounts for both bedload transport and the bed material that is eroded and transported out of the inlet as suspended load.

Inlet deposition is evaluated using two approaches. When the thalweg is below high tides in the ocean, inlet deposition is based on the adjacent wave power. When the inlet accretes above the high tide level, deposition becomes a function of the total water level (combined tide and wave runup levels), which has a decreasing likelihood of depositing sediment when the inlet thalweg rises higher above the total water level.

At each time step, the change in the inlet thalweg elevation is taken as the sum of the deposition and erosion at that time step. The total net rate of deposition and erosion is achieved by multiplying by the time step, and the total rate of bed movement in the vertical direction (i.e. net erosion or accretion) is attained by dividing this volume by the total area of the inlet bed. This operation influences the depth, but not the cross sectional area, which we estimate empirically. The change in inlet depth subsequently influences the inlet flows.

Determining Inlet State

Prior to evaluating the water balance and inlet morphology at each time step, the model evaluates the following rule: "Is the inlet thalweg higher than both the ocean and lagoon stage?" When this is true, the inlet is considered to be "closed", and inlet flows are assumed to be zero. When this is false, inlet flows are above zero, and the inlet is either tidal or has one-way flow over the beach.

The model automatically transitions from having a closed inlet to an open inlet when ocean or lagoon water levels surpass the inlet thalweg elevation. In the latter case, the model reintroduces a small channel on the beach, which either leads to non-breaching perched overflow conditions or a full inlet breach depending on hydraulic conditions (predominantly driven by slope between the lagoon and ocean stages).

Inlet shape (cross sectional area, width, depth) can vary in response to channel hydraulics and wave deposition in the model. For this study the inlet is assumed to be oriented perpendicular to the beach, and does not move laterally (migrate) along the beach. Deflection of the mouth due to sedimentation in one side of the channel and eventual mouth migration are important processes, as continued migration can lead to channel lengthening and increased wetted area (and thus seepage to the ocean). This is an area of ongoing research.

MODEL VALIDATION

The aim of the validation process is to use the QCM to reproduce observed historic conditions as closely as possible, in order to establish confidence that the QCM produces a realistic representation of the physical system and to reveal potential shortcomings or limitations of the model. The QCM was validated based on observed water levels in Goleta Slough from 2010 to 2014. This period includes dry and wet years, as well as varying degrees of active lagoon mouth management. Several managed breaches are believed to have occurred during the validation period: July 11, 2011, October 25, 2011, February 12, 2012, and March 1, 2014 (Andrew Bermond, pers. coms. 2014). For the validation scenario managed breaches were specified to occur on these dates in order to accurately model these events, since these breaches were not the result of natural physical processes and therefore would not otherwise have been captured by the model.

Figure G-4 shows the measured and modeled lagoon stage within Goleta Slough for the validation period. The model was found to perform well during the simulation of the validation period. During the validation period, and throughout the period from 2010 to 2014, the QCM predicted lagoon stages that replicated the patterns of observed lagoon stage.

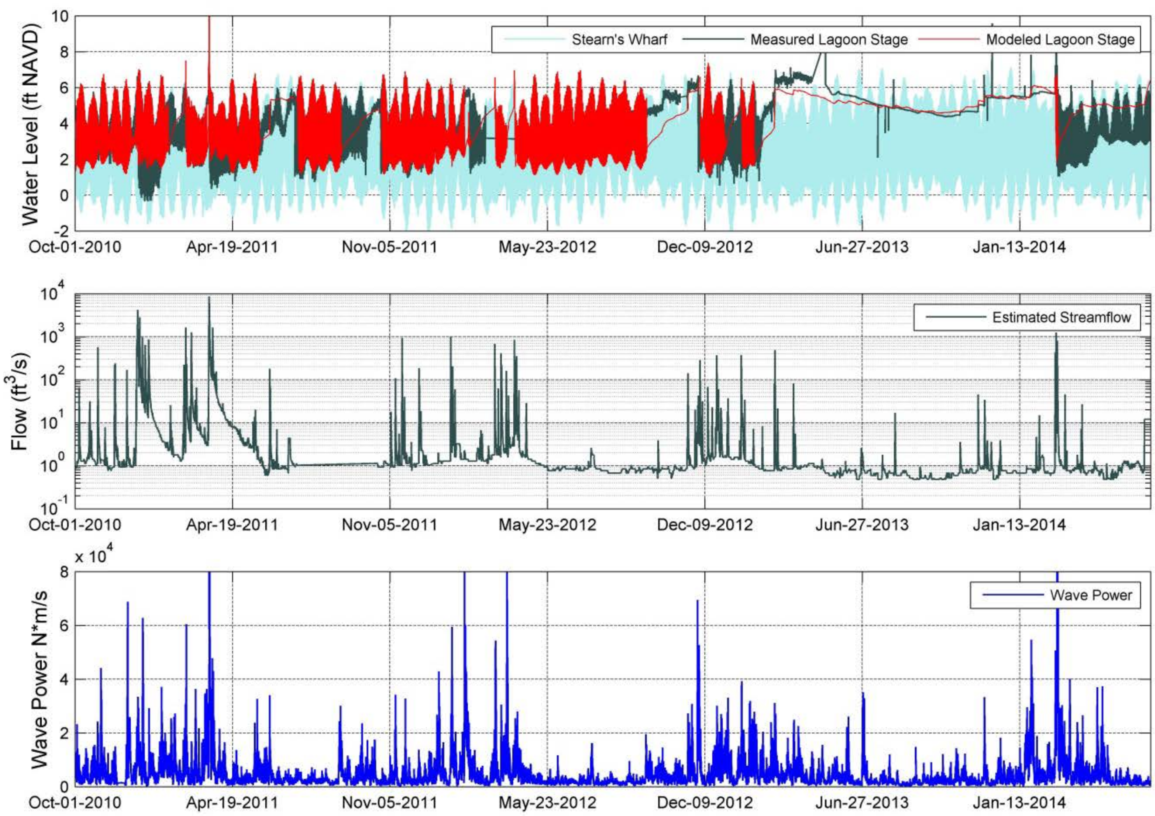

Figure G-4 – Predicted vs Observed Water Levels at Goleta Slough, with Watershed and Wave Inputs

This model skill was achieved even with simplified representations of the relevant processes. Although there are a few events where the model does not accurately predict the timing or duration of closure events, the validation simulation nevertheless demonstrates that many of the key physical processes governing lagoon behavior are accurately represented by the QCM. Some of the processes observed to be captured by the model include:

- coincidence of modeled and observed closure events during periods of high wave power and/or low shear stress from flows in the inlet,
- a slow rise in modeled lagoon stage during inlet closure events that is generally consistent with observations,
- a tendency of the modeled inlet thalweg to shoal during neap tides, leading to subsequent tidal muting in the lagoon and risk of closure,
- fluvial floods causing similar increases in modeled and observed lagoon stage, and
- coincidence of modeled and observed self-induced breach events induced by lagoon flows overtopping the beach.

One of the challenges of applying a QCM approach to Goleta Slough is that there are no direct measurements of flow rates through the mouth, wave overwash into the lagoon, subsurface seepage through the beach, or evaporative losses at Goleta Slough. Although these are all crucial hydrologic processes, it is rare for any of these data to be available for California lagoons. The only indicator that these processes are being captured by the model is the modeled lagoon water level time series, which we found closely matches observed water levels. Most breach and closure events were predicted within several days of the observed events, and the modeled water levels generally matched the observed water levels. The model appears to underestimate the depth of scour during large rain events, including the the 2010 winter rains and the spring 2014 breach event, however it appears to accurately capture scour during moderate rain events. The model does show minor errors in the predicted timing of breach events, and appears to slightly overestimate the speed at which the lagoon mouth closes during times when the lagoon experiences muted tidal conditions. Such errors are to be expected given the difficulty in modeling a complex coastal system.

Model Limitations/Uncertainty

The QCM provides estimates of lagoon conditions based on our best understanding of the various processes which shape the beach, slough, and inlet. Coastal lagoons are highly complex systems which are influenced by a wide range of physical forces, and which can be highly sensitive to modest changes in the timing and/or magnitude of the physical forcing which drives the system. Efforts were made to use the best available input datasets and numerical parameterizations to drive the QCM, however these efforts were constrained by the limited availability of data documenting historic lagoon conditions and by the general uncertainty related to several key physical processes known to occur at the lagoon. In particular, the following factors introduce uncertainty with respect to the accuracy of the QCM’s predictions:

- The rate of beach growth/accretion and the geometry of the lagoon channels are not well documented at Goleta Beach.
- The rate of subsurface outflows (“seepage”) through the beach is not well understood.
- Stream gages are present on only 2 of the 5 main creeks flowing into Goleta Slough (Atascadero and San Jose Creeks.). Attachment A describes the method used to adjust the streamflow input time series to account for the ungaged streams.
- There is only limited documentation for the timing of historic lagoon management actions.
- There is significant uncertainty with respect to the expected impacts of climate change on the Goleta Slough region. For this study we have evaluated scenarios which consider the impact of increased sea levels, however the QCM does not capture other potential impacts due to climate change, including changes to stream flow rates, evaporation, and wave conditions.
- The ability to establish confidence in the model results through calibration/validation is limited by the relatively short duration (~4 water years) of observed water level data within the lagoon, and lack of historic beach elevation surveys.

Each of the above-listed factors represents an area of uncertainty that may influence the model results leading to potentially inaccurate predictions. In some cases uncertainty introduced by these factors could be reduced by the incorporation of additional historic data or field observations. In particular, we recommend continued observations of lagoon water levels, beach elevation and inlet channel dimensions over the coming years.

SCENARIO MODELING

The Goleta Slough QCM has been used to evaluate a range of potential future scenarios in order to provide additional understanding of the role that key processes in driving lagoon dynamics, and to inform future lagoon management. These scenarios were developed in order to evaluate the following topics:

- Changes to the Lagoon Storage Volume

  For these scenarios the Stage-Storage relationship that is used to represent the volume of the lagoon was increased and decreased by +/-25% in order to represent the hydrodynamic impact of potential future projects which may cause alterations to the Goleta Slough landscape, changing the size of the lagoon. Additional sensitivity tests representing larger changes to the lagoon Stage-Storage relationship were also conducted in order to evaluate the sensitivity of the system to larger scale landscape alterations.

- Sea Level Rise

  Sea Level Rise scenarios were developed by applying a vertical shift to the tidal boundary condition in order to represent +0', +1', +3' and +5' of sea level rise.

- Inlet Management Practices

  The Inlet Management scenarios simulate mechanical breaches of the lagoon inlet whenever lagoon water levels within the lagoon exceed a pre-determined threshold elevation. This study assumes mechanical breaches area shallow (2-3' deep).

The QCM was used to model each scenario based on wave and watershed conditions observed during a continuous period spanning from 2010 to 2014. Results tracking the duration of closures and breach frequency were tabulated for separately for Wet (2011) and Dry (2013) years in order to highlight the range of variability which may occur due to year-to-year variations in precipitation. Table G-4, at the end of this memorandum, lists output statistics for the key model runs used for this analysis. Detailed descriptions of each of these scenarios, as well graphics highlighting the modeled changes in lagoon dynamics for each scenario are presented in the sections below.

Storage Volume Scenarios

The storage volume adjustment scenarios are intended to examine the expected impact of changes to the Goleta Slough landscape which alter the volume and tidal prism of the lagoon. The construction of levees to reduce the flood risk to infrastructure such as the airport and other low-lying parcels may result in a decrease in the lagoon volume and tidal prism. Creating hydraulic connections between existing diked areas and the existing marsh network (e.g. as part of habitat restoration efforts) would increase the lagoon volume and tidal prism.

The stage-storage adjustments used for these scenarios were implemented by multiplying the existing conditions stage-storage curve by a constant factor. Consequently, these scenarios represent conditions where the lagoon storage has been increased or decreased by a constant factor at all elevations. These storage volume adjustment scenarios are intended to test the Slough's response to volume changes in general, and do not represent any particular physical project or landscape alteration. The impact of real landscape altering projects (restoration or flood control) would most likely only alter a specific range of the Slough's stage-storage curve, and the impact of said alterations on the Slough's hydrodynamics will vary depending on the elevation of the changes to the lagoon volume.

Figure G-5 shows time series and water level exceedance curves for existing conditions and for scenarios where the lagoon storage volume has been increased or decreased by 25%.

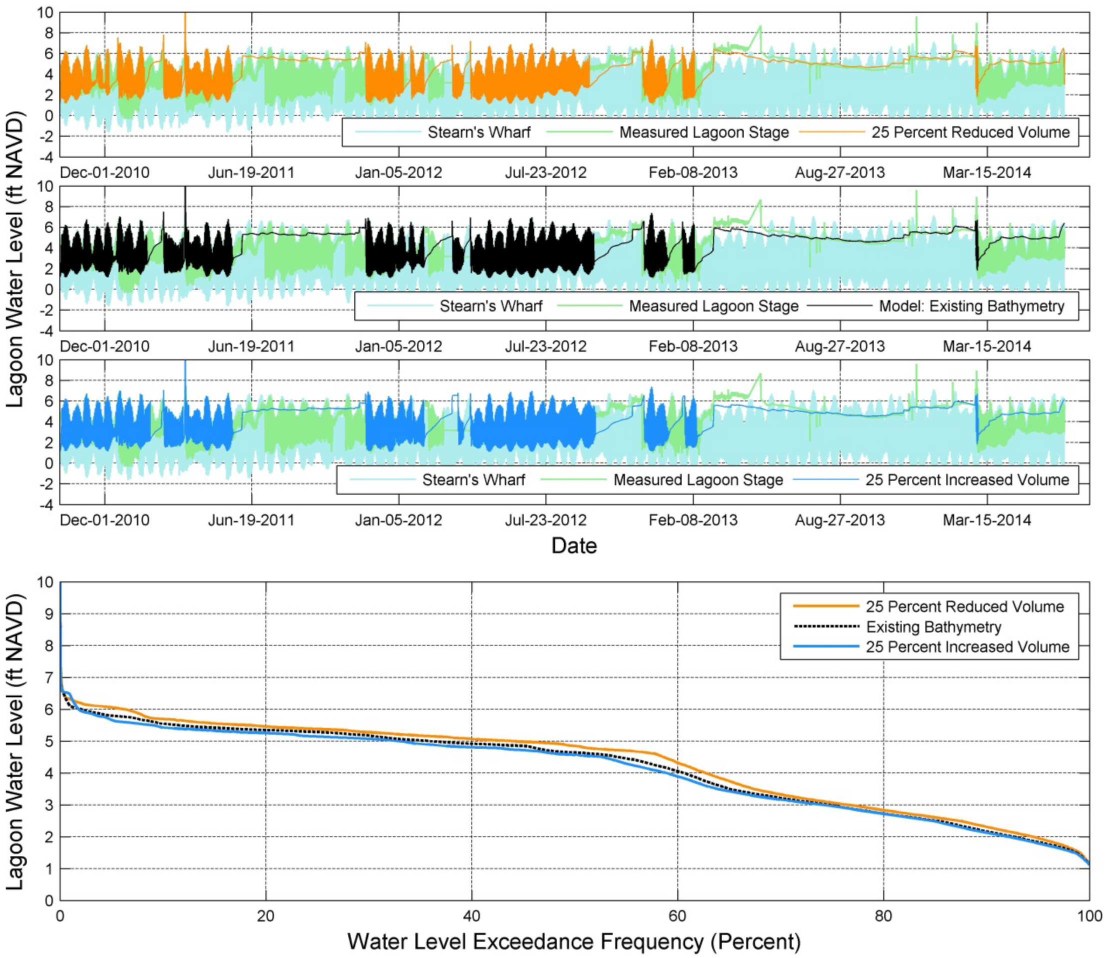

Figure G-5 – Model Results for Storage Volume Scenarios

While the differences between the increased and decreased storage volume scenarios were subtle, adjusting the tidal prism of the Slough was found to have two notable effects:

1. Increasing the size of the Slough delays breaching during rain events (and possibly causes the Slough to not breach during small rain events), while decreasing the size of the Slough accelerates breaches due to rain events. This effect is most strongly influenced by

changes in the storage area at elevations between MHHW and the beach berm crest elevation.

2. Increasing the size of the Slough delays the closure of the lagoon due to an increase in tidal scour (possibly preventing closure altogether), while decreasing the size of the Slough reduces tidal scour and makes it more likely for the lagoon mouth to close earlier in the season. This effect is primarily influenced by changes in the storage are at elevations between MLLW and MHHW.

There is a complex relationship between lagoon tidal prism and the fraction of time that the lagoon mouth is closed. For small coastal estuaries (like the existing Goleta Slough), modest increases in the tidal prism can result in an increase in the percent of time that the lagoon is closed. This occurs because for small systems Effect #1(delayed breaching during rain events) is stronger than Effect #2 (delayed closure during the dry season). As the tidal prism of the lagoon increases, Effect #2 becomes increasingly important, to the point that very large estuaries (eg. Bolinas lagoon, Elkhorn Slough, Tomales Bay) rarely close even during prolonged droughts. Figure G-6 shows a diagrammatic representation of this relationship for un-managed conditions.

Under present day conditions the Slough has an estimated potential tidal prism of ~200 ac-ft. The QCM results show that a 25% increase in lagoon volume results in a net increase in percent time that the lagoon mouth is closed. However, sensitivity tests also indicate that a much larger increase in volume (eg. +300%) results in a self-scouring lagoon mouth that is open year round during all but the driest years. Historic maps suggest that Goleta Slough likely had a tidal prism approximately five times greater than that occurring under existing conditions. The QCM indicates that with a tidal prism greater than 1000 acre-feet the lagoon experiences only brief closures during dry years and no closures during wet years.

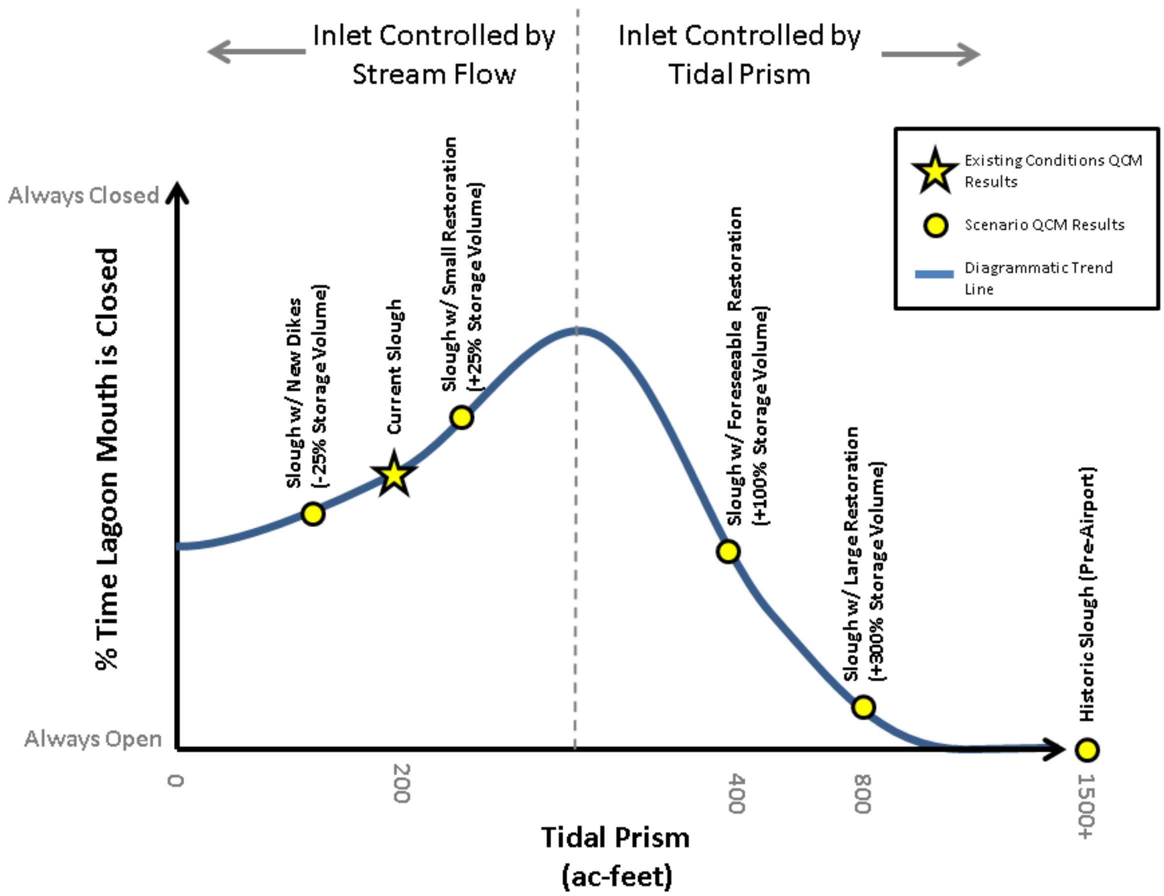

Figure G-6 – Trends in Frequency of Inlet Closure with Adjustments to Tidal Prism

While this study has only evaluated changes in the stage storage relationship that were applied uniformly across all elevations, real-world projects typically only increase or decrease the storage volume within a certain elevation range. The elevation range affected by such projects can be tailored during project design in order to achieve desired effects. For example, in order to manage for a more frequently open lagoon mouth it would be desirable to implement projects which increase the storage volume between MLLW and MHHW in order to encourage tidal scour, while not increasing the storage area above MHHW in order to avoid delayed breaches during rain events. In contrast, in order to manage for a more frequently closed lagoon mouth it would be desirable to reduce the storage volume between MLLW and MHHW so as to minimize tidal scour, and increase the storage volume between MHHW and the beach berm elevation, delaying breaching during rain events.

The historic strategy for managing the lagoon favors more frequent open conditions in order to reduce flood risk, maintain water quality, and to provide existing tidal wetlands within the Slough with a suitable tidal inundation regime. Increasing the inter-tidal storage volume of the lagoon through restoration and enhancement of tidal wetlands within the Slough is one method that may encourage extended periods of open conditions while potentially reducing the need for managed breaches.

Sea Level Rise Scenarios

The QCM was used to evaluate conditions under +0, +1’, +3’ and +5’ of sea level rise. Rising sea levels were represented by applying a uniform upward shift to the tidal water level input time series. The elevated tide levels in turn increase the predicted elevation of wave run-up and beach berm elevation. No other lagoon input parameters were changed. Current climate change projections indicate that the Santa Barbara/Goleta area may experience warmer and slightly drier conditions by the end of the next century. These projections suggest that changes in the local climate could lead to a reduction in the average watershed inflows entering Goleta Slough; however this effect was not included in this study.

Additionally, climate change may alter prevalent wave conditions at Goleta Breach. Changes in wave conditions may alter the rate of growth of the breach berm, which would in turn affect the frequency of lagoon mouth closure. There is currently no consensus as to the expected impact, if any, that climate change and rising sea levels will have on wave patterns in the Pacific. For the present study we have assumed that future wave patterns will be similar to those observed in the present day.

Figure G-7 shows time series of water levels and water level exceedance curves for three sea level rise QCM scenarios. These runs show QCM results for 0’, 1’ and 5’ of sea level rise, with managed breaching when lagoon water levels exceed MHHW + 1.25’ (El. 6.5’, 7.5’ and 11.5’, respectively).

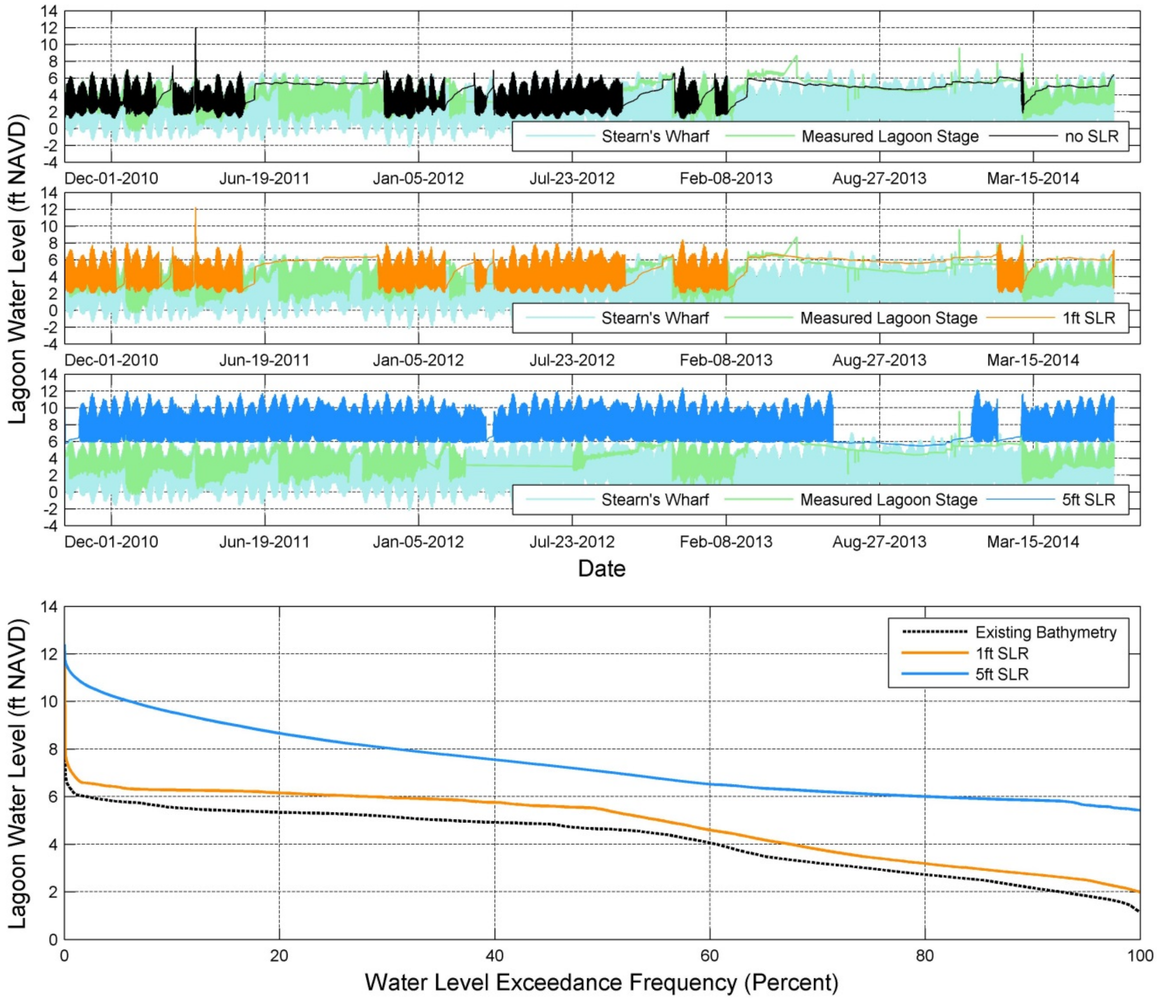

Figure G-7 – Model Results for Sea Level Rise Scenarios (with managed breaches at MHHW +1.25')

The main effect of elevated sea levels is to shift water levels within the lagoon upwards. The higher tidal water levels increase the tidal prism of the lagoon, while also increasing the elevation of the beach berm due to the increased elevation of wave runup. If the lagoon mouth is not managed, the net effect of these shifts is that for small amounts of sea level rise (+1ft) the lagoon will remain closed more often as the higher beach berm increases the storage capacity of the lagoon, delaying breaching during rain events. The higher beach berm and increased duration of closure leads to more frequent ponding, and generally increased water levels within the Slough. For larger amounts of sea level rise, the lagoon tends to be open more frequently due to the larger tidal prism and increased tidal scour of the inlet channel. Figure G-8 shows a diagrammatic representation of the general trends in lagoon inlet closure for various amounts of sea level rise:

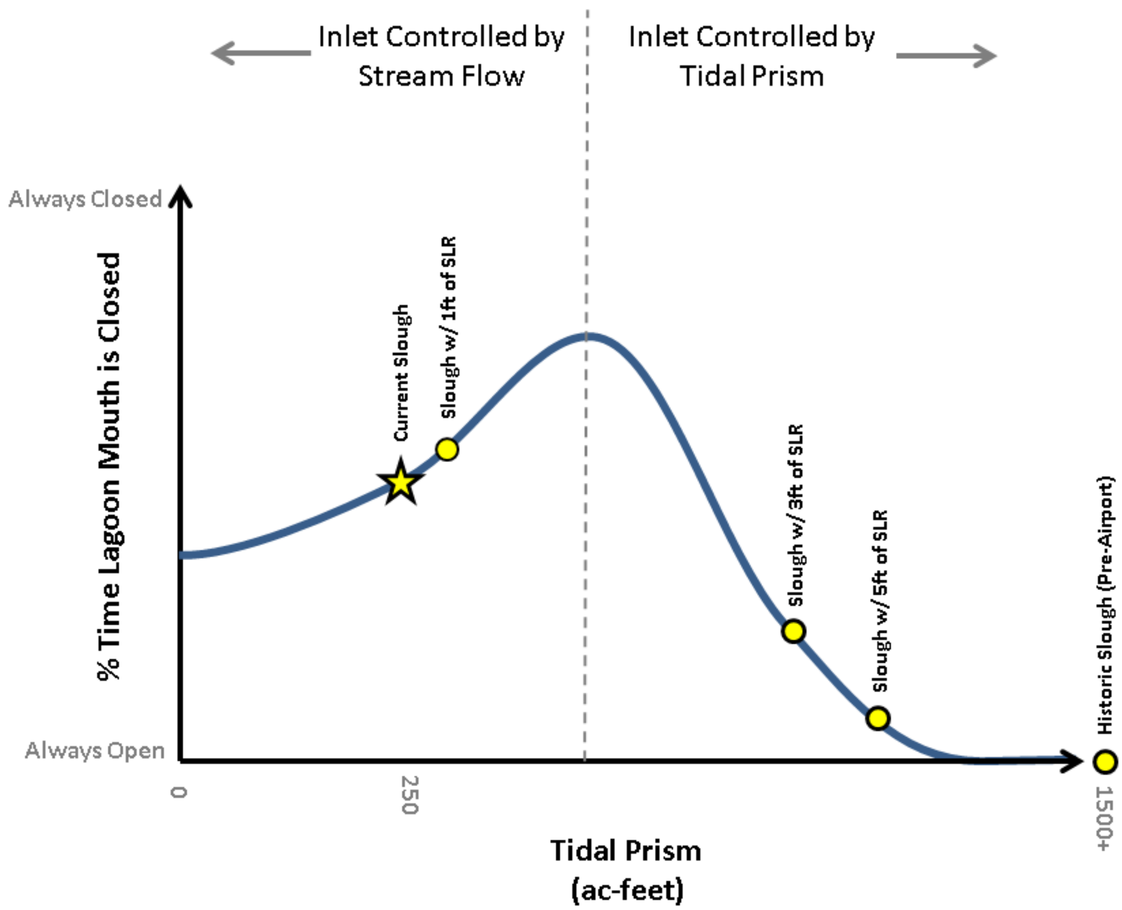

Figure G-8 – Trends in Frequency of Inlet Closure with Rising Sea Levels

Inlet Management Scenarios

Stillwater Sciences, in collaboration with Rincon Consultants and the City of Santa Barbara, has developed a set of proposed lagoon mouth management strategies that are intended to protect existing marshplain habitat which is adapted to historic managed lagoon conditions and also to provide flood protection to the airport and other infrastructure near the lagoon. The proposed strategies include seasonal management actions which will be conducted should water levels within the lagoon exceed a pre-determined threshold elevation. During the winter season (October 15 to March 31) the lagoon mouth would be mechanically breached if water levels exceed the threshold elevation. During the summer season a siphon would be installed and operated during times when lagoon water levels exceed the threshold elevation. The siphon would be used to lower water levels to an acceptable elevation. The proposed management strategies also include triggers for managed breaches in the event of increased waterfowl populations in close proximity to the airfield runways in order to minimize the hazard to aircraft operations.

ESA has analyzed the expected impact of the use of various threshold elevations to trigger managed breaches at Goleta Slough on overall trends in lagoon water levels and frequency of breaches and closures. ESA has not evaluated the suitability of these proposed management strategies for the achievement of specific ecological or flood objectives, nor has ESA evaluated the potential environmental impacts and engineering feasibility of mechanical breaching. More information concerning the proposed management strategies will be provided in the forthcoming management plan currently under development by Stillwater Sciences and the City of Santa Barbara.

For this study, we have evaluated a set of management scenarios based on mechanically breaching the lagoon when water levels within the Slough exceed a pre-determined threshold elevation. These scenarios have been evaluated for conditions both with and without sea level rise. The modeled scenarios only include managed breaching based on water levels exceeding the threshold elevation, the modeled scenarios do not include the other management interventions proposed by Stillwater Sciences (pumps, siphons, breaching due to waterfowl, etc.).

There is uncertainty regarding the long-term management of the lagoon inlet as sea levels rise. For the purposes of this study, it was assumed that the threshold elevation for inlet management will be tied to the tide elevation, specifically the mean higher high water tidal datum ("MHHW"), and thus will shift upwards to match rising sea levels. Threshold inlet management elevations of MHHW +1.25', MHHW +2.25' and MHHW+3.75' were modeled. Under present day conditions these correspond to elevations of 6.5', 7.5' and 9.0' NAVD, respectively.

In addition, a "no-management" scenario was also modeled. Under the no-management scenario the beach is allowed to grow until it reaches the estimated maximum equilibrium beach berm elevation. Under the no-management scenario no managed breaches were simulated and natural breaches were assumed to occur whenever the inboard lagoon water levels exceed the elevation of the beach berm. For purposes of this study it was assumed that the beach berm elevation would grow to a maximum equilibrium elevation of MHHW +4.5' (9.75' NAVD under existing conditions). This elevation was identified based on the surveyed elevation of the low-point in the beach berm following the year-long inlet closure of 2013-2014 (CCBER 2015). This elevation was found to correspond to the 99.2-percentile of wave run-up elevation (a.k.a. "Total Water Level") at Goleta Beach during the 2010 to 2014 study period.

Figure G-9 shows time series of water levels and water level exceedance curves for three inlet management QCM scenarios. These runs show predicted conditions for three scenarios:

1. Unmanaged: max beach berm elevation at MHHW +4.5 (9.75' NAVD)
2. Managed breaches at MHHW +1.25' (6.5' NAVD)
3. Managed breaches at MHHW +3.75' (9.0' NAVD)

These scenarios represent present day conditions with no sea level rise.

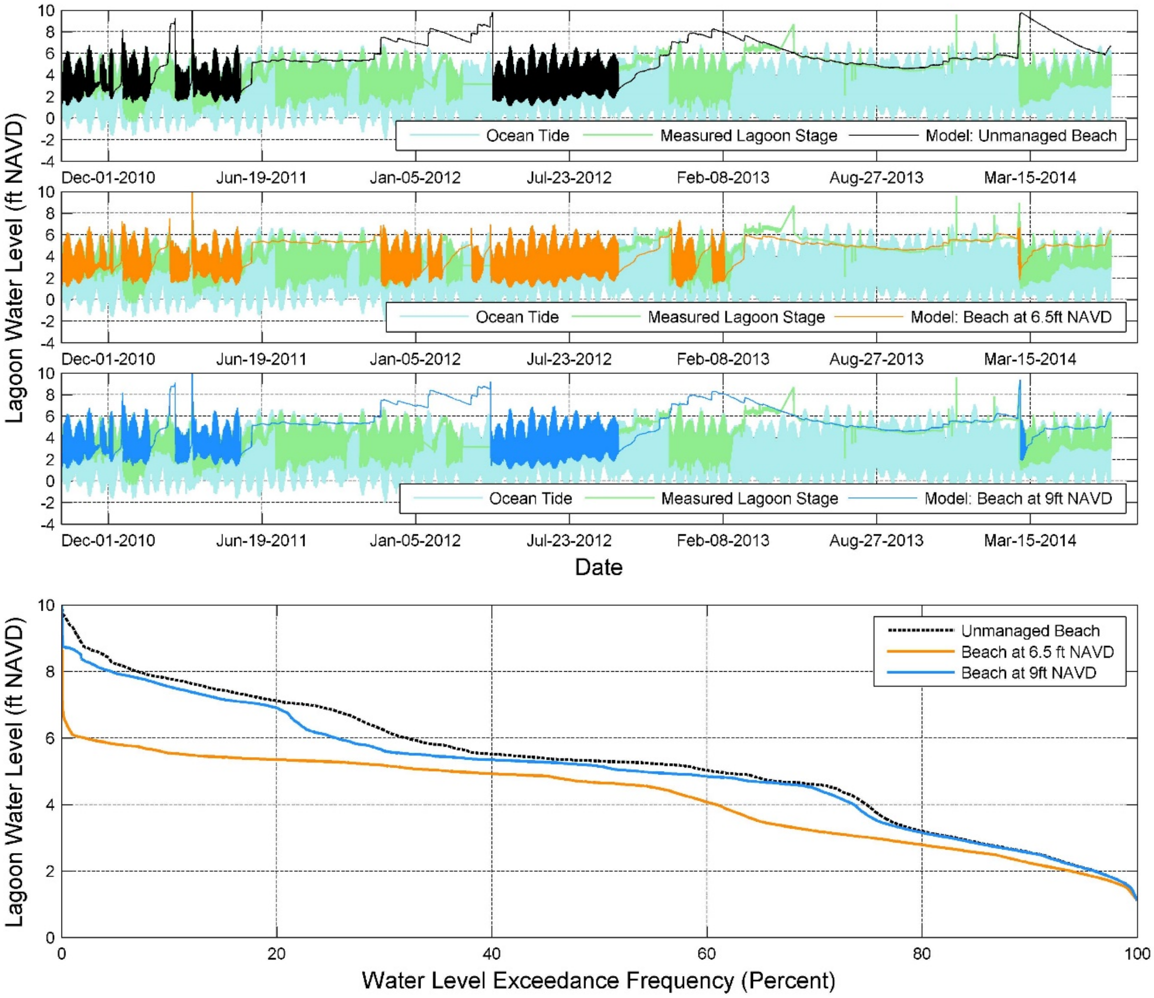

Figure G-9 – Model Results for selected Inlet Management Scenario (with no Sea Level Rise)

Figure G-10 shows the percent time that the lagoon is predicted to be closed for the several management scenarios modeled, with and without sea level rise. The x-axis on Figure G-10 shows the breach elevations normalized to the MHHW datum for each sea level rise scenario. For this study it is assumed that MHHW will be 6.25’ NAVD under conditions with +1’ sea level rise (1’ higher than MHHW under present day conditions); 8.25’ NAVD for +3’ of sea level rise; and 10.25’ NAVD for +5’ of sea level rise. This convention is also used for Figures G-11 and G-12.

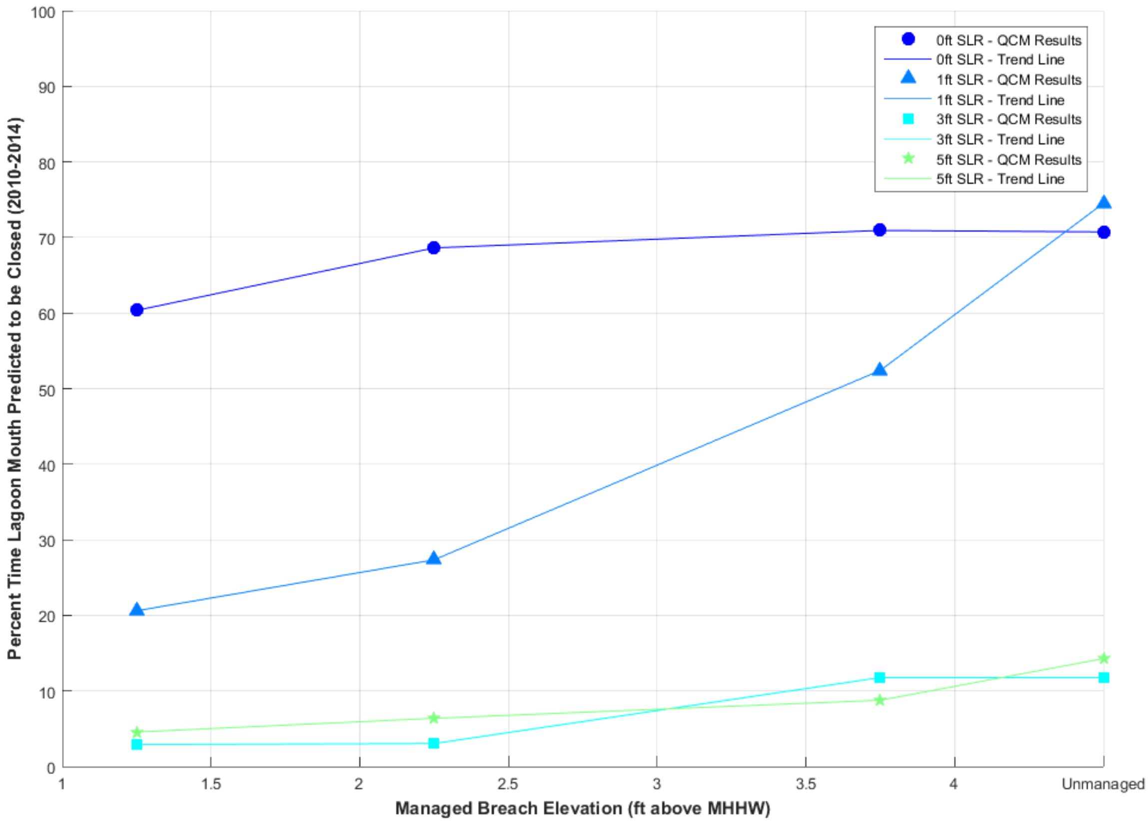

Figure G-10 – Frequency of Inlet Closure with Rising Sea Levels and Inlet Management

These results indicate a key trend in the effectiveness of inlet management for various amounts of sea level rise. In general, the QCM shows that breaching at lower elevations results in more frequent open conditions. One measure of the effect of a managed breaching regime is the predicted change in the percent time that the lagoon mouth is closed due to managed breaching relative to unmanaged conditions. Table G-3 lists the predicted potential change in frequency of inlet closure due to inlet management, as calculated by comparing the frequency of closure for the no-management scenario vs the breach at MHHW +1.25ft scenario, for various amounts of sea level rise.

Scenario	Wet Year (2011)	Dry Year (2013)	2010 to 2014
0ft SLR	0%	-15%	-11%
1ft SLR	0%	-86%	-55%
3ft SLR	0%	0%	-9%
5ft SLR	-9%	0%	-8%

Table G-3 – Absolute Change in Predicted Frequency of Closed Inlet Conditions for Managed Breaches at MHHW +1.25' Relative to No-Management Scenario

The QCM predicts that inlet management is only marginally effective altering the percent time that the lagoon mouth is closed under existing conditions, but it has the potential to have a much larger influence on the inlet condition under future conditions with small amounts of sea level rise. The QCM results also indicate that, for scenarios with +0' or +1' of sea level rise, the impact of managed breaching is most significant during dry years and relatively insignificant during wet years. The QCM results show that the effectiveness of inlet management will decrease as sea level rise increases over the coming century since rising sea levels will increase the effectiveness of tidal scour in maintaining an open lagoon inlet. The differences between wet and dry years disappears for scenarios with higher sea level rise as the lagoon mouth is more strongly influenced by tidal scour rather than watershed inflows.

Figure G-11 shows the percent time that water levels within the Slough are predicted to exceed El. 9.0' NAVD. El. 9.0' is approximately the elevation of the lowest-lying critical infrastructure, including the lowest airfield runways and several streets adjacent to the Slough.

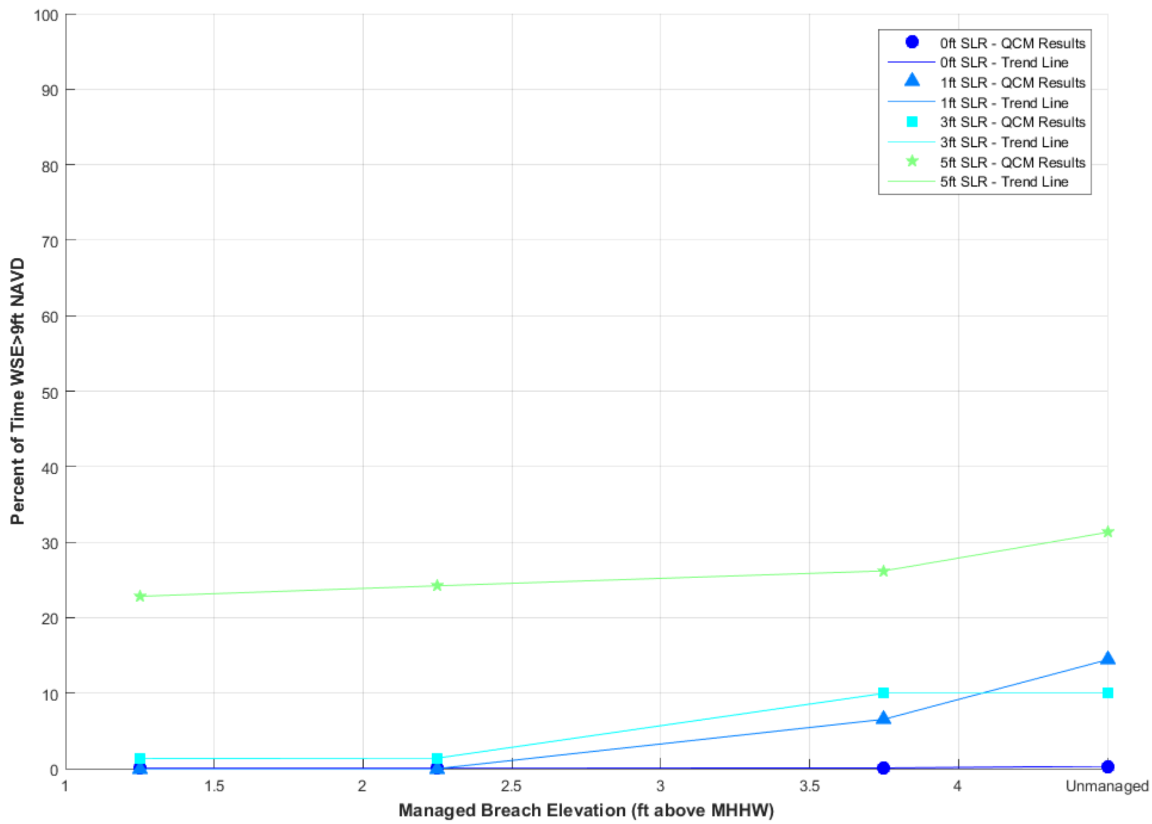

Figure G-11 – Frequency of Flood Conditions with Rising Sea Levels and Inlet Management

Figure G-12 shows the percent time that water levels within the Slough exceed El. 7.0' NAVD. El. 7.0' is approximately the elevation at which the pickleweed marsh plain becomes inundated under existing conditions. There is concern that continuous inundation of the marshplain for several days or weeks may result in the conversion of existing pickleweed marsh to unvegetated tidal mudflat. Such habitat conversion may be harmful to sensitive species including Coulter's Goldfields and Belding's Savanah Sparrow (David Hubbard, pers. coms. 2014).

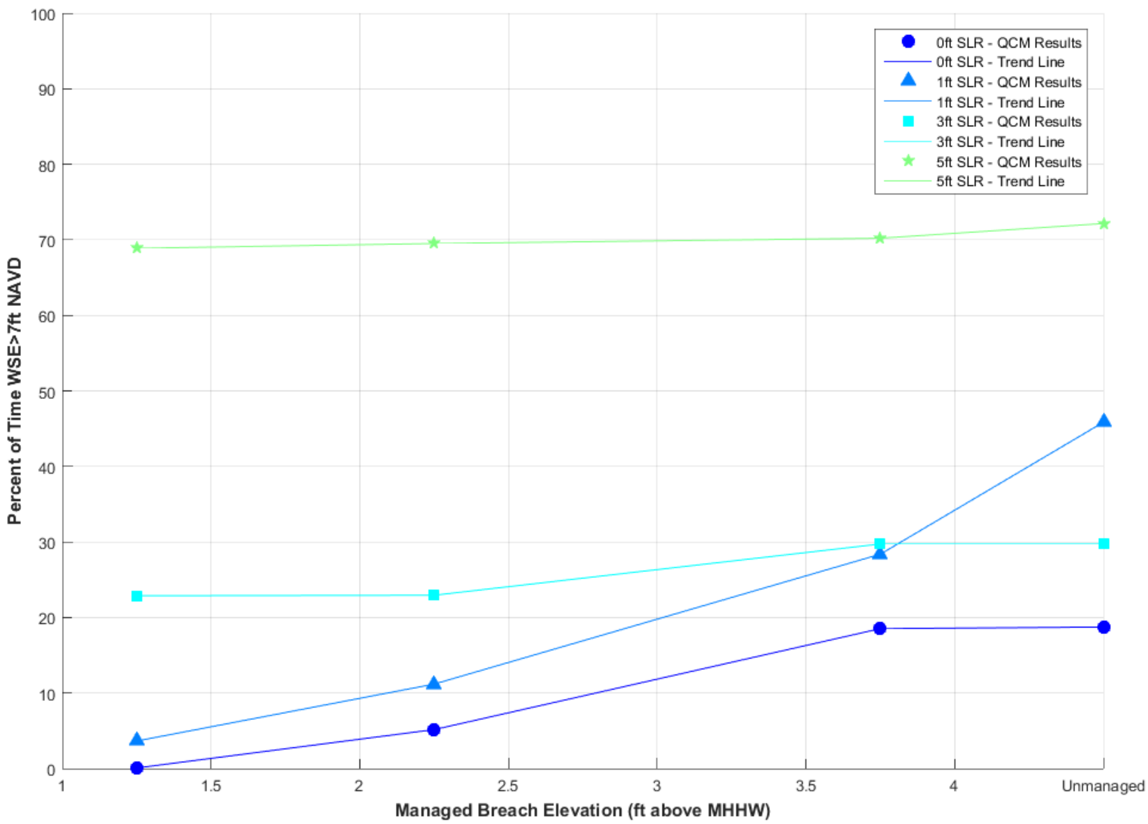

Figure G-12 – Frequency of Pickleweed Marshplain Inundation with Rising Sea Levels and Inlet Management

A key observation revealed by Figures G-10, G-11 and G-12 is that without lagoon inlet management, water levels within the lagoon will initially increase faster than the rate of sea level rise. For scenarios without inlet management the percent time the lagoon is closed, and the percent time water levels exceed El. 9.0' and 7.0' are higher for the scenario with 1ft of sea level rise than for the scenarios with 0ft or 3ft of sea level rise. This is a result of the more frequent ponding which occurs with 1 foot of sea level rise, compared to the more frequent open conditions which occur for +3ft of sea level rise due to the lagoons larger tidal prism causing stronger tidal scour of the inlet channel.

Figures G-11 and G-12 show a similar trend to that observed in Figure G-10: the QCM results indicate that inlet management appears to be a viable strategy for managing water levels within the Slough for the short- to medium-term but will become less effective as sea level rise increases over time.

The QCM results also show that the selection of managed breach elevation can be used to influence the percent time that the pickleweed marsh plain is inundated for scenarios with +0' or +1' of sea level rise. With no sea level rise the marsh plain is predicted to be submerged 19% of the time if the lagoon mouth is not managed, however with breaching at MHHW +1.25' the marshplain is inundated less than 1% of the time. With one foot of sea level rise the marsh plain is predicted to be submerged 46% of the time if the mouth is not managed, and with breaching at MHHW +1.25' the marshplain is inundated 4% of the time. The choice of managed breach elevation has much less of an impact on the frequency of marshplain inundation for scenarios with +3' and +5' of sea levels rise.

The QCM results indicate that managed breaches can greatly reduce the risk of tidal flooding for scenarios with +0' or +1' of sea level rise. With zero feet of sea level rise the predicted water levels exceed the flood stage (El. 9.0') ~1% of the time (generally during large rain events) if the inlet is not managed. The predicted water levels never exceed 9.0' with inlet management thresholds at MHHW+0.5' or MHHW+1.5'. At one foot of sea level rise the unmanaged water levels exceed El. 9.0' nearly 15% of the time, indicating significant and frequent flooding, but the QCM predicts that with inlet management at MHHW+0.5' or MHHW+1.5' water levels once again never exceed El. 9.0'. However, once sea levels rise by 3', water levels exceed El. 9.0' regardless of the inlet management threshold elevation.

Figure G-13 shows a diagrammatic representation of how the choice of inlet management elevation shifts the general patterns of inlet closure as sea levels rise.

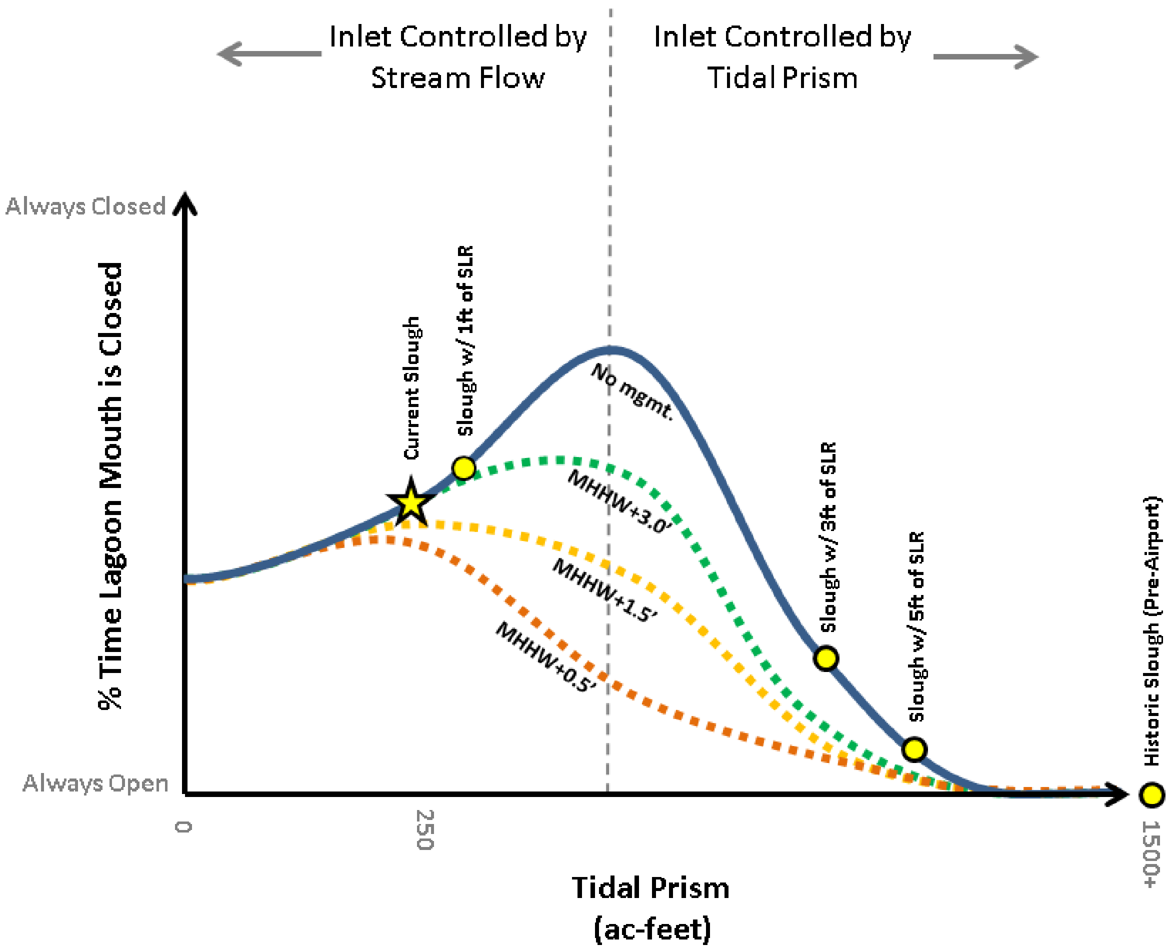

Figure G-13 – Trends in Frequency of Inlet Closure as Sea Levels Rise for Various Inlet Management Elevations

TABULATED QCM RESULTS:

Table G-4 tabulates detailed statistics from the QCM results conducted for this study:

Scenario			# of Closure Events			# of Breach Events			% Time Closed			% Time WSE>9.0’			% Time WSE>7.0’		
Storage Volume	Breach Elevation	Sea Level Rise	2011 “Wet”	2013 “Dry”	2010 to 2014	2011 “Wet”	2013 “Dry”	2010 to 2014	2011 “Wet”	2013 “Dry”	2010 to 2014	2011 “Wet”	2013 “Dry”	2010 to 2014	2011 “Wet”	2013 “Dry”	2010 to 2014
+0%	MHHW +1.25’	+0ft	3	3	9	2	2	8	40	85	60	0.2	0	0.05	0.3	0.05	0.1
		+1ft	3	0	5	2	0	4	4.3	14	20	0	0	0	1.4	1.5	3.7
		+3ft	0	0	1	0	0	1	0	0	2.9	1.4	1.2	1.3	21	21	23
		+5ft	1	0	2	0	0	2	9.3	0	4.6	24	22	23	67	69	69
	MHHW +2.25’	+0ft	2	1	8	2	1	7	41	96	69	0.2	0	0.05	0.3	5.9	5.2
		+1ft	2	1	5	2	1	6	4.4	21	27	0	0	0	1.4	7.7	11
		+3ft	0	0	1	0	0	1	0	0	3.1	1.4	1.2	1.4	21	21	23
		+5ft	1	0	2	0	0	2	15	0	6.4	29	22	24	69	69	70
	MHHW +3.75’	+0ft	3	0	5	2	0	4	41	100	71	0.2	0	0.1	0.7	34	19
		+1ft	2	1	7	1	1	8	4.4	97	52	0	10	6.5	1.4	5.5	28
		+3ft	0	0	1	0	0	0	0	0	12	1.4	1.2	10	21	21	30
		+5ft	1	0	2	0	0	2	18	0	8.8	31	22	26	70	69	70
	No Managed Breaches	+0ft	3	0	5	2	0	4	41	100	71	0.2	0	0.3	0.7	34	19
		+1ft	2	0	3	1	0	3	4.4	100	75	0	11	14	1.4	56	46
		+3ft	0	0	1	0	0	0	0	0	12	1.4	1.2	10	21	21	30
		+5ft	1	0	2	0	0	2	18	0	14	31	22	31	70	69	72
+25%	MHHW +0.5’	+0ft	3	2	9	2	2	9	39	84	60	0.2	0	0.04	0.2	0.05	0.1
+0%			3	3	9	2	2	8	40	85	60	0.2	0	0.05	0.3	0.05	0.1
-25%			5	2	12	4	2	12	45	85	62	0.2	0	0.05	0.3	0.05	0.1
+25%		+1ft	2	0	7	3	0	6	0	19	18	0	0	0	1.4	6.7	4.4
+0%			3	0	5	2	0	4	4.3	14	20	0	0	0	1.4	1.5	3.7
-25%			2	1	7	1	1	6	9.0	80	59	0	0	0	1.4	1.0	1.7
+25%		+3ft	0	0	1	0	0	1	0	0	2.4	1.4	1.2	1.3	21	22	23
+0%			0	0	1	0	0	1	0	0	2.9	1.4	1.2	1.3	21	21	23
-25%			0	0	2	0	0	2	0	0	2.3	1.4	1.2	1.3	21	21	21
+25%		+5ft	0	0	2	0	0	2	0	0	2.2	21	22	22	69	69	69
+0%			1	0	2	0	0	2	9.3	0	4.6	24	22	23	67	69	69
-25%			1	0	3	2	0	3	7.0	0	3.8	23	22	23	67	69	69

Table G-4 – QCM Results for Key Model Runs

Note: The results for the storage volume adjustment scenarios represent uniform 25% percent increase/decrease of basin volume at all elevations, as explained in a ”Storage Volume Scenarios” section above. Additional sensitivity tests (not shown in Table G-4) suggest that slough expansion alternatives which include larger increases in storage volume could lower lagoon water levels to the ocean levels by changing the lagoon state to open or mostly open.

DISCUSSION OF WATER QUALITY IMPACTS

Expected changes in lagoon hydraulic conditions may lead to changes in water temperature, dissolved oxygen and salinity which could have impacts on habitats within the Slough. Higher temperatures and lower dissolved oxygen are generally considered to be characteristics of degraded lagoon water quality although these characteristics are known to occur in natural lagoon systems. Salinity is not a pollutant but can be considered an indication of degraded water quality relative to some flora and some fauna at particular times, especially when anadromous fish are not yet acclimated to salinity and have limited fresh / brackish water refuge in the estuary. The following is a brief discussion of the expected general trends in water quality that may result from changes in breach frequency and lagoon water level. This discussion is informed by the QCM results and general observations of water quality at Goleta Slough and similar coastal lagoons. No water quality parameters were directly modeled as part of this study.

The QCM results indicate two main trends in lagoon hydrodynamics as sea levels rise over the coming century:

1) Generally increased water levels within the Slough
2) Sensitivity of the mouth conditions (open vs closed) to the selected management practices, but with a general long term trend towards more frequent open conditions.

Increased water levels are expected to result in greater water depths and a larger overall volume of water in the lagoon. Deeper water is less likely to experience complete mixing due to wind and channel flows, and thus is more likely to become stratified due to temperature and density gradients.

Stratified conditions are characterized by an upper layer of fresh water with relatively high dissolved oxygen that sits above a lower layer of saltier water with relatively low dissolved oxygen. The existence of stratified conditions at a coastal lagoon is not necessarily problematic, however fish kills have been observed at other lagoons along the California coast when stratified lagoons breach suddenly, and the upper layer drains from the lagoon leaving behind only the low dissolved oxygen lower strata of the water column. Care should be taken when planning and conducting mechanical breaches to avoid sudden or rapid breaches, especially when stratified conditions may exist.

The state of the lagoon mouth is also an important factor influencing water quality in the lagoon. Open mouth conditions allow for greater mixing between ocean and lagoon waters. This leads to higher salinities and lower temperatures within the lagoon. Tidal flushing tends to increase mixing in open lagoons, leading to relatively higher dissolved oxygen levels and reducing (but not necessarily eliminating) stratification.

Closed lagoons experience less mixing, and are more likely to tend towards stratified conditions. Conditions within a closed coastal lagoon are strongly influenced by the rate of freshwater inflows and seepage through the beach berm. High inflows and seepage rates tend to force the lower layer of saltier water out of the lagoon through the beach berm. This reduces the likelihood of stratification and leads to brackish or freshwater conditions within the lagoon. A closed lagoon with low inflows and seepage rates will tend towards strongly stratified conditions.

RECOMMENDATIONS

Based on the results of the inlet modeling study, we offer the following recommendations to help guide future planning actions:

- We recommend the development of a long-term management plan for Goleta Slough which clearly articulates goals and objectives for habitat management, land use and flood protection.
- The QCM results suggest that flood protection can be achieved under a range of managed breach thresholds (eg. 6.5' and 7.5' NAVD). We recommend further refinement of the proposed mechanical breach thresholds to achieve optimum benefits for the local ecology.
- The QCM results do not predict the occurrence of elevated water levels above El. 6.5' NAVD during the summer months for scenarios with +0 and +1 feet of sea level rise (with or without inlet management). This finding indicates that summer time pumps/siphons are unlikely to be needed under typical conditions.
- Long-term plans for the Goleta Slough region should anticipate the decreasing effectiveness of inlet management as a management tool for achieving flood protection and habitat goals as sea level rises reaches +3 feet.
- Long term plans for the Goleta Slough region should incorporate adaptation strategies that anticipate significant increases in lagoon water levels and near-continuous open-lagoon conditions by the end of the century.
- We recommend additional study to evaluate the feasibility of large-scale landscape shaping and to evaluate specific opportunities for multi-benefit projects for habitat enhancement, restoration and lagoon management. We recommend that the evaluation of potential project alternatives include a refined analysis of impacts on local channel hydraulics and lagoon inlet dynamics.
- We recommend that future studies include a statistical analysis of coastal and hydrologic processes in order to better characterize the expected frequency occurrence of extreme conditions including prolonged droughts, El Nino and extreme rain/flood events.

In addition, we encourage local planning agencies to continue data collection efforts to enhance the understanding of the physical processes which shape Goleta Slough. In particular, we feel that the following monitoring actions would provide highly valuable data for refining the QCM model:

- Continued monitoring of water levels within the Slough
- Regular surveys of the elevation of the beach berm and the dimensions of the lagoon channel. Survey data collected immediately before and after the lagoon mouth breaches is expected to be most useful for continued model refinement.
- Documentation of future managed and natural breaches, including timing of the breach, excavated channel width and depth, and the timing of future lagoon mouth closures.

Finally, while this study has not considered the impacts of climate change on watershed inflows and evaporation rates, we acknowledge that these impacts may be significant in shaping future conditions at Goleta Slough. We recommend that future studies evaluate the projected changes in hydrologic conditions and the potential impacts of these changes on water levels and breach and closure patterns at the lagoon.

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Attachment A – Watershed Analysis for Goleta Slough Inlet Modeling

INTRODUCTION

The Goleta Slough QCM requires a time-series of watershed discharge as one of the key inputs driving the lagoon water levels. This document discusses two methods which were used to estimate the watershed discharges for the ungaged streams which flow into Goleta Slough: a peak flow scaling method and the Rational Method. These two methods were found to produce generally similar results. The peak flow scaling method was selected to develop the input streamflow time series used in the Goleta Slough QCM.

BACKGROUND

There are 5 major creeks that flow into Goleta Slough. Only two of these creeks have active or historic streamflow gages, the Atascadero Creek gage is located at the weir near the S. Patterson Ave. crossing, while the San Jose Ck. gage is located near the N. Patterson Ave. crossing. Figure G-1 shows the Goleta Slough watershed. Atascadero Creek has by far the largest watershed of the 5 major creeks entering Goleta Slough, so it is no surprise that the creek is responsible for the largest fraction of total annual stream flow entering the slough. Streamflows from Atascadero Creek are recorded at USGS gage # 11120000 near the confluence of Atascadero Creek with the slough proper.

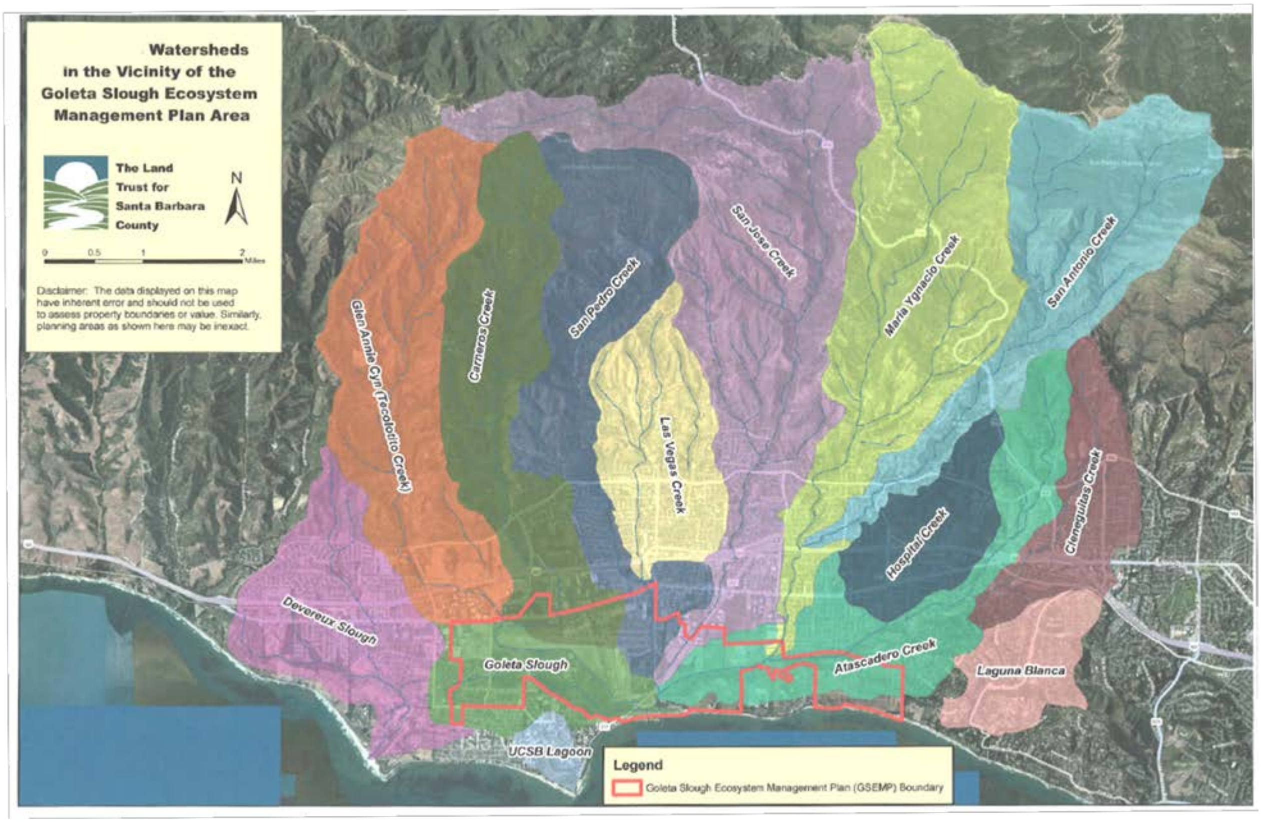

Figure 1 – Goleta Slough Watershed

Figure 2 shows the estimated recurrence intervals for streamflows at the Atascadero and San Jose Creek gages.

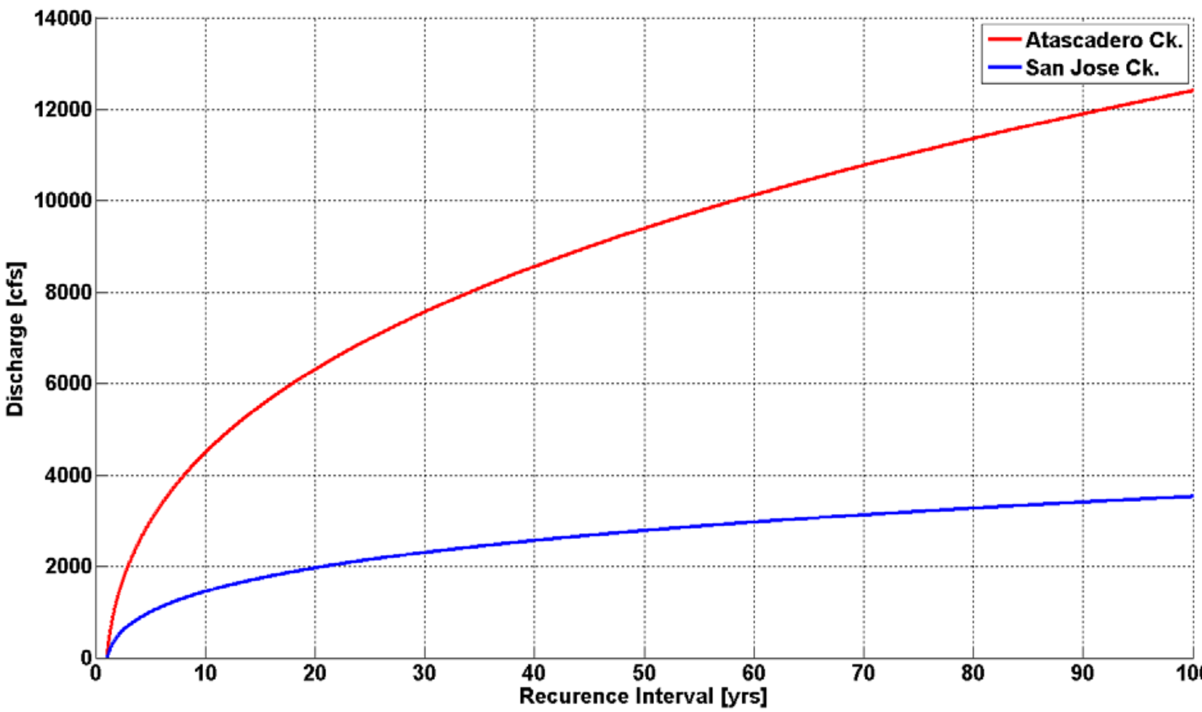

Figure 2 – Estimated Recurrence Interval for Streamflows on Atascadero and San Jose Creeks, based on records from 1940 to 2014.

PEAK FLOW SCALING METHOD

Synthetic hydrographs for each of the 5 creeks were developed for the period of interested (2010-2014) using a peak-flow-scaling method in order to estimate the contribution of each stream to the total watershed discharge entering Goleta Slough. The peak-flow-scaling method estimates a streamflow time-series for an ungaged stream by scaling streamflow data from a nearby, gaged stream. A scaling relationship was developed for each creek based on the estimated peak discharge for storms of various recurrence intervals using the method presented in Gotyald, et al (2012). Goleta Slough and the 5 major creeks which flow into the slough are located within the South Coast region (Region 5 in Gotyald, et al).

The estimated recurrence intervals of various peak discharges along each of the 5 creeks are shown in Figure 2. The ratios between the peak discharges on the gaged creek (Atascadero Ck) and each of the four ungagged creeks were calculated for storm events of with 2, 5, 10, 25, 50, 100, 200 and 500 year recurrence intervals. These ratios are used to develop rating curves which relate the flows on the gaged creek with the predicted flows on the ungagged streams over a wide range of streamflows. These rating curves were then used to scale a time-series of observed discharges on Atascadero Ck. to estimate the discharges for each of the 4 other creeks in the watershed.

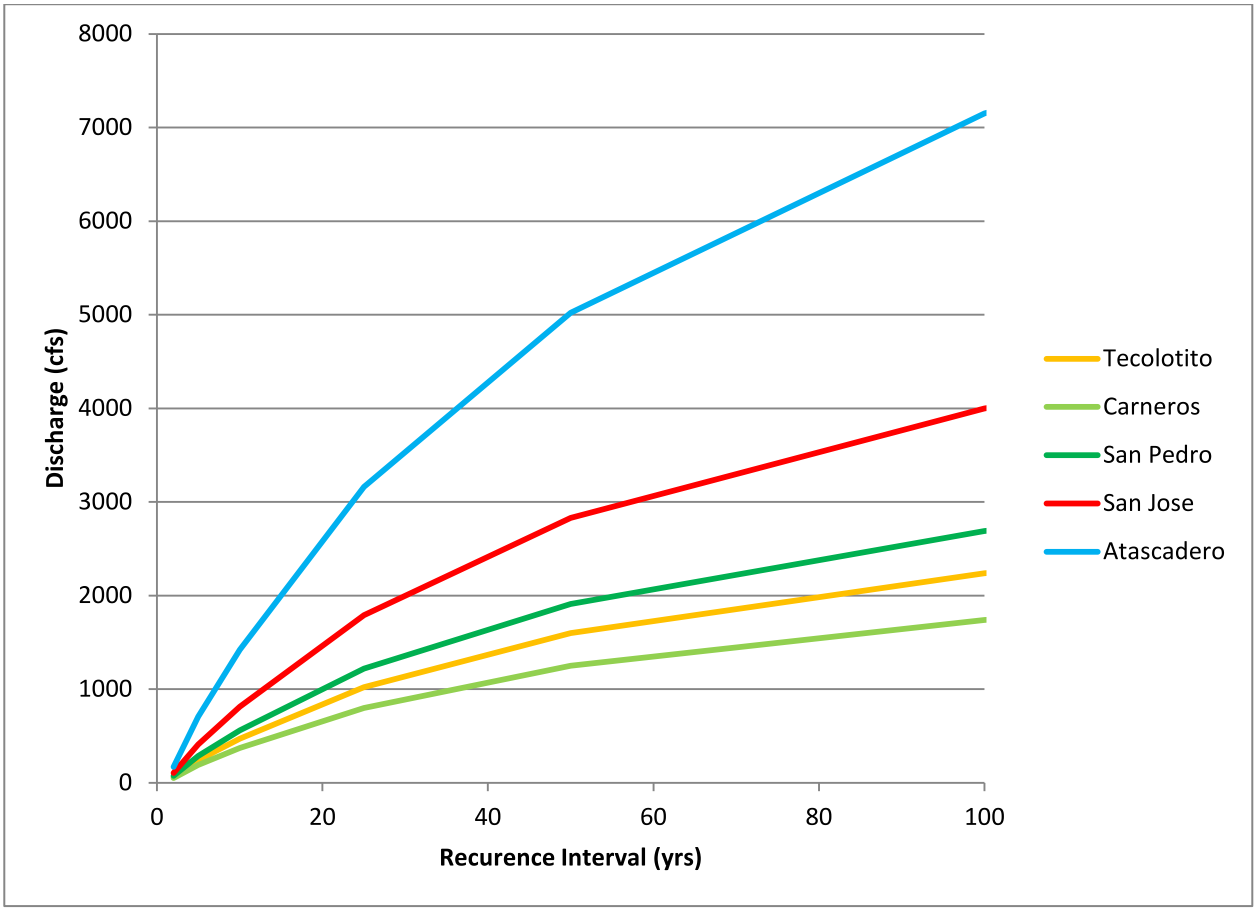

Fig 2 – Estimated recurrence interval of flows for creeks in Goleta Slough watershed

This analysis includes a considerable amount of inherent uncertainty. The uncertainty related to the use of regional regression equations to estimate peak discharges on ungaged streams is discussed in great detail in Gotyald et al.

This analysis assumes that the recurrence interval associated with the discharge on two neighboring streams will be similar for the same storm event. We have not been able to rigorously test this assumption for the Goleta watersheds due to the lack of data on the ungagged streams, and we acknowledge that this assumption is less likely to hold for basins where there is a larger difference in watershed area, land use, climate and topography is for between the various creeks.

RATIONAL METHOD

The total average annual streamflow for each creek for the period of interest was also estimated using a Rational Method calculation. The Rational Method is a method for estimating the volume of stormwater runoff as the product of the watershed area, precipitation rate, and a runoff coefficient. The runoff coefficient describes the fraction of rain falling on the watershed that leaves the watershed as streamflow. Runoff coefficients were estimated for each of the 5 major watershed using land use data available on StreamStats (USGS, 2012), typical runoff coefficients for 4 different land use categories (Lindeberg, 2012), and calibrated using precipitation measured at the Goleta Fire Station and stream flows measured at the Atascadero gage.

RESULTS

The results of these two sets of streamflow estimates are summarized in Table 1:

	Watershed Area	**Peak Flow Scaling Method**		**Rational Method**	
		Avg. Annual Streamflow 2006-2013	% of Total Annual Streamflow	Avg. Annual Streamflow 2006-2013	% of Total Annual Streamflow
	Square Miles	Ac-Ft	%	Ac-Ft	%
Atascadero	19	2950*	35	2950*	46
San Jose	8	1800	22	1200	18
San Pedro	7	1450	17	1050	16
Los Carneros	4	975	12	550	8
Tecolotito	5	1200	15	750	11
Total	44	8375	-	6500	-

Table 1 – Estimated Watershed Discharge for Creeks flowing to Goleta Slough
*Discharge measured at USGS Gage

The Peak Flow Scaling Method predicts higher stream flows from the 4 smaller creeks compared to the Rational Method. This is a result of the regional regression equations placing less weight on watershed area for small storm events, and the lack of major storm events during the study period. The largest stream flow observed during the period of interest was in Marsh, 2011, when flows reaching 3600cfs were observed on Atascadero Creek. This was a 10-20% chance annual exceedance event. While there remains uncertainty with respect to the accuracy of the Peak Flow Scaling Method, and the validity of several of the assumptions inherent in the use of this method, we have found that the synthetic flow time series produced by this method provides a satisfactory input dataset for the Goleta Slough QCM based on the satisfactory performance of the QCM during the model validation scenario. Note that this estimate includes considerable uncertainty, however we believe that the error introduced by the use of the synthetic streamflow input time series is less than or on the order of the error related to other flow rates used in the QCM model, including wave overtopping and seepage through the beach berm. Consequently we believe that the stream flow rates developed using the peak flow scaling method provide an adequate input dataset for the QCM modeling, given the limitations of the available input data.

RAINFALL VS LAGOON WATER LEVELS

As an additional investigation, the rational method calculation was also used to estimate the rate at which water levels within the lagoon rise during rain events. The USGS StreamStats utility was used to estimate the land use distributions of each watershed flowing into Goleta Slough. Each land use category (Forrest, Open Water, Impervious and Developed) was assigned a typical runoff coefficient, listed in table 2:

Land Use Category	Runoff Coefficient	Area in GS Watershed	Fraction of GS Watershed
Forrest	0.14 in/in	6380 acres	21%
Open Water	1	60	0.2%
Impervious	0.97	3280	10.8%
Developed	0.4	20670	68%
Area Weighted Average	0.41	-	-
Calibrated Average	0.132	-	-

Table 2 – Land Use in Goleta Slough Watershed

These values were used to calculate an area-weighted Average runoff coefficient, representing the expected runoff coefficient of the whole watershed. Finally, a calibrated average runoff coefficient was calculated based on the comparison on the area-weighted average runoff coefficient for the Atascadero watershed (0.40) with the observed runoff coefficient calculated from the measured rainfall with the discharge at the Atascadero Creek gage (0.132). This analysis of the Atascadero watershed suggests that the typical runoff coefficient values over-estimate the discharge entering Goleta Slough by a factor of 3.

The resulting calibrated average runoff coefficient describes the estimated fraction of rain falling on the watershed that flows into Goleta Slough during a major storm event (with the calibration factor assumed to account for flows diverted into storm sewers, retention basins, infiltration, etc.).

A first order approximation for the total runoff entering the Slough during a storm event can be found by using this effective runoff coefficient and the area of the Goleta Slough watershed (30400 acres). For example, if 1” of rain falls on the Goleta Slough watershed during a storm event, the runoff entering the Slough can be estimated as follows:

Runoff = Rainfall * Watershed Area * Runoff Coefficient
= 1/12ft * 30400 Acres * 0.132
= 334 acre*ft

One can then use the hypsometry of the lagoon to estimate the expected change in lagoon water surface elevation. Figure G-3 shows the hypsometry of Goleta Slough based on the 2010 NOAA coastal LiDAR and channel cross section surveys conducted by CCBER in 2013 and 2014.

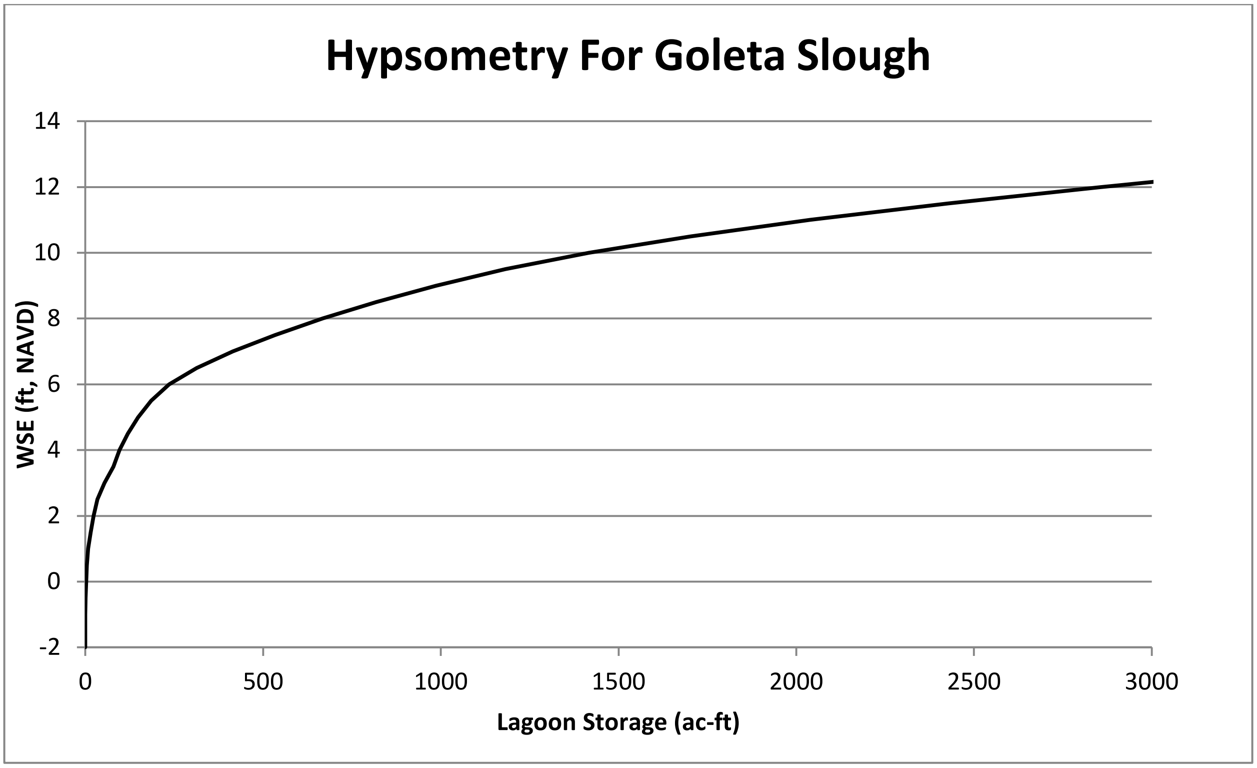

Fig 3 – Goleta Slough Hypsometry (from NOAA, 2012; CCBER 2015)

If we know the initial water level in Goleta Slough, say it is at elevation 6.0’ NAVD, we then estimate the expected change in water level from the storm event.

Initial water level:	6.0
Initial Lagoon Storage (from Fig 3):	236 ac-ft
Final Lagoon Storage:	236+334= 560 ac-ft
Final Lagoon water level(from Fig 3):	~7.5 ft

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