ATTACHMENT 3

Sea Level Rise Analysis (ESA, 2016)

SSLOCSD WASTEWATER TREATMENT FACILITY REDUNDANCY PROJECT

Sea Level Rise Analysis

Prepared for
South San Luis Obispo County Sanitation District (under contract to Kennedy/Jenks Consultants)

August 3, 2016

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1 INTRODUCTION

The South San Luis Obispo County Sanitation District (SSLOCSD; District) is undertaking a project to improve the redundancy of the wastewater treatment facility (WWTF) in Oceano, California (Figure 1). The project proposes additional development at the District's existing facility site, located adjacent to the Meadow Creek Lagoon and Arroyo Grande Creek. The project will require the California Coastal Commission (CCC) to issue a Coastal Development Permit (CDP), which may include special conditions that the project would need to address to comply with the California Coastal Act of 1976. The CCC recently adopted the Sea Level Rise Policy Guidance document, which provides the best available science on sea level rise (SLR) for California and a recommended methodology for addressing SLR in CCC planning and regulatory actions (CCC 2015). In accordance with CCC (2015) and OPC (2013), ESA conducted a SLR vulnerability analysis to evaluate the existing and future exposure of the WWTF to flooding. This report presents a summary of findings and a description of the analyses conducted to evaluate existing and future flooding at the site with SLR.

Source: ESRI 2016

Figure 1
Project Location and Vicinity Map

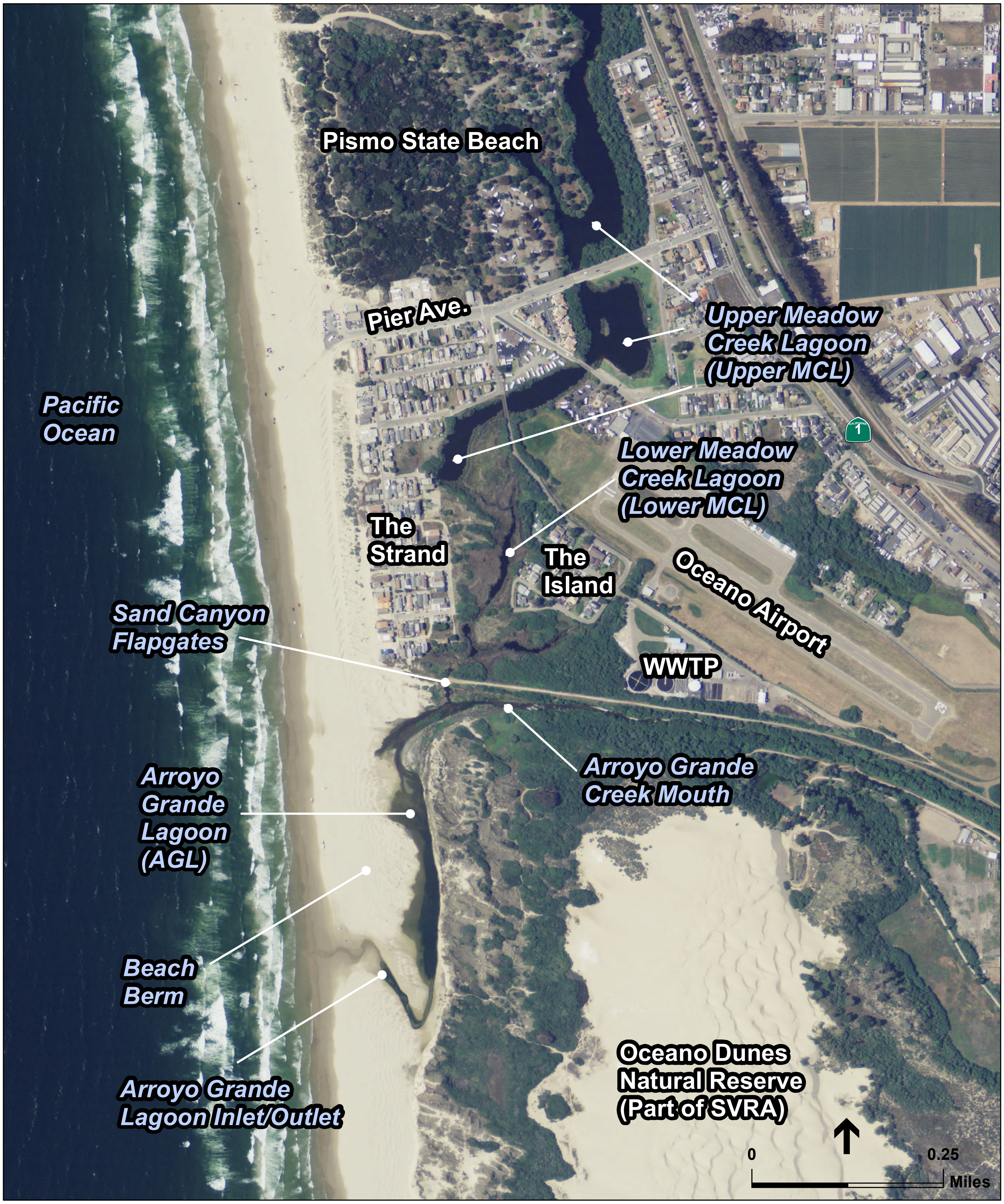
1.1 Background

The District's WWTF is situated approximately 2,000 feet from the Pacific Ocean shoreline in Oceano, California, at the confluence of Arroyo Grande and Meadow Creeks, which form a series of lagoons that are influenced by the elevation of the beach berm (Figure 2). These creeks convey the majority of runoff for the southern San Luis Obispo County region including portions of Pismo Beach, Oceano, Grover Beach and Arroyo Grande. A levee is located between the WWTF and Arroyo Grande Creek. The mouth of Arroyo Grande Creek forms a perched lagoon on the beach. The elevation of the beach berm controls the water surface elevation in Arroyo Grande Lagoon. Meadow Creek discharges to the Arroyo Grande Lagoon through a tide gate when the water levels in Arroyo Grande Lagoon lower below the water surface elevation of Meadow Creek Lagoon.

Historically, San Luis Obispo County (County) managed water levels in Meadow Creek Lagoon by inducing periodic breaching of the sand bar at the Arroyo Grande Lagoon, allowing water to drain out of the Meadow Creek Lagoon before reaching the residential flood thresholds of approximately 10.4 feet NAVD[1] (ESA PWA 2013). However, resource agencies now regulate breaching practices due to adverse impacts on habitats for Central Coast steelhead, requiring a permit to be issued for artificial breaches. The County recently implemented a mechanical breach of the Arroyo Grande Lagoon on January 29, 2016 as an emergency action to lower Arroyo Grande Lagoon water levels by six inches to create additional storm water capacity in the Meadow Creek Lagoon. This effort involved several resource agencies, including the California Coastal Commission, California Department of Fish and Wildlife, Central Coast Regional Water Quality Control Board, National Oceanic and Atmospheric Administration (NOAA) Fisheries, U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, California State Parks.

For extreme fluvial flood events on Arroyo Grande Creek, the County has developed an Emergency Response Plan (ERP) that describes preparedness measures and emergency procedures concerning the operation of the Arroyo Grande Creek levees by the County Public Works Department (SLO County 2016). The ERP defines flood triggers defined by specific creek stage measurements relative to the levee crest, as well as actions that the County will take, including manual breach of the levee about two miles upstream of the WWTF. The intention of the mechanical levee breach is to lower flood stage of the creek by allowing water to flow into agricultural fields south of Arroyo Grande Creek, relieving downstream flooding. Although these actions may provide flood relief to the WWTF site during a 100-year flow event on Arroyo Grande Creek, this study does not address the possible changes to flood stage associated with the emergency breach of the Arroyo Grande Creek levee.

[1] NAVD refers to the North American Vertical Datum of 1988, a fixed reference for elevations determined by geodetic leveling. The datum was derived from a general adjustment of the first-order terrestrial leveling nets of the United States, Canada, and Mexico.



SOURCE:Aerial-NAIP 2012

SSLOCSD WWTF Redundancy Project Sea Level Rise Analysis. D150915.00

Figure 2
Site Map

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The WWTF may be subject to flooding by three mechanisms:

- Existing and future coastal flooding and erosion impacts associated with wave overtopping of the levee and into the Meadow Creek Lagoon
- Fluvial flooding on Arroyo Grande Creek, associated with extreme rainfall-runoff events, which overtops the levee
- Estuarine flooding caused by elevated water levels in Meadow Creek Lagoon, and associated with moderate fluvial flows in combination with a closed and elevated Arroyo Grande Lagoon.

Current FEMA maps have indicated the Base Flood Elevations (BFE) at the site to be approximately 2.5 feet above the existing ground elevations. Cannon recently completed a survey of the site in 2016, including measurements of the elevations of the WWTF assets. The elevations of the assets were compared to the 100-year flood elevation, which was used to compute the required flood proofing elevation and height including freeboard. Site grades range from approximately 11 feet NAVD to over 14 feet NAVD, with much of the WWTF site between 12 and 13 feet NAVD.

1.2 Purpose

The purpose of this study is to assess the existing and future flood exposure of the WWTF, including estimates of the flood elevations and frequencies, which will be used to inform the environmental review, permitting, and design of the redundancy project. Descriptions of flood proofing concepts and adaptation alternatives are not addressed in this report, but are expected to be developed using information presented in this study. This SLR analysis complies with guidance issued by the state for addressing impacts of SLR (CCC 2015; OPC 2013).

1.3 Report Organization

This report is organized as follows:

- ***Section 2*: Summary of Findings** – the major findings and results of the analysis are presented
- ***Section 3*: Data Gathering and Description of Historical Flood Events** – summary of the data gathered to inform the technical analyses, and a description of known historical flood events that have occurred at and near the site
- ***Section 4*: Climate Change Background and Planning Horizons** – description of climate change projections and planning horizons used in this study
- ***Section 5*: Flood Exposure Analyses** – methods and results of technical studies conducted to evaluate coastal, fluvial, and estuarine flood exposure for existing and future conditions

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2 SUMMARY OF FINDINGS

The following summary of findings presents the primary conclusions of the various sections of this report. The summary of findings is organized to first present general findings, and then findings for each of the three flood sources analyzed: Coastal, Fluvial, and Estuarine.

2.1 General Findings

- Three flood sources were analyzed to evaluate their respective changes resulting from future sea level rise:
  - Coastal flood source: coastal flooding and erosion impacts associated with wave overtopping of the levee and into the Meadow Creek Lagoon
  - Fluvial flooding on Arroyo Grande Creek, associated with extreme rainfall-runoff events, which overtops the levee
  - Estuarine flooding caused by elevated water levels in Meadow Creek Lagoon, and associated with moderate fluvial flows in combination with a closed and elevated Arroyo Grande Lagoon
- Flood thresholds for the WWTF site were selected to evaluate the relative changes in flood exposure over time due to sea level rise, and were based on survey elevations. However, these thresholds do not necessarily imply damage would occur at these elevations. Critical facilities are protected with flood barriers and gates to approximately 14.4 feet NAVD according to District staff. The following thresholds are defined for the analysis:
  - County threshold for residences and WWTF access: 10.4 feet NAVD
  - December 2010 Event Benchmark: 12 feet NAVD
  - Existing Flood Protection: 14.4 feet NAVD
- The County of San Luis Obispo has a number of operational conditions, controls and plans in the Arroyo Grande Creek watershed that may be implemented depending upon the type, size and duration of a future flood event on Arroyo Grande Creek.
- Flood protection installed at the site since 2010, and additional flood protection resulting from the future design of the Redundancy Project, may be able to mitigate future flooding events and impacts.

2.2 Coastal Flood Source

- The coastal flood source, caused by wave overtopping and coastal erosion during extreme conditions, was determined not to be a dominant mechanism of flooding of Meadow Creek Lagoon for existing and future conditions with sea level rise.
- Assuming that the levee is maintained and raised over the century, the 100-year TWL is not expected to overtop the levee into Meadow Creek Lagoon.
- Coastal flood and erosion impacts to the WWTF are unlikely, unless the north levee at the mouth of Arroyo Grande Creek is not maintained or raised in the future. The existing elevation of the levee crest is sufficient to limit overtopping during extreme events. However, conservatively high estimates of coastal erosion indicate that the shore may migrate landward toward the levee, which would likely result in human response and

adaptation strategies that could affect the future wave runup heights. Therefore, some wave overtopping into Meadow Creek Lagoon could occur in the future depending on the future management strategies, but is not expected to have a significant impact on water levels.

- The geomorphic response of the shore to sea level rise is expected to cause the shore to transgress landward and upward, with the vertical change in elevation of the beach berm and the Arroyo Grande Lagoon to be equal to the amount of sea level rise.

2.3 Future Changes to Extreme Fluvial Flood Flows on Arroyo Grande Creek

- The existing 100-year fluvial flow on Arroyo Grande Creek will become more frequent under all emissions scenarios, increasing in frequency to a 76-year event in 2050 and to a 39-year event in 2100. Recurrence intervals describe the probability that an event will be exceeded in any given year. For example, the 100-year recurrence is equivalent to the 1% annual exceedance probability each year. However, over a 30-year period, the probability that the 100-year event will occur increases to 26%. A 76-year event has a 1.3% chance of occurrence in each year, and increases to 33% chance of occurring over a 30-year period.
- Climate change is expected to increase the extreme flows in Arroyo Grande Creek, and today's 100-year flow is expected to be 1.3 to 1.5 times more likely to occur by 2050, and 2.0 to 2.6 times more likely to occur by 2100. However, flooding at the WWTF associated with the extreme fluvial flows (like the 100-year storm event) is not expected to be affected by sea level rise.

2.4 Estuarine Flood Source

- The primary flood mechanism that will increase due to climate change is direct inundation from Meadow Creek Lagoon. This is called the "estuarine flood source" because it is not caused solely by ocean (coastal flood source) or rainfall runoff (fluvial flood source) conditions. The estuarine flood is manifested when high water levels in Arroyo Grande Lagoon block drainage through the tide gate and back up water levels in Meadow Creek Lagoon. The high Meadow Creek Lagoon water levels can flood the access road (and adjacent residential areas) at approximately 10.4 feet NAVD and parts of the WWTF site at approximately 12 feet NAVD. This type of flood event occurred in December 2010. The WWTF will be exposed to more frequent flooding in the future with sea level rise.
- The limited record of 7 years of data is not sufficient to conduct an extreme value analysis to estimate return periods of extreme events, and therefore we rely on describing the relative frequency of events using percent exceedance and by assigning categories. In the context of this study, we use the term frequency as a semi-quantitative approach that defines how often a given water level would occur over time in a general sense. To facilitate understanding of the percent exceedance, we define the following event frequencies:
  - **Rare (extreme) water levels:** less than 1% exceedance, expected to have a 10-year return period or greater and occur during a relatively large storm

- **Nuisance water levels:** between 1% and 10% exceedance, expected to have approximately a 1-year return period
- **Typical water levels:** greater than 10% exceedance, expected to be representative of typical conditions and daily water levels

- Our analysis indicates that extreme flood levels increase less than the amount of sea level rise. This is likely because of the flat land elevations at the higher flood levels (hypsometry) surrounding the Meadow Creek Lagoon basin: the area of flooding increases dramatically above elevation 13 feet NAVD and "spreads out laterally" rather than rising as much as projected sea level.

- Typical water levels that occur regularly will increase approximately equal to the amount of sea level rise.

- Depth of flooding for a given recurrence interval will not change much in the future with climate change, but the extents of flooding will likely increase. In other words, the depth of 100-year flooding at the plant will not be measurably by sea level rise according to this analysis.

- The frequency of flooding of the site will increase with climate change and sea level rise, and specifically, the flood threshold will be crossed more frequently
  - Typical water levels will exceed the access thresholds of approximately 10.4 feet NAVD on a regular basis by mid-century.
  - Water levels will exceed the WWTF threshold of 12 feet NAVD rarely by 2050 (limited to storm events), and will exceed the threshold on a regular basis by the end of the century (typical water levels).

- Maximum simulated flood elevations for existing and future conditions are as follows:
  - Existing: 12.3 feet NAVD
  - 2050: 12.7 to 13.2 feet NAVD
  - 2100: 13.9 to 15.6 feet NAVD

- Existing flood protection installed since the December 2010 event will protect the WWTF against the estuarine flood source through about 2070 with the high sea level rise curve.

- Flood thresholds for the plant of 12 feet NAVD will continue to be exceeded somewhat rarely by 2050, but by the end of the century will be exceeded on a regular basis. Flooding will exceed the access threshold of approximately 10.4 feet NAVD on a regular basis by mid-century.

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3 DATA GATHERING AND DESCRIPTION OF HISTORICAL FLOOD EVENTS

3.1 Historical Flood Events

Historical flood events at the WWTF were researched for the study. While the nearby residences have been exposed to several historic floods, the WWTF is located at a site about two feet higher than much of the residential areas subject to flooding. Therefore, the analysis is based on one documented flood event. Prior to 2010, the primary practice of water level management in Meadow Creek Lagoon was to breach the sandbar manually at the Arroyo Grande Lagoon, which would allow the Arroyo Grande Lagoon water level to decrease and accommodate drainage from Meadow Creek Lagoon through the Sand Canyon Tide Gate structure. The following sections describe the December 2010 event and flood elevations, and the selected flood thresholds for the study.

3.1.1 December 2010 Event

Limited information on historical flooding of the WWTF is available, except for documentation of a flood that occurred December 19-20, 2010. The peak water level was reported by the County and the District to be approximately 12 feet NAVD. Floodwaters damaged several low-lying residences and access to the WWTF, which typically flood at elevation 10.4 feet NAVD (ESA PWA 2013). Key plant personnel that responded to the event, and were present at the WWTF, have testified that at its extreme, no more than one foot of standing water at the Emergency Generator Building drainage culvert was observed.[2] In no case was the entire plant ever underwater, nor did it have the same standing water conditions observed in the residential community directly outside the plant, and the vast majority of the plant continued to be accessible and undamaged/unaffected by this event.[3] During the December 2010 event, flooding damaged the electrical system that powered the pumps, which resulted in a spill and operational failures.[4] This is one reason the District is pursuing the Redundancy Project to reduce the risk to critical assets at the WWTF. District staff has indicated that the electrical and institutional failures that occurred at the plant were addressed after the 2010 flooding event so that a future flooding event does not cause a failure from similar causes.

3.1.2 Flood Threshold

ESA selected two flood thresholds to consider in the analysis: a flood threshold of 10.4 feet NAVD limited to access impacts, and a flood threshold of 12 feet NAVD related to prior experience at the plant. The elevation 12 feet NAVD threshold is selected as a benchmark that relates to prior experience at the plant. Although damages occurred at the WWTF, the damages

[2] Personal Communication, John Clemmons, SSLOCSD Plant Superintendent / CPO, July 26, 2016.
[3] Personal Communication, John Clemmons, SSLOCSD Plant Superintendent / CPO, July 26, 2016.
[4] Personal Communication, John Clemmons, SSLOCSD Plant Superintendent / CPO, June 30, 2016.

were attributed to other independent factors, and the District has asserted that these factors have been rectified if the event were to happen again. However, this elevation threshold is useful to use this as a benchmark even if it is not a damage threshold to the WWTF. The elevation 12 feet NAVD is a significant threshold to the County because the residents were flooded, and therefore it is useful to use as a benchmark. Higher threshold elevations may be warranted, but once the flood elevations reach 15 feet NAVD, the entire wastewater collection system is overwhelmed, according to District Staff. Since the occurrence of the December 2010 event, critical facilities have been protected with flood barriers and gates to approximately 14.4 feet NAVD.[5]

The 100-year base flood elevation (BFE) mapped in the FEMA FIRM for the site ranges from 14 to 15 feet NAVD (downstream to upstream). This BFE is calculated by FEMA and is based on the extreme 100-year flow in Arroyo Grande Creek. This regulatory flood elevation is used for regulating flood insurance, and is dependent on several assumptions. For example, it appears that the levee between Meadow Creek Lagoon and Arroyo Grande Creek is not certified, and therefore it is standard practice by FEMA not to consider that existing and protective feature. Overtopping of the levee by extreme fluvial flow may also contribute to defining the BFE at the WWTF. However, based on the analysis in Section 5.2 on changes to the extreme fluvial event with climate change, we found that this event is not likely to be affected by SLR. Therefore, the analysis is focused on the estuarine flood source described in Section 5.3, which was shown to be affected by SLR.

This approach is used to consider the maximum flooding of the site, assuming that no actions are taken in the future to protect the site or modify the drainage and flood protection systems. It should be noted that this is a very conservative approach since flood protection measures have already been installed at the plant since the December 2010 flood event, and additional flood protection measures are being contemplated. This study and the thresholds described here are used to develop an understanding of the potential exposure of the WWTF site to future flooding associated with SLR, to identify likely future flood elevations and timing of SLR impacts, and to provide information for the design engineer (Kennedy/Jenks) to develop additional flood mitigation measures for new and existing critical facilities.

3.2 Data Gathering

A variety of datasets were compiled and processed by ESA to analyze the Arroyo Grande-Meadow Creek System using the following models:

- A Hydraulic Engineering Center River Analysis System (HEC-RAS) model of the fluvial estuarine system
- A quantified conceptual model (QCM) for Arroyo Grande Lagoon
- Water balance model of the Meadow Creek Lagoon

These models utilize data collected by San Luis Obispo County and other government agencies, including the U.S. Geological Survey (USGS), National Oceanic and Atmospheric

[5] Personal Communication, John Clemmons, SSLOCSD Plant Superintendent / CPO, July 26, 2016.

Administration (NOAA) and the State of California. The following sections briefly describe the data that was accessed and used in this study.

3.2.1 SLO County Water Level Data

SLO County Water Resources maintains a network of gages that monitor rainfall and water levels throughout the Arroyo Grande-Meadow Creek system. Table 1 lists the gages used in this project's analyses and Figure 3 shows the locations of the installed gages. The water level data for the listed gages are also plotted in Figure 3.

TABLE 1
SLO COUNTY WATER RESOURCES WATER LEVEL GAGES

Gage ID	Location	Established	Data
4615	Meadow Creek Lagoon at Pier Avenue	March 2011	Water Level
769	Arroyo Grande Lagoon on downstream side of flap gates	January 2009	Water Level
770	Meadow Creek Lagoon on upstream side of flap gates	February 2011	Water Level
734	Arroyo Grande Creek at 22nd Street	January 2008	Water Level
736	Arroyo Grande Creek at Highway 101	December 2011	Water Level

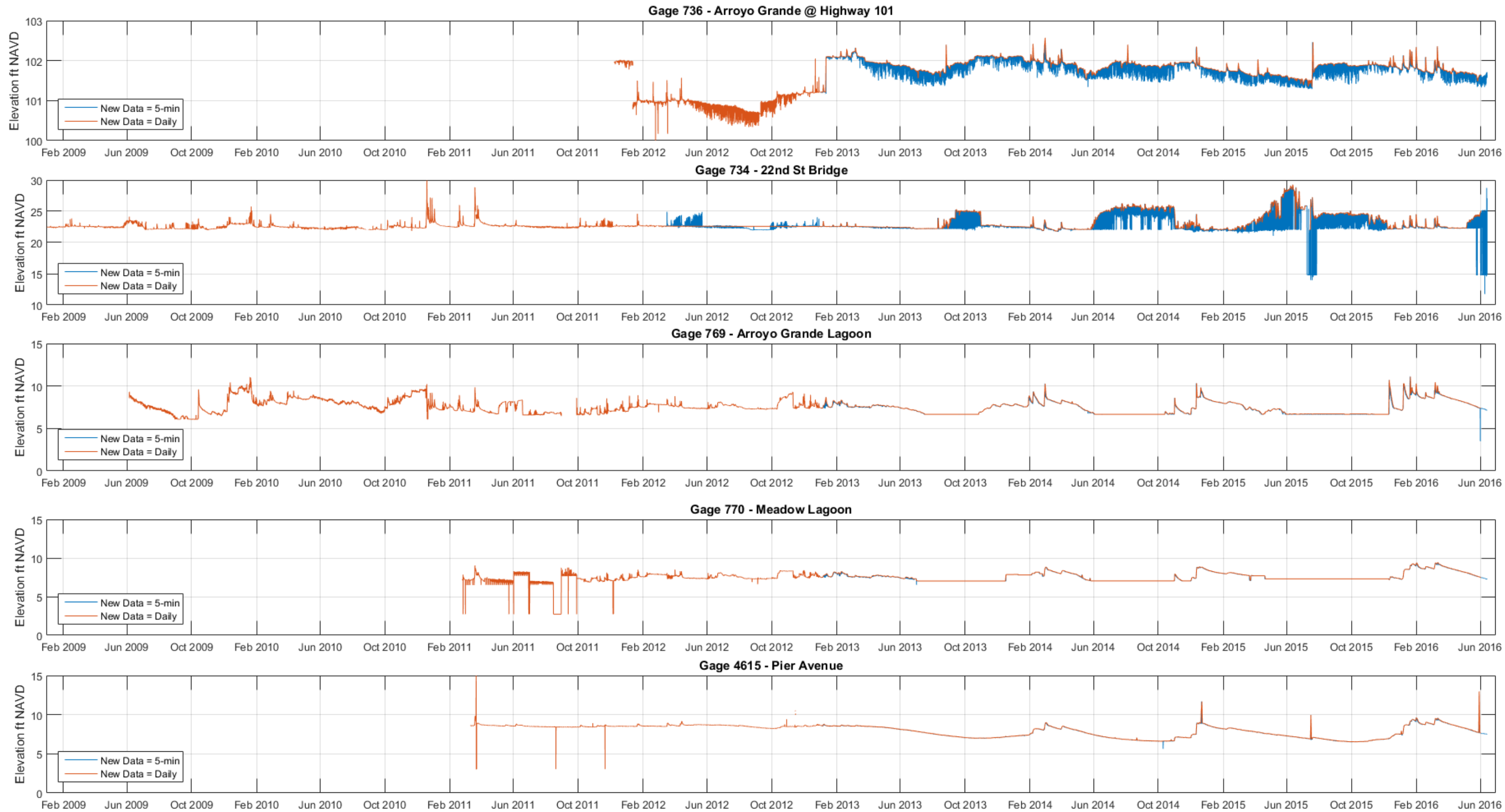
The County transmitted water level data collected between April 2011 and June 2016 to ESA. As part of a sand bar management study that ESA conducted for the County in 2013, the County also provided rating curves for Arroyo Grande Creek at 22nd Street and Highway 101 to convert water surface elevations to streamflow (ESA PWA 2013).

Source: ESRI

Figure 3
Location of SLO County water level gages

Note that the gages at Arroyo Grande Creek at 22nd Street and Highway 101 are radar gages. This type of gage is prone to report incorrect values when water depths are very low or zero. This error can be seen in the water level record at 22nd Street in the summer and fall of 2013, 2015, and 2015. Figure 4 shows that water level measurements in dry periods fluctuate multiple times per day between approximately 22 feet NAVD and 26 feet NAVD (or greater). Such rapid water level fluctuations are highly unlikely, and observations at the 22nd Street gage indicate that the creek was dry during these times. Adjustments to this data set to account for the sensor issues are discussed in the Section 3.2.5 Data Processing. There also appears to be noise and sensor datum inconsistencies in Arroyo Grande at Highway 101, though the gage was not used directly in any modeling for this project.

In Figure 4, the Arroyo Grande Lagoon and Meadow Creek Lagoon water elevations appear flat during much of the summer and fall in 2013, 2014, and 2015. This pattern is indicative of the lagoon’s water surface lowering below the measurable gage elevation during periods of drought. This page intentionally left blank



Source: SLO County

Figure 4
SLO County gages
Water level time series

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3.2.2 Tides and Tidal Datums

Tides at the site are characterized by a mixed semi-diurnal tide signal, typical of the California coast, with two high tides and low tides occurring per day, each with unequal heights. The diurnal tide range, or the difference between mean higher high water (MHHW) and mean lower low water (MLLW), is approximately 5.3 feet. Table 2 presents the tidal datum used for the technical analyses described in this report. Tide data and tidal datums were based on the NOAA Tide Gage Station 9412110 at Port San Luis, located about eight miles from the project site, but assumed to be representative of the actual conditions at the site.

TABLE 2
TIDAL DATUMS AT PORT SAN LUIS GAGE – NOAA #9412110

Datum	Value (ft NAVD)	Description
HOWL	7.57	Highest Observed Water Level (1/18/73, 9 AM)
HAT	7.02	Highest Astronomical Tide
MHHW	5.25	Mean Higher-High Water
MHW	4.54	Mean High Water
MTL	2.75	Mean Tide Level
MSL	2.72	Mean Sea Level
MLW	0.96	Mean Low Water
NAVD88	0	North American Vertical Datum of 1988
MLLW	-0.08	Mean Lower-Low Water
LAT	-2.07	Lowest Astronomical Tide
LOWL	-2.48	Lowest Observed Water Level (1/7/51, 12 AM)

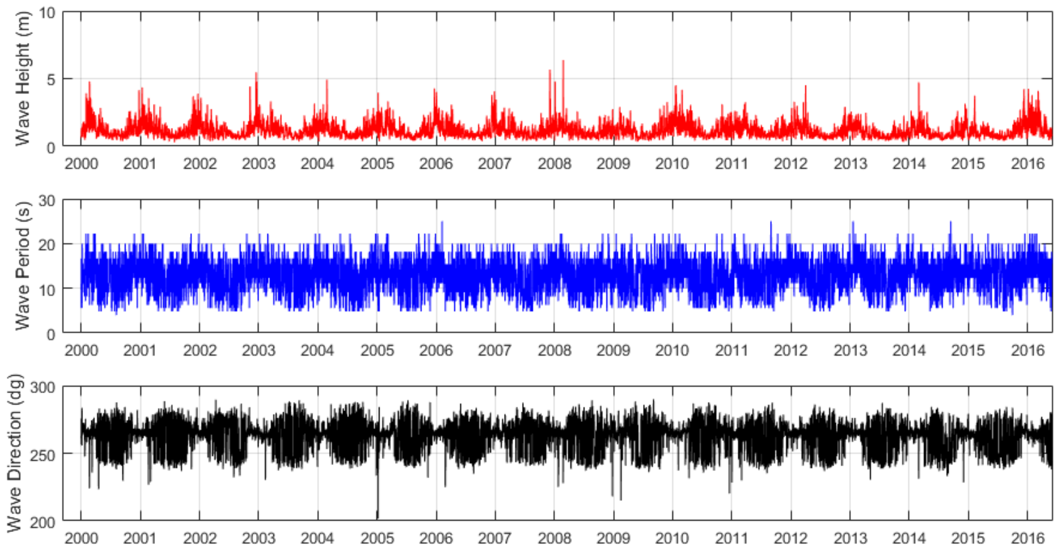
Tidal Datum Analysis Period: 01/01/1983-12/31/2001

3.2.3 Waves

Hourly wave height, period, and direction near the Arroyo Grande Lagoon mouth was obtained from nearshore transformed wave data provided by the Coastal Data Information Program (CDIP) California Coastal Wave Monitoring and Prediction System (O'Reilly et al. 2016) at the CDIP model output point number SL068. MOP SL068 is located in about 45 feet of water approximately one-half mile offshore. Figure 5 presents hourly wave data at MOP SL068, transformed from deep water measurements using transformation coefficients computed by CDIP.[6] Note the seasonal patterns, with large wave heights and long periods approaching the site with a narrow band from the west-northwest in the winter, and smaller waves with shorter periods approaching from a wide band ranging from west-southwest to northwest. The wave data is an important consideration in the analysis as it is a driver of the beach elevation that contributes to establishing the water levels in the Arroyo Grande Lagoon, and it influences the state of the lagoon (i.e. open, closed, perched overflow, etc.).

[6] Data were furnished by the Coastal Data Information Program (CDIP), Integrative Oceanography Division, operated by the Scripps Institution of Oceanography, under the sponsorship of the U.S. Army Corps of Engineers and the California Department of Parks and Recreation, http://cdip.ucsd.edu/

Recent nearshore wave data from CDIP and historic water levels at the Port San Luis tide gauge (NOAA station 9412110) were used as input to the coastal erosion model and flooding calculations. Since these same meteorological and climatic conditions affect water levels and waves, these conditions are correlated. In fact, the worst coastal hazards are associated with coincident occurrences of high waves and high storm surge and the effect on coastal hazard responses such as total water level are not necessarily linear (FEMA, 2005; Garrity et al, 2006).

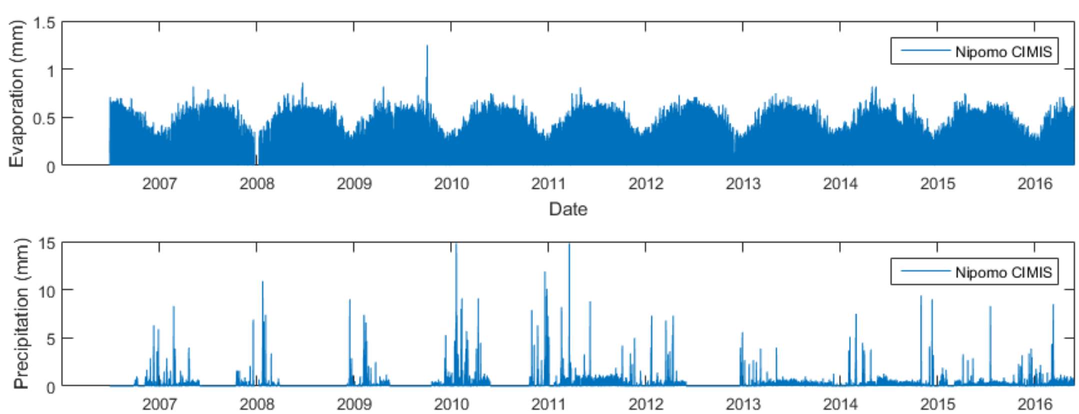


Source: CDIP, NOAA

Figure 5
Wave parameters at MOP SL068

3.2.4 Precipitation and Evaporation

Precipitation and evaporation data were downloaded for the Nipomo CIMIS station #202. The site is assumed to be representative of rainfall in the drainages upstream from the WWTF. Precipitation data was obtained as daily rainfall totals. Evaporation data was obtained as hourly measurements. Figure 5 presents time series of the precipitation and evaporation data.



Source: UC IPM, Accessed online: http://ipm.ucanr.edu/calludt.cgi/WXSTATIONDATA?STN=Nipomo.A

Figure 6
Evaporation and Precipitation data

3.2.5 Data Processing

In order to utilize the aforementioned datasets for the modeling, the data were adjusted slightly. All time series were converted into hourly intervals and abnormally high and low values were removed. Older water level data Arroyo Grande Creek at 22nd Street measured relative to the NGVD29 datum was converted to NAVD88 by adding 2.78 feet. Gaps in the tide data record were filled with the mean water level over the model period from 2009 to 2016.

The 22nd Street Gage was adjusted more substantially to account for sensor errors during periods of low to no flow. Based on the rating curve provided by the County, the bed elevation of the stream is at 21.6 feet NAVD. During periods when the Arroyo Grande Lagoon was very low or dry, the 22nd Street gage was set to 21.6 feet to indicate zero streamflow. During other periods in which water levels at 22nd Street appeared to be erroneous (rapid fluctuations of greater than about a foot), the data were adjusted to the stage approximately equal to the baseline stage before and after the period of suspect data.

3.2.6 Development of Existing Topography

A surface model of the existing topography and bathymetry of the project site was created by ESA in 2013 (ESA PWA 2013), and was used as the base for most of the Meadow Creek-Arroyo Grande Lagoon area. The surface model was based on topographic survey of the project site by ESA staff in December 2011 and spring 2012, bathymetry data of the Meadow Creek Lagoon collected by Cannon in 2011, and a recent survey of the WWTF site conducted by Cannon in 2016.[7] The coverage of the area was expanded to include additional beach and upstream areas using LiDAR data from 2011 (NOAA 2013). Minor corrections were made to beach elevations to account for prior lagoon mouth positions during surveying. The updated surface was then delineated into Meadow Creek Lagoon basin and Arroyo Grande Lagoon basin for the generation of stage-storage and stage-area curves that were used in the technical analysis and modeling.

[7] ESA performs land surveys and collects hydrographic data to augment traditional surveying services for the purposes of geomorphic interpretation, monitoring of project performance, and other specific uses consistent with Geologic and Landscape Surveys as defined in the Professional Land Surveyors' Act (California Business and Professionals Code). ESA does not provide traditional land survey services such as property boundaries and maps for general use by others. ESA recommends that these traditional surveying services be accomplished by a licensed, professional land surveyor either under direct contract with the client or as a sub-consultant to ESA.

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4 CLIMATE CHANGE BACKGROUND AND PLANNING HORIZONS

4.1 Climate change scenarios

The accumulation of greenhouse gases in the Earth's atmosphere is causing and will continue to cause global warming and resultant climate change. For the coastal setting, the primary exposure will be an increase in mean SLR due to thermal expansion of the ocean's waters and melting of ice sheets.

State planning guidance for coastal flood vulnerability assessments call for considering a range of scenarios (OPC 2013; CCC 2015). These scenarios bracket the likely ranges of future greenhouse gas emissions and ice sheet loss, two key determinants of climate whose future values cannot be precisely predicted. Scenario-based analysis promotes the understanding of impacts from a range of scenarios and identifies the amounts of climate change that would cause impacts.

The guidance recommends using scenarios that represent low, medium, and high rates of climate change. Recent studies of current greenhouse gas emissions and projections of future loss of ice sheet indicate that the low scenario probably underrepresents future SLR (Rahmstorf et al. 2012; Horton et al. 2014). Also, note that even if SLR does not increase as fast as projected for the high scenario, SLR will undoubtedly continue beyond 2100, such that the medium scenario is likely to yield the same amount of SLR. It just would occur a few decades after 2100 instead of at the turn of the century.

While the interim state recommended SLR scenarios have not yet been finalized, we are expecting the state to recommend dropping the "low" SLR scenario. This study thus focuses on the Medium and High SLR scenarios. The assumptions that form the basis for these scenarios are:

- ***High Scenario*** – The high scenario assumes population growth that peaks mid-century, high economic growth, and development of more efficient technologies. The associated energy demands would be met primarily with fossil-fuel intensive sources.

- ***Medium Scenario*** – The medium scenario assumes same population, economic, and technologic growth as the high scenario, but also assumes that energy would be derived from a balance of sources, thereby reducing greenhouse gas emissions.

4.2 Planning Horizons

The planning horizons analyzed for this project are 2050 and 2100, selected to inform the potential impacts to the WWTF project site for mid- and late-century conditions, and consistent with the CCC (2015) SLR Policy Guidance document. This set of planning horizons is recommended so that decisions about land use can be matched to the timeframe for project lifespans and to facilitate the identification of triggers for adaptation measures. Although the typical design life for infrastructure such as a WWTF may be shorter than the 2100 planning horizon, it is unlikely that the WWTF would be removed at the end of this project life. Therefore, planning horizons for a SLR analysis are typically longer than the periods associated with near-term decision-making.

4.3 Relative Mean Sea Level Rise Amounts

Two SLR scenarios were evaluated to estimate the change in coastal water levels under medium and high degrees of climate change. This conforms to state planning guidance for coastal flood vulnerability, which recommends analyzing a range of climate scenarios due to uncertainty about future climate predictions (OPC 2013; CCC 2015). For assessing the impacts of SLR on the project site, we used mean SLR projections through 2100 based on a recent study by the National Research Council (NRC 2012) for the West Coast, which was adopted by the State of California (OPC 2013; CCC 2015). Table 3 presents the NRC values for relative mean SLR at 2050 and 2100 for the Los Angeles Region relative to 2000. The relative mean SLR includes regional projections of both mean SLR and vertical land subsidence of 1.5 millimeters per year for the San Andreas region south of Cape Mendocino (see OPC 2013).

TABLE 3
RELATIVE MEAN SEA LEVEL RISE PROJECTIONS FOR THE LOS ANGELES REGION, FROM NRC (2012), TABLE 5.3

Year	Medium SLR	High SLR
2050	11 inches	24 inches
2100	37 inches	66 inches

4.4 Rainfall-Runoff and Climate Change

In addition to rising sea level conditions, future streamflow conditions may increase because of higher intensity rainfall events driven by climate change. To estimate the change in streamflow conditions, ESA used publically available downscaled climate model output developed for the fifth assessment report (AR5) by the International Panel on Climate Change (IPCC). The data was downloaded from the World Climate Research Programme’s Coupled Model Intercomparison Phase 5 (CMIP5) website[8] on 2/10/2015. These data include surface runoff and shallow groundwater flow (baseflow) on a 7.5 x 7.5 mile grid for the entire Western US. The datasets contain daily surface and baseflow values from 1950-2100. These datasets were developed through a multi-agency collaboration led by the United States Bureau of Reclamation (USBR, 2013). ESA used the hydrologic routing routine from the same model used in this study[9] to combine surface runoff and baseflow within the AGC and MC watershed and generate a time series of daily streamflow at the outlet of the two systems. The daily time series was used to estimate change in streamflow statistics within these watersheds.

[8] http://gdo-dcp.ucllnl.org/
[9] Model used is the Variable Infiltration Capacity (VIC) model from the University of Washington

As for the SLR analysis, two emissions scenarios (medium and high) were selected to provide a range of potential future climate conditions. The emissions scenarios developed for AR5 are referred to as Representative Concentration Pathways (RCP) and are described by the net change in energy per unit area of ground surface by the end of the century (in Watts/square-meter) relative to pre-industrial levels. The medium scenario, RCP 4.5, represents a future climate trajectory where emissions are curbed by mid-century and stabilized by the end of the century. The high scenario, RCP 8.5, represents a future climate trajectory with little to no control on global greenhouse gas emissions. It should be noted that observed global emissions to date have matched more closely with RCP 8.5. A low emissions scenario was not selected as the existing conditions simulation brackets the low end of emissions, which would not significantly change rainfall or sea level conditions. Datasets from several climate models are available for each emissions scenario, and vary considerably. To avoid bias toward a particular subset of models, all of the available climate models were used for this analysis. The total number of models for which data was available was 31 models for medium emissions and 29 models for high emissions.

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5 FLOOD EXPOSURE ANALYSES

This section describes the analyses and results of three separate flooding mechanisms: coastal, fluvial and estuarine. Each of these mechanisms considers existing and future conditions with climate change, including changes to precipitation and flows, and its impacts due to SLR.

The coastal analysis considers exposure of the WWTF to impacts of wave runup and coastal erosion, including the historic erosion rate, the accelerated geomorphic changes associated with SLR, and the potential erosion caused by a storm event. The analysis evaluates how the exposure changes with SLR.

Future fluvial flooding on Arroyo Grande Creek was assessed using hydrologic techniques with the downscaled global circulation model (GCM) data available from the State. This approach is based on linking an existing flood threshold with the local intensity-duration-frequency (IDF) precipitation curve, and then calculating the future recurrence intervals of the precipitation intensity based on GCM future projections. This future precipitation recurrence frequency is an indicator of how the frequency of the historic flood event increases with the changing climate.

The exposure of the WWTF to the estuarine flood source (Meadow Creek Lagoon, also impacted by Arroyo Grande Lagoon and River water levels) was assessed using a combination of hydrologic and hydraulic models for the lagoon and creek system. The estuarine flood source is important because of the complicated drainage system that is controlled by the beach berm elevations.

These three flood mechanisms are described in the sections below.

5.1 Coastal Flood Source

This section summarizes the analysis for considering the potential impacts to the WWTF caused by a coastal flood source. Specifically, the existing and future exposure of the WWTF to the following:

- Direct impact of wave runup and overtopping
- Increased water levels in Meadow Creek from wave overtopping
- Erosion impacts

The following sections summarize the analysis conducted to review these potential coastal-related impacts to the WWTF.

5.1.1 Total Water Level

Coastal flooding was assessed by performing a total water level (TWL) analysis of the observed tide and wave data. The total water level is defined as the maximum elevation of wave runup above a reference water level, and is calculated by adding the wave runup height to the elevation of the tidal still water level. Typically, one must include other components, including storm surge and wave setup, depending on the methods of analysis.

A time series of TWL was generated for the period of coincident wave and tide data. Wave runup was calculated using the Stockdon equation, based on the average beach slope along the shore and offshore significant wave height and peak spectral period (Stockdon et al. 2006). Beach slope is defined between mean high water and mean low water on the beach profile. Beach slope in the study reach is 0.018. Wave runup was added to the coincident ocean water to produce a time series of TWL. The Stockdon equation was developed using data from natural beaches without significant backshore barriers such as cliffs or seawalls. For these conditions, the TWL is typically higher than predicted by Stockdon. Therefore, to the extent that the existing dunes obstruct runup now or in the future, or coastal armoring is contracted, we can expect the wave runup to be higher.

The 100-year TWL for existing conditions was estimated to be 14.3 feet NAVD. Figure 7 presents several extreme value distributions fit to the annual maximum TWL data. For the Gumbel Least Squares fit, the most conservatively high of the distributions tested, the 100-year TWL at the Arroyo Grande Lagoon mouth was estimated to be 14.3 feet NAVD. This is similar to the base flood elevations (BFE) mapped in the Preliminary 2015 FEMA FIRM for the project area (FEMA 2015):

- 15 feet NAVD in the area to the north of the creek mouth in front of the residential housing (zone VE)
- 16 feet NAVD in the area to the south of the creek mouth in front of the beach lagoon and dunes (zone VE)
- 13 feet NAVD in the area at the creek mouth (zone AE)

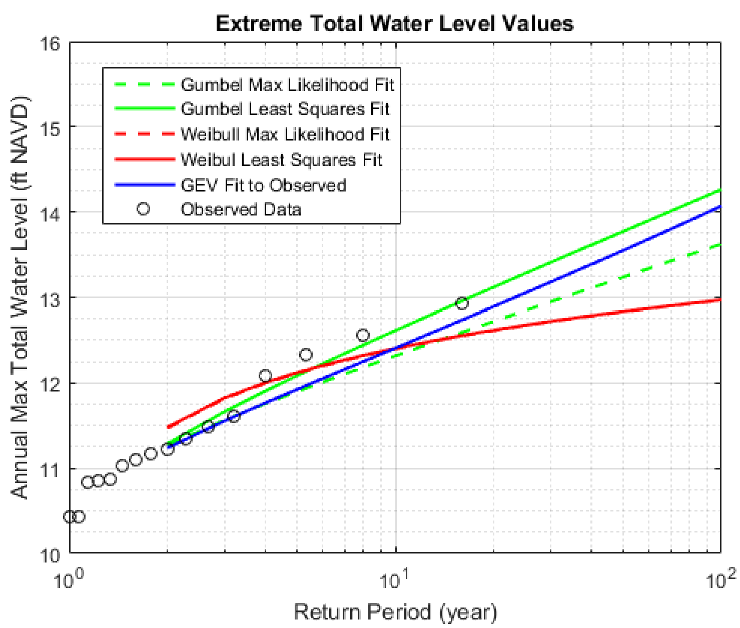


Figure 7
Extreme Value Analysis for Modeled Annual Max Total Water Levels for Existing Conditions

The reason that the area of beach directly in front of the creek mouth is mapped as zone AE is not clear, but is likely the BFE associated with the 100-year flow on Arroyo Grande Creek. However, The FEMA BFEs for the wave hazard zones are slightly higher than the ESA estimate of the 100-year TWL using the Stockdon equation. A more accurate elevation can be computed, and often a range of values and equations are considered owing to method uncertainty. Regardless, there are existing levees between Arroyo Grande and Meadow Creek, which has an approximate crest elevation ranging from 19 to 21feet NAVD near the beach. Therefore overtopping of the levee into Meadow Creek Lagoon is considered unlikely or very rare.

Assuming that the levee is maintained and raised over the century, the 100-year TWL is not expected to overtop the levee into Meadow Creek Lagoon. Table 4 summarizes the values of existing and future 100-year TWL. The higher levels are high enough to indicate potential for overtopping by year 2100 for the high scenario. The future TWL was estimated by adding the sea level rise amounts for each planning period and emissions scenario to the existing 100-year TWL. For this calculation, we assumed that the future wave climate and tidal conditions are consistent with the historic records and SLR governs future changes to coastal hazards.

TABLE 4
ESTIMATED EXISTING AND FUTURE 100-YEAR TOTAL WATER LEVEL (FEET NAVD)

Emissions Scenario	Existing	2050	2100
Medium	14.3	15.2	17.4
High	14.3	16.3	19.8

However, the future wave runup heights and resulting TWL will likely be influenced by the future adaptation strategies pursued in the area. For example, protecting the development and levee with a hard structure may increase the wave runup height by a factor of 3 to 4 and raise the TWL by approximately 4 to 5 times the amount of SLR. Allowing the natural shore to erode would not cause the wave runup height to increase, and the TWL would increase directly with the amount of SLR (Vandever et al. 2016). However, the following section will address the proximity of the levee to the future coastal erosion hazard zones, which may also have an effect on the TWL and potential for wave overtopping into the Meadow Creek Lagoon.

5.1.2 Coastal Erosion

ESA estimated hazard zones associated with coastal erosion due to the historic shoreline retreat rate, anticipated geomorphic changes due to SLR, and the potential impacts of a large storm. The coastal erosion hazard zones were estimated for 2050 and 2100 for both the medium and high SLR scenarios. The coastal erosion hazard zones prepared for this study are presented for long-term erosion and impacts of a 100-year storm. This separation was provided to delineate long-term SLR induced changes from storm-induced changes.

Historic Shoreline Erosion

The historic erosion rate of the shoreline fronting Arroyo Grande Lagoon was determined by updating the USGS National Assessment of Shoreline Change for Sandy Shorelines (Hapke et al. 2006). This California wide USGS assessment calculated short- (1970s to 1998) and long-term

(1870s to 1998) shoreline change rates for sandy shorelines along the California Coast and was downloaded from the USGS website (http://pubs.usgs.gov/of/2006/1251/). Shoreline change rates were computed from the USGS 2006 National Assessment of Shoreline Change updated with a 2010 MHW shoreline extracted from the 2009-2011 LiDAR dataset. Shoreline erosion rates were estimated using linear regression techniques at 50-meter increments along the shore. Between 1976 and 1998, the shoreline in the vicinity of Arroyo Grande Lagoon has accreted at an average rate of four feet per year (fpy). Therefore, as a conservative approach, the shore analyses described in this report assumed a background erosion rate of zero fpy.

Geomorphic Response of Shore to SLR (Long-Term Erosion)

Since the shoreline has accreted in recent years (1976-2010), long-term retreat of the shoreline is comprised solely of recession due to SLR. The shoreline retreat from SLR is calculated based on the methods described by Bruun (1954; 1962), where retreat is calculated as the increase in sea level divided by the overall profile slope measured between the backshore toe and the depth of closure, and estimated to be approximately 0.015 for this site. This approach yields a future shoreline that transgresses landward and upward. Sufficient availability of sediment is a key assumption for this method, which is likely valid based on the presence of the adjacent sand dunes and the accreting beach. Figure 8 presents a schematic of the existing and future shore profiles because of SLR. Note that the beach lagoon is assumed to rise with SLR.

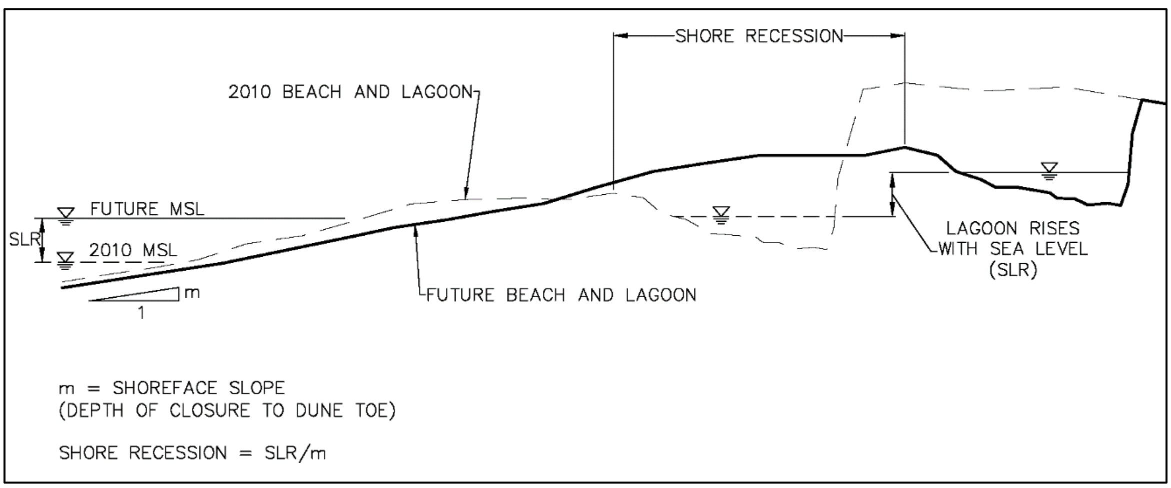


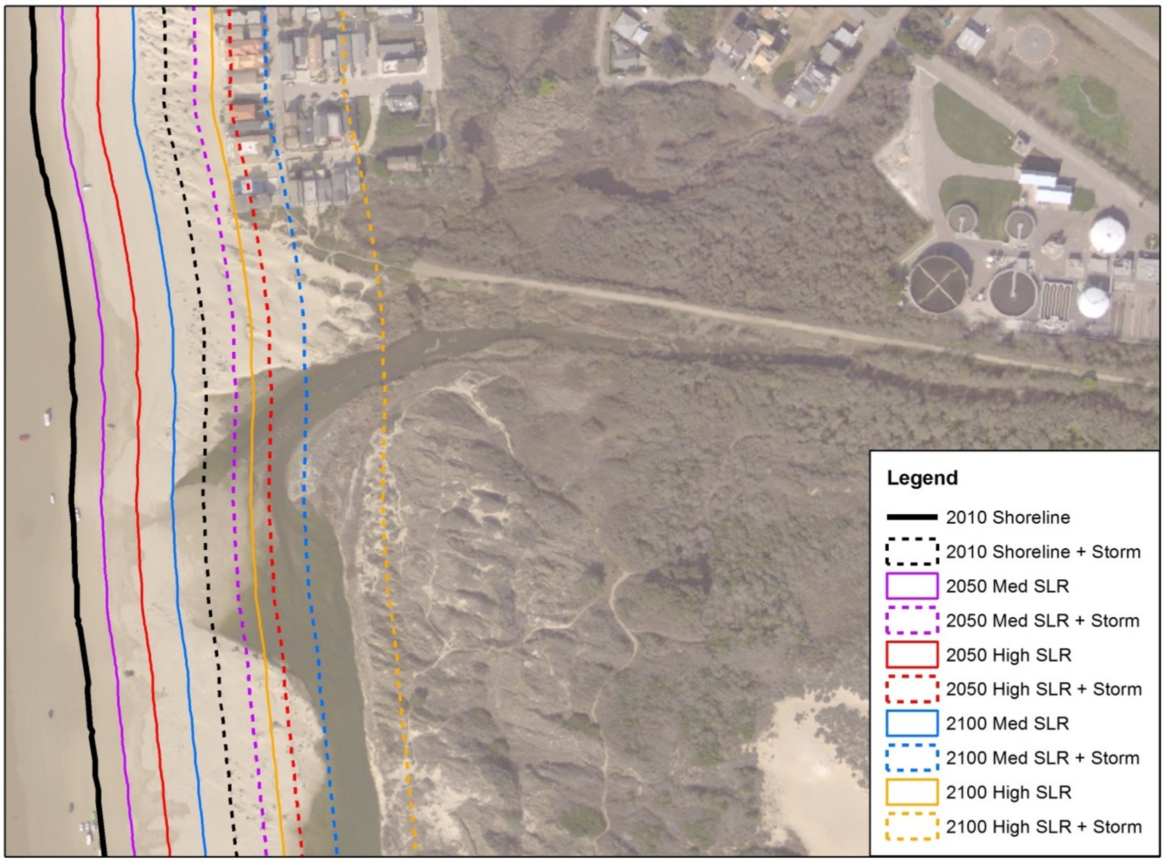
Figure 8
Schematic of Geomorphic Response of Shore to Sea Level Rise

Shore Response to 100-year Storm (Short-Term Erosion)

The potential inland shoreline retreat caused by the impact from a large storm event (100-year) was estimated using the geometric model of dune erosion originally proposed by Komar et al. (1999) and applied with different slopes to make the model more applicable to SLR (Revell et al. 2011). This method is consistent with the FEMA Pacific Coast Flood Guidelines (FEMA 2005), and uses the 100-year TWL. A 50% duration factor was applied to the geometric model for storm erosion to adjust for limited storm duration.

Coastal Erosion Hazards Map

Figure 9 shows the 2010 shoreline location and offsets for future shoreline locations considering long term changes in the shoreline as well as erosion from a large coastal storm. By inspection of the proximity of the future MHW contours to the existing levee, the risk of wave overtopping into the Meadow Creek area is likely to increase by mid- to late-century, but unlikely to impact the WWTF or to have a great effect on the water levels in Meadow Creek Lagoon. Therefore, the coastal hazard risk to the WWTF is not considered further in this study. However, SLR is expected to have a significant effect on the estuarine water levels in the Arroyo Grande Lagoon, and this is discussed in Section 5.3.



Source: ESA 2016, NOAA 2012.

Figure 9
Coastal Erosion Hazard Zones

5.2 Future Changes to Extreme Fluvial Flood Flows on Arroyo Grande Creek

The statistical analyses of the climate model data described in Section 4.4 indicated that flow rate magnitude is decreasing for the very small magnitude, more frequent events and increasing for events above a 2-year return period. Table 5 tabulates the percent change in flow magnitudes for a variety of event frequencies at 2050 and 2100 for medium and high emissions.

The values reported in Table 5 represent the median, or 50th percentile, of the climate models analyzed. Thus, half of the models show less of a change in flow magnitude while half of the models show a higher change in flow magnitude. The range of results underscores the uncertainty in the analysis. For this study, we used the 50th percentile of model output. A greater change in flow would be expected if the 90th percentile were used. This suggests that the relative change in extreme flows could be even higher than considered in this analysis, and may warrant further analysis to understand future flows in more detail, as well as evaluating the water surface elevations associated with these future flows.

TABLE 5
CHANGE IN FLOW MAGNITUDE FOR RANGE OF EVENTS (MEDIAN OF RANGE OF MODEL OUTPUT)

Return period (years)	% Change in flow			
	2050		2100	
	Medium emissions	High emissions	Medium emissions	High emissions
1	-47%	-32%	-11%	-59%
2	12%	17%	12%	10%
5	10%	25%	19%	22%
10	7%	21%	20%	27%
25	8%	16%	21%	28%
50	9%	16%	23%	36%
100	10%	14%	22%	43%
500	10%	21%	20%	39%

Another metric for evaluating the change in extreme streamflow events is the future frequency of an existing event. For example, how frequent will today's 100-year discharge event be at a future time horizon? The flood extents of the 100-year event have been mapped by FEMA thus this is a useful return period to focus on. The future return period for the 100-year event is summarized for the two emissions scenarios at 2050 and 2100 in Table 6. The existing FEMA 100-year floodplain is shown in Figure 10. Note that the BFE mapped at the WWTF is approximately 15 feet NAVD.

TABLE 6
CHANGE IN FREQUENCY FOR 100-YEAR FLOW (MEDIAN OF MODEL OUTPUTS)

Emissions scenario	Future return period for current 100-year flow (yrs)	
	2050	2100
Medium	76	50
High	65	39

The results indicate that the 100-year flow will become more frequent under all emissions scenarios, increasing in frequency to a 76-year event in 2050 and to a 39-year event in 2100. The return period is an estimate of the likelihood that an event will occur in any given year. For example, the 100-year recurrence is equivalent to the 1% annual exceedance probability each year. The return period can also be used to calculate the risk over time, such as for the design life of a facility or structure. For example, over a 30-year period, the probability that the 100-year event will occur increases to 26%. A 76-year event has a 1.3% chance of occurrence in each year, and increases to 33% chance of occurring over a 30-year period. These results indicate that by 2100 the current 100-year event, and the associate flood extent shown in Figure 10, will be 2.6 times more likely to occur than it is today under the highest emissions scenario. The majority of the climate models agree with this trend.

Figure 10
Existing conditions FEMA 100-year floodplain (in blue)

The percent and number of models that show a more frequent 100-year discharge are summarized in Table 7. The values in Table 7 indicate that more than half of the models show a consistent increase in the frequency of the current 100-year flood event with 70% of the models showing higher frequency at the end of the century under both medium and high emissions.

TABLE 7
PERCENT AND NUMBER OF CLIMATE MODELS SHOWING MORE FREQUENT 100-YEAR DISCHARGE

Emissions Scenarios	% of Models		Number of Models	
	2050	2100	2050	2100
Medium (RCP 4.5)	60%	70%	19	22
High (RCP 8.5)	70%	70%	20	20

In this analysis, because the elevations of the future extreme fluvial flows are not known, the effect that SLR applied to the downstream tailwater has not been explicitly considered. However, it is unlikely that SLR will have a significant effect on the hydraulic grade line through the project site, and therefore have little effect on extreme fluvial flood elevations. However, future analyses of the flood system in the vicinity of the WWTF should consider how the future extreme flows may relate to the flood elevations.

5.3 Estuarine Flood Source: Arroyo Grande and Meadow Creek Lagoon Water Levels

The WWTF is located in a low-lying area adjacent to the Meadow Creek Lagoon. Tailwater effects of the perched Arroyo Grande Lagoon have a backwater effect on the water levels in the Meadow Creek Lagoon, which tend to increase when the Arroyo Grande Lagoon mouth is closed and the water levels are high. Because the beach berm and mouth elevations control the Arroyo Grande Lagoon water level, and Arroyo Grande Lagoon affects the water levels in Meadow Creek Lagoon, the estuarine flood source is highly dependent on sea level. This section describes the technical approach used to estimate the impacts of SLR on the estuarine flood source in the Meadow Creek Lagoon.

ESA developed a hydrologic model of the Meadow Creek Lagoon to analyze the estuarine flood source at the WWTF site (Section 5.3.3). The hydrologic model of the Meadow Creek Lagoon comprises a water balance that computes the Meadow Creek Lagoon stage resulting from the inflow and outflow dynamics. ESA developed a quantified conceptual model (QCM) of the Arroyo Grande Lagoon to generate the downstream boundary conditions of the Meadow Creek Lagoon water balance (Section 5.3.1). A hydraulic model of the Meadow Creek Lagoon was used to estimate the inflow boundary conditions of the Meadow Creek Lagoon water balance (Section 5.3.2). This approach was used so that a synthetic time series of water levels in Meadow Creek Lagoon could be generated for existing and future cases with sea level rise and changes to fluvial inflows.

Although the hydraulics of the system are coupled, we made some simplifying assumptions to run the three interrelated models separately. The QCM of the Arroyo Grande Lagoon is used to simulate the existing and future lagoon water levels, as a function of creek inflows, waves, and sediment dynamics. The water levels in Arroyo Grande Lagoon are important because they control the timing and extent of drainage of Meadow Creek Lagoon through the tide gate structure, and act as the downstream tailwater of the Meadow Creek Lagoon. Flows through the Meadow Creek Lagoon are complicated due to the flat topography, dense marsh vegetation, limited detailed survey data through the lagoon, and limited information on lagoon inflows from Meadow Creek. Therefore, we used a hydraulic model to replicate specific events for which measured water levels exist, and calibrated the inflow parameters.

The following sections summarize the methods of the models, and present results of the estuarine flood analysis. The exposure of the WWTF to flooding is characterized using the synthetic time series of water levels in Meadow Creek Lagoon for existing and future cases with sea level rise. The exceedance of the flood threshold elevation and maximum water surface elevations are described.

5.3.1 Quantified Conceptual Model of Arroyo Grande Lagoon

The dynamics of the water levels in Arroyo Grande Lagoon play an important role in the behavior of the flood elevations in Meadow Creek Lagoon. The Arroyo Grande Lagoon water level acts as a tailwater to Meadow Creek Lagoon flows, which drains when Arroyo Grande Lagoon is low, or backs up when water levels in Arroyo Grande Lagoon are high. The balance between the outflows of the Arroyo Grande Creek and sediment dynamics associated with beach building and wave forcing primarily controls the Arroyo Grande Lagoon water levels. Intermittent breaching of the lagoon allows the lagoon to drain, affecting water levels through the lagoon system. This section summarizes the QCM used to establish synthetic time series of Arroyo Grande Lagoon water levels for existing and future cases with sea level rise and changes in precipitation, which were used as downstream boundary conditions in the Meadow Creek Lagoon water balance.

Methods and Input Data

A QCM was built for Arroyo Grande Lagoon to model the water levels within the lagoon. Background on ESA's general QCM approach and methodology is included in Appendix A, and is applicable to the Arroyo Grande Lagoon QCM. The model uses time series of nearshore waves and tides, streamflow, and evapotranspiration data as boundary conditions (Figure 11). Nearshore input wave data was obtained from CDIP SL068 model output point and tide input data was taken from the Port San Luis gage, as described in Section 3. Streamflow input data was the adjusted streamflow record from Arroyo Grande at 22nd Street, as described in the Data Processing Section 3. Note that rainfall was not utilized as a direct input into the model. Instead, streamflow from Arroyo Grande Creek was assumed to be representative of local watershed runoff. Evaporation input data consisted of the CIMIS Nipomo data.

Stage-storage and stage-area curves were developed for Arroyo Grande Lagoon using the project surface described in Section 3. Note that drainage from Meadow Creek Lagoon into Arroyo Grande Lagoon was considered negligible for the QCM, and flow through the tide gate was relatively minor as compared to other input and output flow terms, such as stream inflow or beach seepage. The drainage from Meadow Creek could be coupled with the Arroyo Grande QCM, although that would require additional time.

The model was run and calibrated from September 2009 to May 2016. Calibration was performed by adjusting model parameters as described in Appendix A and in Behrens et al. (2015) to simulate water levels and closure events in the measured lagoon water level record.

ESA also analyzed the future conditions of the Arroyo Grande Lagoon to consider changes in flow magnitudes and sea level rise. First, the Arroyo Grande Creek inflow time series was modified by scaling the existing events greater than 50 cfs by corresponding percent changes tabulated in Table 5. This required assignment of recurrence intervals to observed flow magnitudes. Four future time series of the Arroyo Grande Lagoon water levels were generated for medium and high emissions scenarios at 2050 and 2100, and the corresponding amount of SLR was added last. Distributions of other parameters in the QCM, such as waves and tide range, were assumed not to change in the future.

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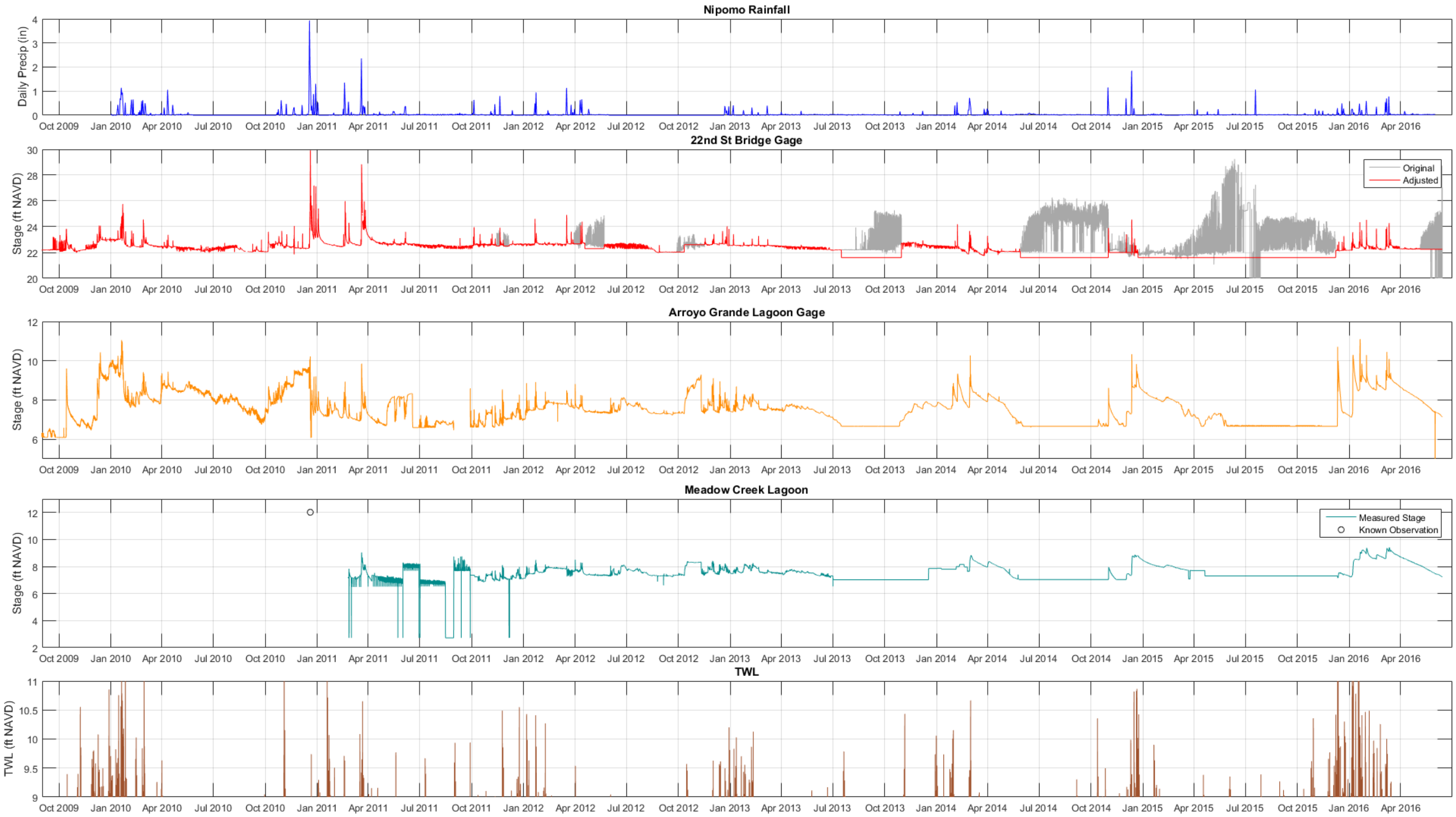

Source: ESA, UC IPM, NOAA, CDIP

Figure 11
Input and Calibration Parameters to Lagoon QCM: Precipitation, Creek Inflow Stage, Arroyo Grande Stage, Meadow Creek Stage, and Total Water Level

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Results & Discussion of QCM

Existing Conditions

Figure 12 is a 3-panel plot showing the measured and modeled lagoon stage (top), flow into the lagoon from wave overtopping and streamflow (middle), and wave power (bottom) for the duration of the existing conditions model run. In the top panel, the solid blue line is the measured Arroyo Grande Lagoon stage, the solid gold line is the modeled lagoon stage, and the dashed gold line is the thalweg elevation of the lagoon mouth, a channel that connects the lagoon to the ocean. The lagoon bed is lower in elevation than the thalweg of the mouth, and is located behind the mouth and the beach berm. Although the exact timing of the closure and beaching events are not always captured, the model reproduces a number of important aspects, including:

- The perched elevation of lagoon water levels above the tides
- Frequent perched overflow conditions, when the thalweg is
- The general seasonal pattern observed during the dry years of 2013-2015

Figure 12
Existing Conditions: Modeled Lagoon Stage (yellow) Compared to Measured Stage (top), Flows into the Lagoon (middle), and Wave Power Time Series (bottom)

Both the measured and modeled lagoon stages are perched above ocean water levels and the lagoon is non-tidal during the modeled period. The model is able to represent this elevated lagoon condition well. Generally, the water surface elevations of the model are predicted to be within one foot of the measured elevations, with a few periods different by about two feet.

As shown in Figure 12, the thalweg elevation of the mouth throughout the majority of the modeled period fluctuates closely around the modeled lagoon stage. The tracking of the thalweg and lagoon stage indicates that the lagoon frequently experiences perched overflow conditions, where the lagoon is full and water is spilling out of the lagoon onto the beach at flows typically less than 10 cfs. The small overflow velocities are unable to erode a large channel, which would lead to a drop in lagoon water levels (lagoon breach). The model is consistent with observations indicating that perched overflow is commonly observed at the site.

During the drought years of 2013 through 2015, a clear seasonal pattern of dry/low lagoon conditions in summer and fall are observed, followed by a filling of the lagoon throughout the winter and drainage into the summer. The QCM is able to roughly model these periods, despite missing some of the peaks in the measured lagoon stage.

The QCM does have several limitations that affect the predictive capabilities of the model. As discussed in Section 3, there are uncertainties in the stage data from the 22nd St gage. Small fluctuations in stage can result in large changes in flow rates. The QCM is highly sensitive to streamflow rates, and thus the prediction accuracy of the modeled lagoon stage is limited by the uncertainties in the 22nd St gage data.

The Arroyo Grande-Meadow Creek Lagoon area is also a highly complicated system that has been simplified in the QCM model. By not including the interaction between Arroyo Grande and Meadow Creek lagoons, some dynamics may not be represented in the modeled lagoon levels. Furthermore, the geometry of the Arroyo Grande Lagoon itself is complex, consisting of an L-shaped lagoon extending alongshore between fore- and backshore dunes. During periods of high flow, sediment is scoured out of the system, changing elevations throughout the lagoon. However, the QCM operates on a fixed stage-storage curve, which may not be representative of the system at all times of the year.

Due to these limitations and other modeling uncertainties, some events in the measured lagoon record were not captured, such as an apparent breach in December 2009 and subsequent lowered water levels, a closure/lagoon filling event in November 2012, and water level peaks during the winter and spring of 2014, 2015, and 2016. Given the complexity of the Arroyo Grande Lagoon, the QCM is best used to reproduce the seasonality of the closures and the expected distribution of water levels in the Lagoon, and not the exact timing of closure or breach events. The model also gives insight into the factors that influence water level conditions in Arroyo Grande Lagoon, and subsequently, water levels in Meadow Creek Lagoon.

Typically, the model would be used to extend the length of the time series so that stable statistics can be derived from the predicted water levels. For this case, however, a limited amount of input data are available, specifically inflows on Arroyo Grande Creek. This could be accomplished by developing a hydrologic watershed model to generate synthetic streamflow using measured precipitation data in the area. However, this is beyond the scope of this study.

Future Conditions

The QCM was used to generate time series of water levels in Arroyo Grande Lagoon for future conditions using the modified Arroyo Grande Creek inflows that account for future changes in precipitation and streamflow per the medium and high emissions scenarios for 2050 and 2100. Based on the findings of the coastal analysis that the geomorphic response of the shore to SLR would effectively lift the lagoon and water levels at the same rate as SLR, the QCM was run for the modified inflows before adding SLR. Figure 13 presents the results of the QCM for the four future cases prior to adding SLR to the time series.

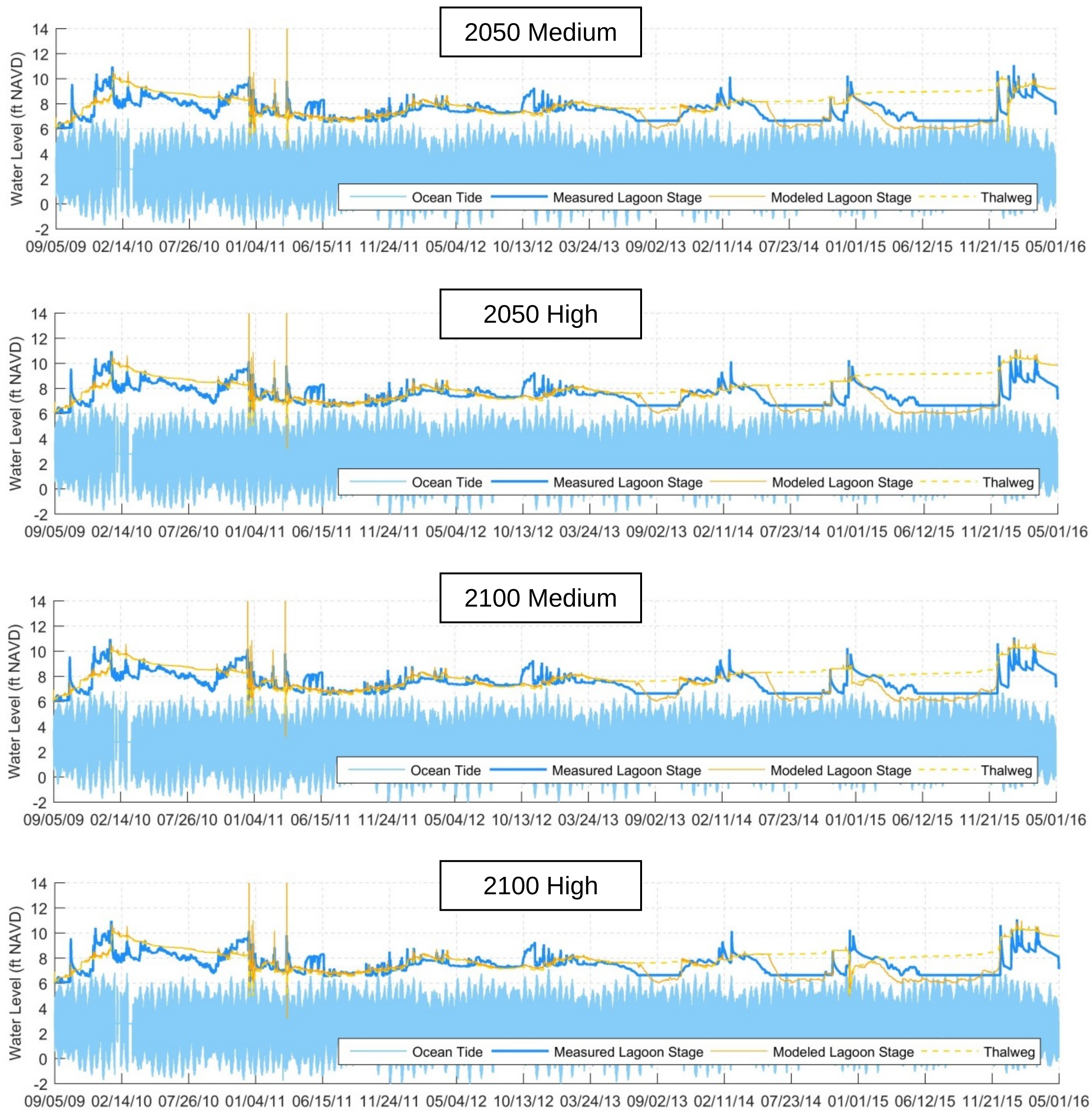

Figure 13
QCM Output for Future Conditions before adding Sea Level Rise:
2050 Medium, 2050 High, 2100 Medium, 2100 High (from top to bottom)

The lagoon water levels and breaching dynamics for the future cases are similar to those observed and modeled for existing conditions, except for during the larger fluvial inflows that cause a greater amount of scour during breaching and slightly increases the number of breach events that occur over the modeled record. SLR amounts were added to the modeled Arroyo Grande Lagoon water levels and the time series were used as the downstream boundary condition in the Meadow Creek Lagoon water balance (Section 5.3.3).

5.3.2 Meadow Creek Lagoon Hydraulic Model Analysis

The inflow boundary conditions to the Meadow Creek Lagoon water balance were generated using a hydraulic model of Meadow Creek lagoon driven by measured (existing) and projected streamflow and tailwater data under the influence of climate change (future). The measured Arroyo Grande Lagoon water levels were used as the tailwater conditions for the simulations. ESA developed at time series of the inflows to the Meadow Creek Lagoon by scaling flows on Arroyo Grande Creek, and calibrating the scale parameter by comparing the modeled Meadow Creek Lagoon water level to observations. The calibrated inflow time series was used in the Meadow Creek Lagoon water balance model that was used to assess the flood elevations. The analysis was conducted using the USACE's HEC-RAS hydraulic modeling software (v5.0.1) to evaluate water surface elevations in Meadow Creek Lagoon in the vicinity of the WWTF for a series of existing events and a range of future climate scenarios.

Each of these events was then analyzed for future periods under a range of climate emissions scenarios. Two time periods, 2050 and 2100, and two emissions scenarios, medium and high, were analyzed for each event to provide a range of potential future water surface conditions based on events known to have caused some degree of flooding in the vicinity of the WWTF.

To simulate future climate change scenarios, ESA developed estimates for future Arroyo Grande Lagoon water levels under the influence of SLR, as well as changes in streamflow in Arroyo Grande Creek and Meadow Creek under the influence of climate change and storm intensification. The following sections provide the methodology ESA developed in applying these datasets to the modeling and flood risk analysis, and key results of the flooding analysis.

Existing Conditions

The hydraulic model applied for this analysis was updated from a prior analysis conducted by ESA (ESA PWA 2013). The development of the original model is documented in the 2013 report. The model was updated by removing the Arroyo Grande Lagoon model geometry and setting the downstream tailwater elevation equal to the measured gage elevation in the Arroyo Grande Lagoon. A series of observed flood events were simulated to verify and calibrate the hydraulic model. The events analyzed and peak stage observed in the Meadow Creek Lagoon are summarized in Table 8.

TABLE 8
EVENTS ANALYZED WITH HYDRAULIC MODEL

Events analyzed	Peak Water Surface Elevation in Meadow Creek Lagoon (ft NAVD)	Source
December 18-25, 2010	12	Anecdotal observations
March 19-22, 2011	9.0	SLO Gage 770
January 20-22, 2012	8.1	SLO Gage 770
January 18-25, 2016	9.2	SLO Gage 770

The December 2010 event caused flooding at the WWTF (eyewitness accounts say approximately 1 foot of standing water at Emergency Electrical Building) and significant flooding in the surrounding residential areas. The water surface gages currently installed in Meadow Creek Lagoon were not active at the time of this event. Thus observed water surface elevations were based on anecdotal evidence of flood locations and depths compared to known elevations at these locations. To simulate flow in Meadow Creek for this event, measured streamflow at Arroyo Grande Lagoon was scaled based on proportional drainage area. This scaling was adjusted to match a peak stage in Meadow Creek Lagoon of 12.0 feet NAVD. This calibrated adjustment factor was then used to scale all flow to Meadow Creek Lagoon in the water balance model described in Section 5.3.3.

For events with measured stage elevations in Meadow Creek Lagoon, we were able to estimate streamflow based on change in stage per unit time and the stage-storage relationship of the lagoon. It was assumed that the change in storage was approximately equal to the inflow to Meadow Creek Lagoon. The event in January 2012 was used to evaluate model performance and adjust the calibration if needed. A comparison of the simulated and measured stage in Meadow Creek Lagoon just upstream of the culverts that drain the lagoon is shown in Figure 14.

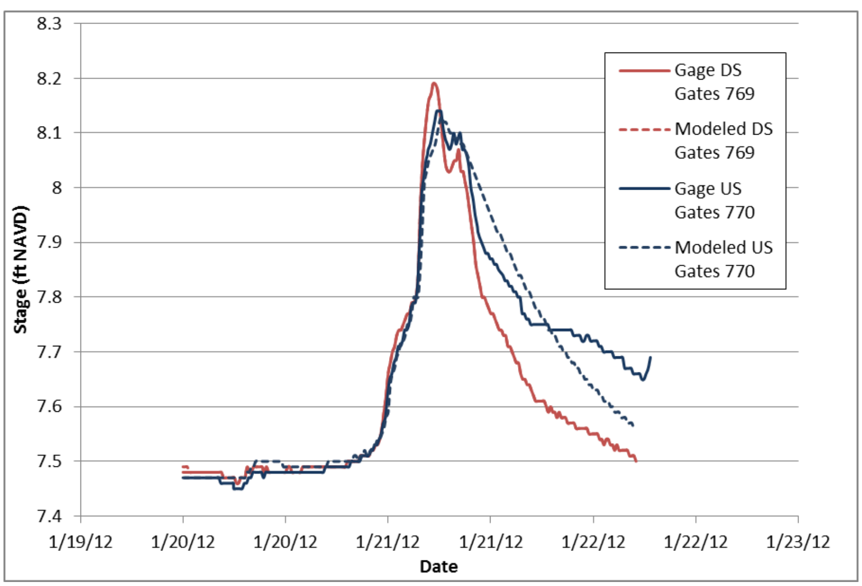

Figure 14
Simulated and measured stage in Meadow Creek Lagoon upstream of the tide gates

The results indicate that the model successfully reproduced the observed water levels in Meadow Creek Lagoon for this event. The existing conditions model was then used to simulate four future climate change scenarios—two emissions scenarios (medium and high) for each of two time horizons (2050 and 2100).

Future Conditions with Climate Change Impacts

The effects of climate change were incorporated into the boundary conditions of the hydraulic model to simulate how water surfaces would change in Meadow Creek Lagoon for a specific set of events. The Arroyo Grande Lagoon water surface governs the downstream water surface boundary condition and the inflow from Arroyo Grande Creek and Meadow Creek drive the upstream inflow boundary conditions on the hydraulic model. Each of the events modeled for existing conditions was adjusted for climate change and analyzed in the hydraulic model. The scenarios and governing boundary conditions are summarized in Table 9.

The computed inflows to Meadow Creek Lagoon were used as the upstream boundary conditions in the Meadow Creek Lagoon water balance described in Section 5.3.3.

TABLE 9
HYDRAULIC MODEL SCENARIOS AND BOUNDARY CONDITIONS

Scenario	Emissions scenario	Time Period	Sea level rise amount (ft)	Peak AGL water level (ft NAVD)	Estimate of Peak AGC flow recurrence interval	% change in peak flow	Peak flow in AGC (cfs)
March 19-22 2011	Existing	Existing	0.0	9.5	16-year	0%	917
	Medium	2050	0.9	10.4		7%	981
		2100	3.1	12.6		23%	1128
	High	2050	2.0	11.5		17%	1073
		2100	5.5	15.0		25%	1146
January 20-22 2012	Existing	Existing	0.0	8.1	2-year	0%	69
	Medium	2050	0.9	9.0		11%	77
		2100	3.1	11.2		11%	77
	High	2050	2.0	10.1		16%	80
		2100	5.5	13.6		10%	76
January 18-25 2016	Existing	Existing	0.0	9.3	1-year	0%	61
	Medium	2050	0.9	10.2		12%	68
		2100	3.1	12.4		10%	67
	High	2050	2.0	11.3		11%	68
		2100	5.5	14.8		1%	62

5.3.3 Meadow Creek Lagoon Water Balance

This section describes the hydrologic water balance model that was used to assess the flood elevations for existing and future conditions in Meadow Creek Lagoon. The water balance model relies on upstream boundary conditions developed using the hydraulic model described in Section 5.3.2 and the downstream boundary conditions developed using the Arroyo Grande Lagoon QCM described in Section 5.3.1.

Methods

A water balance model was developed to estimate the existing and future Meadow Creek Lagoon water levels under the climate change scenarios described in Section 4. The model estimates Meadow Creek Lagoon water levels on an hourly basis by summing precipitation and streamflow inflows to Meadow Creek Lagoon and losses via evaporation and discharge through the Sand Canyon Flap Gates. The model was calibrated to measured Meadow Creek Lagoon water levels from 2010 to 2016. Future Meadow Creek Lagoon water levels were estimated by running the model using scaled streamflow from Arroyo Grande Lagoon water levels adjusted for climate change (see Section 5.3.2). The downstream boundary was defined by the output from the Arroyo Grande Lagoon QCM (see Section 5.3.1).

Assumptions

Several assumptions were used in the development of this model:

- Losses (such as seepage out of the lagoon and discharge to the northwest) and gains (such as possible reverse flow through the tide gates), were considered minor relative to the other inflows and outflows and were neglected.
- Evaporation and precipitation over the lagoon were assumed to remain constant in the future.
- Erosion and deposition of sediment in Meadow Creek Lagoon was assumed to be minor and was neglected.
- Meadow Creek Lagoon was presumed to have a minimum water level driven by surrounding groundwater elevation. Groundwater elevations were assumed to rise the same amount as changes in sea level.
- Future peak flows above 50 cfs in Arroyo Grande Creek were assumed to change in magnitude as described in Section 5.2.1. Flows below 50 cfs were assumed to remain unchanged.

Inputs

Inputs to the model consisted of several existing hourly time series from 2010 to 2016. Two of the time series (Arroyo Grande Lagoon water levels and Meadow Creek streamflow) were adjusted to simulate future conditions over the same timeframe.

Evaporation and precipitation data from the Nipomo CIMIS station were converted into volumes by multiplying over an approximate lagoon surface area of 29.7 acres. These values were assumed to remain constant in the future. Arroyo Grande Lagoon water levels from Gage 769 were used for existing conditions. For future conditions, the Arroyo Grande Lagoon outputs from the QCM were used. Existing streamflows along Meadow Creek were estimated by scaling the

22nd Street Arroyo Grande Creek flows as described in Section 5.2.2. Future Meadow Creek inflows were calculated by scaling the future Arroyo Grande Creek flows, which were estimated by scaling peak flows (>50 cfs) by the change in flow magnitude associated with their return period for the four climate cases (see Table 5).

In addition to the existing and future time series, a head-discharge curve for the Sand Canyon Flapgates was also provided previously by the County, and was used to calculate flow out of Meadow Creek Lagoon into Arroyo Grande Lagoon. A stage-storage curve for Meadow Creek Lagoon was also used to calculate water level changes given inflow and outflow volumes to the lagoon.

Application

At every hour, the model calculates a change in Meadow Creek Lagoon volume based on gains from precipitation and streamflow, and losses from evaporation and flow out the flap gates. The volume change is then used to calculate a new water level in Meadow Creek Lagoon using the stage-storage relationship for Meadow Creek Lagoon.

The model was initially run and calibrated for existing conditions. High water level events in MCL, such as the December 2010 event, were given priority during calibration. The model was then re-run to simulate the future water level time series for Meadow Creek Lagoon using future streamflows and Arroyo Grande Lagoon water levels at the downstream boundary, as described above.

Results

Time Series of Existing and Future Water Levels

Figure 15 presents the time series of simulated Meadow Creek Lagoon water levels for existing and future conditions output from the water balance model. The modeled existing condition is generally close to the measured existing water levels, and the peak water level of 12.3 feet NAVD during the December 2010 storm is close to observations of approximately 12 feet NAVD. In general, the increase in future water levels over time is approximately equal with the amount of SLR. However, extreme events increase less than the amount of SLR. This is likely due to the increase in flood extents associated with the hypsometry, where the area of flooding increases dramatically above 13 feet NAVD. This is shown by the spreading or smoothing of events in the time series results for the various cases.

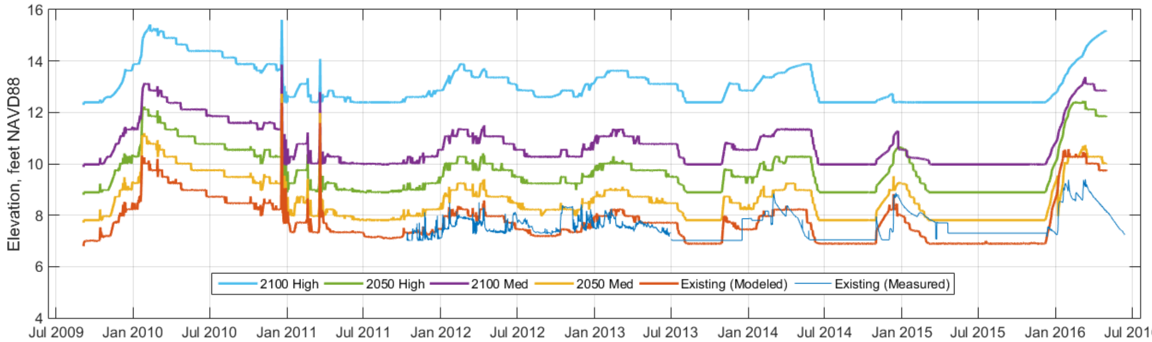

Figure 15
Time Series of Modeled Water Levels in Meadow Creek Lagoon for Different SLR Scenarios

Figure 16 presents the same time series results with a focus on the December 2010 event. For all cases, this event yielded the maximum simulated water surface elevation. This event is noteworthy in that it illustrates that the increase in flood elevation for the large event is less than the amount of SLR, even with the concurrent increase in precipitation and flows. This also suggests that an increase in up to 1 foot is expected by 2050, followed by potential rapid SLR and increase in flood elevations by up to 3.3 feet is expected by 2100.

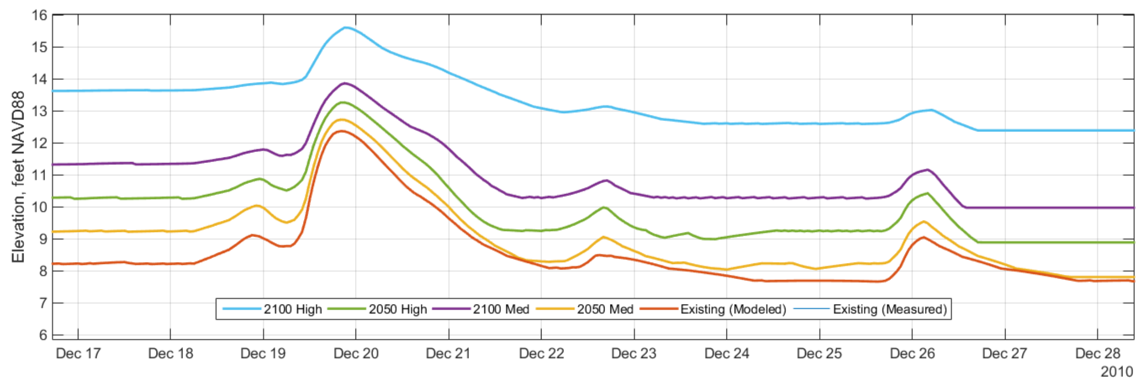

Figure 16
Modeled Hindcast of December 2010 Flood Event in Meadow Creek Lagoon

Frequencies of Existing and Future Flood Events

Figure 17 presents the percent exceedance plots of the time series data of the existing and future simulated water levels in Meadow Creek Lagoon. The plots present the simulated stage as a function of the percent of time that value is exceeded for the period of record (for this analysis, the record is seven years). For example, the median value corresponds to the 50% exceedance. The plot is used in the absence of a longer time series that can be used to tabulate annual maximum water levels and to conduct an extreme value analysis to estimate annual exceedance probabilities (e.g. 100-year water level). Because the amount of data is limited to seven years, an extreme value analysis cannot be performed to evaluate return periods of extreme events with sufficient confidence. Estimates of the 100-year event typically require at least 30 years of annual maximum data. Therefore, in the context of this study, we use the term frequency as a semi-quantitative approach that defines how often a given water level would occur over time in a general sense. To facilitate understanding of the percent exceedance, we define the following event frequencies:

- **Rare (extreme) water levels:** less than 1% exceedance, expected to have a 10-year return period or greater and occur during a relatively large storm
- **Nuisance water levels:** between 1% and 10% exceedance, expected to have approximately a 1-year return period
- **Typical water levels:** greater than 10% exceedance, expected to be representative of typical conditions and daily water levels

Note that these terms are defined relative to existing site grades at the WWTF and the associated potential flood consequences. The terms may be defined differently if other assets were under consideration, such as the residential areas that begin flooding at a lower elevation than the WWTF site. For this case, the flooding of the access to the WWTF is not of high consequence, and therefore has been identified as a nuisance water level. Of course, the percent of time that a given water level is exceeded can be used to indicate how frequently flood impacts can be anticipated.

Figure 17 shows the percent of time that the existing and future water levels in Meadow Creek Lagoon are exceeded for the seven-year record evaluated. The flood thresholds, existing elevation of flood protection, and the range in site grades is included in the figure. For a given elevation or threshold, the relative change in frequency over time can be estimated by comparing the future water level curves to the existing (red) curve. Three horizontal lines are depicted in the figure, and represent the following:

- **County Threshold for Residences and WWTF Access:** Flooding of the residential areas occurs when the water level reaches 10.4 feet NAVD, and access roads to the WWTF experience flooding
- **December 2010 event:** From prior experience at the site, the elevation of the Meadow Creek Lagoon during the December 2010 event is used as a benchmark for flooding at the WWTF, though it may not necessarily be representative of a damaging condition
- **Existing Flood Protection:** District staff indicate that improvements to the flood protection of WWTF were implemented since the December 2010 event, and that the facilities are flood proofed to elevation 14.4 feet NAVD

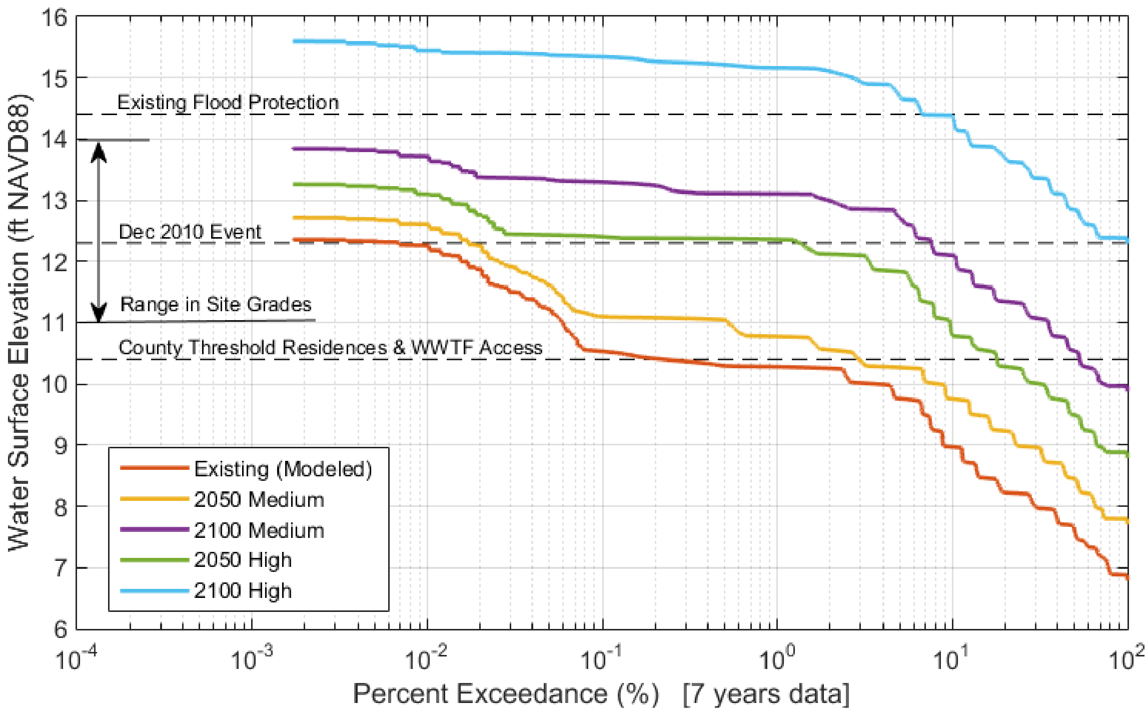

Figure 17
Water Level Exceedance Curves for Existing and Future Conditions with Sea Level Rise

The data in Figure 17 indicate the primary findings of the study:

- Increase in flood elevations for rare events is less than the amount of SLR, even with the concurrent increase in precipitation and inflows
- Depth of flooding for a given recurrence interval won't change much with climate change, but the extents of flooding will likely increase
- The frequency of flooding of the site will increase with climate change, and specifically, the flood threshold, or benchmark, will be crossed more frequently
- Typical water levels that occur regularly will increase approximately equal to the amount of SLR

Table 10 tabulates the percent exceedance values over time for the three thresholds shown in Figure 17. These values are useful to illustrate the relative frequency of flood impacts over time for different degrees of flooding. Because the WWTF is currently protected to elevation 14.4 feet NAVD, flood impacts related to SLR are not anticipated until approximately 2070 under the high SLR projection. However, the thresholds for lower elevations will be impacted by SLR sooner, with existing access to the WWTF likely to be impacted by 2050. The typical water levels in the Meadow Creek Lagoon will be greater than 10 feet NAVD by 2050, and greater than 12 feet NAVD by 2100. Changes in the typical water levels represent permanent inundation and imply that land use changes will need to be implemented.

TABLE 10
TABULATED EXCEEDANCE AND FREQUENCIES OF DIFFERENT FLOOD THRESHOLDS OVER TIME

Flood Threshold	Elevation (feet NAVD)	Percent Exceedance (Frequency)		
		Existing	2050	2100
Existing Flood Protection	14.4	0%	0%	<0.001% to 7% (Rare to Nuisance)
December 2010 Event Benchmark	12.3	<0.01% (Rare)	0.01% to 1% (Rare)	8% to 100% (Nuisance to Typical)
County Threshold for Residences and WWTF Access	10.4	0.2% (Rare)	3% to 18% (Nuisance to Typical)	50% to 100% (Typical)

Note: Ranges in percent exceedance represent the range associated with the medium and high emissions scenarios

Table 11 summarizes the median and maximum simulated water level in Meadow Creek Lagoon for existing and future scenarios. This suggests that flood thresholds for the plant of 12 feet NAVD will continue to be exceeded somewhat rarely by 2050, but by the end of the century will be exceeded on a regular basis. Flooding will exceed the access threshold of approximately 10.4 feet NAVD on a regular basis by mid-century.

TABLE 11
MEDIAN AND MAXIMUM SIMULATED WATER LEVEL IN MEADOW CREEK LAGOON FOR EXISTING AND FUTURE SCENARIOS (FEET NAVD)

Simulated Water Level	Existing	2050		2100	
		Medium	High	Medium	High
Median (50th Percentile)	7.6	8.5	9.5	10.5	12.8
Maximum	12.3	12.7	13.2	13.9	15.6

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7 ACKNOWLEDGEMENTS

This report was prepared by the following ESA staff:

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James Gregory, PE

Dane Behrens, PhD, PE

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Hannah Snow, EIT

Ellen Buckley, EIT

ESA thanks San Luis Obispo County staff for providing hydrologic data used in this analysis:

Mark Hutchinson

Ray Dienzo

ESA thanks the South San Luis Obispo County Sanitation District and their Contractors for providing information used in this analysis, and for review and comments of this report:

Gerhardt Hubner – SSLOCSD

John Clemons – SSLOCSD

Michael Nunley – MKN Associates

John Rickenbach – JFR Consulting

APPENDIX A

Description of ESA's Quantified Conceptual Model (QCM) for Small Coastal Lagoons

APPENDIX A: Description of ESA's Quantified Conceptual Model (QCM) for Small Coastal Lagoons

ESA has developed a quantified conceptual model (QCM), which evaluates tidal inlet morphology and the resulting hydrology of the Lagoon. The QCM approach was originally developed for Crissy Field Lagoon, in San Francisco Bay (Battalio et al. 2006). The approach was then refined for river mouth systems by Rich and Keller (2013). Using lessons learned from both approaches, ESA further developed the QCM as a more complete tool to assess systems with both tidal and fluvial characteristics.

The QCM approach is centered on a water budget for the Lagoon, which is coupled with a sediment budget for the Lagoon mouth (inlet). 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.

The model uses time series of nearshore waves and tides, watershed runoff or streamflow, and evapotranspiration data as boundary conditions. Using these as forcing conditions, the model dynamically simulates time series of inlet, beach, and Lagoon state. With each time step, the net inflows or outflows to the system are estimated, along with the net sedimentation or erosion in the inlet bed. As shown in Figure X, the flow terms vary depending on whether the mouth of the Lagoon is open or closed. During closed conditions, net inflows are based on watershed runoff, wave overwash into the Lagoon, and losses from beach berm seepage and evapotranspiration. When the inlet is open, tidal flows into and out of the inlet are included. Sand deposition in the inlet channel is based on wave power when the inlet bed is lower than ocean tides, and based on both wave power and wave runup when it is perched above tide levels. To approximate scour, inlet flows are used to estimate both the bedload rate and the rate that bed sediments mix with the water volume to become suspended load (see Behrens et al. 2015). For more information on how the model resolves different processes, refer to Behrens et al. (2015).

As the model steps forward in time, it continuously transitions the mouth through tidal, perched, and closed conditions. When deposition in the inlet bed exceeds erosion, the bed rises vertically, eventually perching above most tidal elevations and closing. Closure occurs in the model when sediment fills the inlet bed higher than Lagoon water levels. Once closure occurs, the inlet thalweg effectively becomes the 'beach', and the beach crest is allowed to grow vertically when wave runup reaches the crest height. Breaching occurs in the model when water levels eventually overtop the beach berm crest, eroding a new inlet.

Model accuracy is tested by comparing modeled Lagoon water level time series against gaged observations, and by comparing the timing and length of inlet closure events to those of historical records. Although there are a large number of processes involved in this modeling approach, closure time series and Lagoon water level time series usually provide a good indication of which processes are dominating the system at a given time, such as freshwater runoff during floods, or powerful waves prior to closure. Thus, reproducing these time series is taken to mean that the dominant processes are meaningfully represented.

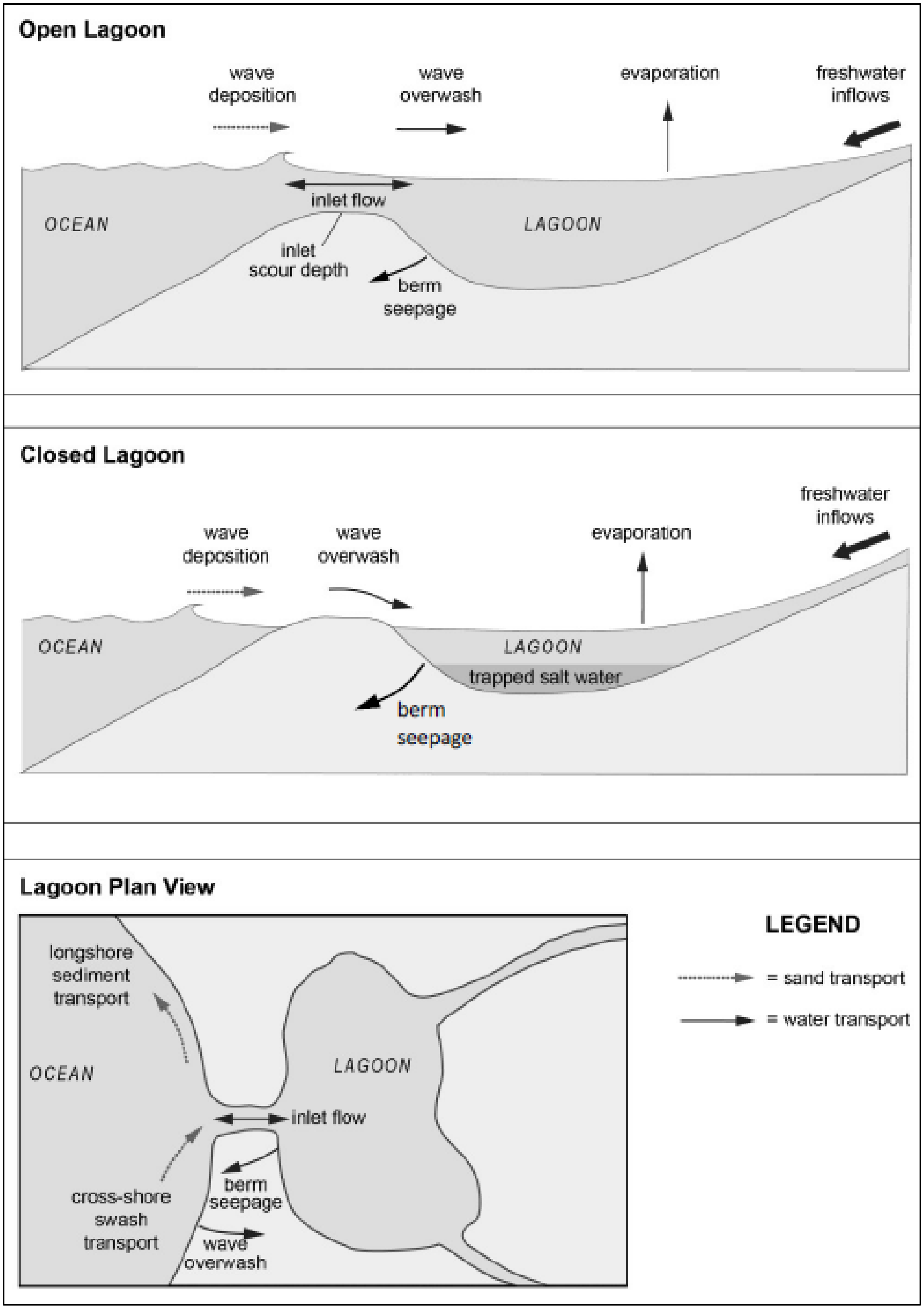

Figure A-1
Conceptual diagram of lagoon processes during open- and closed-mouth conditions

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