ARROYO GRANDE LAGOON

Interim Sandbar Management Plan

Prepared for
County of San Luis Obispo
Department of Public Works

October 9, 2013

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EXECUTIVE SUMMARY

Arroyo Grande and Meadow Creek Lagoons (AGL and MCL, respectively) are two small coastal estuarine systems located near Oceano, California within San Luis Obispo county. The lagoons are remnants of formerly extensive backbarrier (landward of dunes) wetland habitats that once extended between Pismo Beach and the Oceano Dunes complex. The intensive development of this area in the 20^{th} century dramatically altered local and regional hydrology, hydraulics, and sediment transport, and much of the former wetlands were replaced with low-lying development and infrastructure that are prone to flooding during intense or prolonged storm events. One such event in December 2010 resulted in the flooding of over 45 properties, including a municipal wastewater treatment plant, resulting in substantial damage.

The San Luis Obispo County Department of Public Works (the Department) requested that ESA PWA assess the flood dynamics of the area and develop an Interim Sandbar Management Plan to reduce the likelihood of similar flooding in the near future. Water can only drain out of MCL when water levels there are higher than levels in AGL. This drainage is typically limited to when AGL is breached and draining to the Pacific Ocean. Therefore, the elevation of the sandbar (beach berm) is the ultimate control on water levels throughout the MCL–AGL system. In order to assess the system's flood dynamics, ESA PWA performed topographic surveys of both lagoons, built a HEC-RAS of the two creek-lagoon systems, and utilized water level data collected by the Department. ESA PWA also assessed the influence of the beach and sand management activities on coastal morphodynamics, and developed a quantitative conceptual model (QCM) to relate beach conditions to lagoon water levels.

The results of these analyses indicated that: (1) The primary driver of water levels in lower MCL appear to be water levels in AGL; (2) water levels in upper MCL appear to be relatively unaffected by water levels in the lower lagoon; (3) Carpenter Creek may be acting as a flood bypass for the Meadow Creek system; (4) the Sand Canyon flapgates between the two lagoons may not close at their designed invert elevation; and (5) existing sand management activities in the area may be contributing to higher berm elevations than would otherwise be present. Therefore, opportunities to reduce flooding include: (1) removing the apparent drainage divide in MCL; (2) potentially retrofitting the Sand Canyon Flapgates; (3) monitoring and maintaining the flapgates; (4) modifying the sand management regime so there is a reduced risk of elevated berm levels, and (5) implementing inlet/sandbar management so that it is managed ("pre-breached") at a maximum elevation, facilitating earlier breaching during storm events.

The interim (and experimental) sandbar management plan proposes that an approximately 200-foot wide wedge of the beach berm be excavated prior to storm events to lower the berm crest elevation to approximately +9.5 ft NAVD (for smaller storms) or +8 ft NAVD (for larger storms). The ultimate elevations and dimensions will be field-fit to local conditions; under no circumstances should SLOC DPW lower the beach berm below existing lagoon water levels (this would result in an artificial breach). Artificial breaching under non-storm conditions could result in potentially significant impacts to lagoon ecology and listed species. The inlet should be excavated such that at least half a foot of freeboard exists between the lagoon water level and the inlet thalweg post-construction. The plan includes provisions to protect biological resources, cultural resources, and public safety. The plan also describes a robust monitoring and adaptive management program to assess the effects of sandbar management and other flood risk reduction provisions (e.g. MCL drainage divide removal, flapgate retrofits, Carpenter Creek maintenance) on flood dynamics, AGL inlet morphodynamics, breach timing, and system drainage.

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1 INTRODUCTION

Arroyo Grande and Meadow Creek Lagoons (AGL and MCL, respectively), are two small coastal estuarine systems located approximately 13 miles south of the city of San Luis Obispo, California in Oceano, California (Figure 1 and Figure 2). The lagoons are among some of the few remaining expressions of formerly extensive backbarrier (landward of dunes) wetland habitats that historically extended between Pismo Beach and the Oceano Dunes complex. The intensive development of this area in the 20th century replaced much of these former wetlands with low-lying residential, commercial, and public infrastructure development (wastewater treatment facilities and airport) that are prone to flooding during intense or prolonged storm events. One such event in December 2010 resulted in the flooding of over 45 properties, including the wastewater treatment plant, resulting in substantial damage.

Meadow Creek Lagoon is hydraulically connected through flapgates to the Arroyo Grande Creek Lagoon, which in turn drains to the Pacific Ocean across a beach managed by the California Department of Parks and Recreation (CDPR) as part of Oceano Dunes State Vehicular Recreation Area (SVRA). Water can only drain from MCL into AGL when the water level on the upstream side (MCL) is high enough above the water level in AGL to open the flapgates. Water can only drain from AGL when the inlet to the Pacific is open. If the inlet is closed, water can back up in AGL, closing the flapgates and preventing drainage from MCL. During the December 2010 storm, the arrival of over 3 inches of rain over a 24 hour period resulted in a significant amount of runoff accumulating in MCL before AGL breached, resulting in flooding of nearby low-lying homes and infrastructure.

In 2011, the San Luis Obispo County Department of Public Works (the Department) requested that ESA PWA assess the flood dynamics of the area and develop an Interim Sandbar Management Plan to reduce the likelihood of similar flooding in the near future. This report contains the Interim Sandbar Management Plan and describes information and analyses used to develop the plan. This report is organized into the following sections:

1. **Introduction** – Presentation of the problem as well as project goals and objectives.
2. **Environmental Setting** – Discussion of site history and evolution.
3. **Existing Conditions** – Descriptions of current physical and ecological conditions and processes in both Meadow Creek and Arroyo Grande Lagoons.
4. **Opportunities and Constraints** – Analysis of the opportunities and constraints to sandbar and flood management in the system, including regulatory concerns.
5. **Interim Sandbar Management Plan -** Description of sandbar management strategy, including methods, timing, equipment, expected endpoints, and recommendations for long-term monitoring and management.

1.1 Goals and Objectives

The primary goal of this management plan is to facilitate breaching of Arroyo Grande Lagoon such that it breaches at lower water surface elevations, to increase the opportunities for water to drain from Meadow Creek Lagoon via the flapgates and reduce the frequency of flooding of the adjacent homes and infrastructure. The objectives of the project include:

- Collect, synthesize, and report the information necessary to develop an emergency breach plan or pre-breach strategy that can be implemented in anticipation of winter storms and is acceptable to local, state, and federal resource agencies.
- Describe the recommended dimensions, timing, and methods of sandbar breaching/ management.

Specific objectives of interim sandbar management include:

- Reduce the frequency and magnitude of flooding of homes, businesses, and infrastructure during 1-5 year storm events.
- Maximize flood storage capacity within Meadow Creek and Arroyo Grande Lagoons such that they can capture local runoff without flooding adjacent homes and infrastructure.
- Prevent or minimize impacts to ecological communities (particularly special-status aquatic species such as steelhead and tidewater goby) in Arroyo Grande Creek/Lagoon, Meadow Creek Lagoon, and along the SVRA beach.

1.2 Project Process

ESA PWA and initiated the project in the fall of 2011, collecting topographic and bathymetric survey information of both lagoons in December 2011. We also began to collect and analyze a broad variety of existing information, including historic maps, flood records, and railroad documents as well as more recent reports developed for the Department. Throughout the winter and spring of 2012, we utilized water level data collected by the Department to assess general trends in lagoon hydrology and initiate hydrologic and hydraulic modeling of the lagoon. We delivered a lagoon hydraulic modeling report to the Department in May 2012 that identified a number of modeling limitations and refinements, and addressed these refinements throughout the rest of 2012 and early 2013. In late 2012, a separate county contractor (Terre Verde) produced a report describing biological resources in Meadow Creek Lagoon. In early 2013, we assessed coastal processes at the site, particularly beach topography and morphology, wave run-up, and total water levels (TWLs). We then integrated these various historic, hydrologic and hydraulic, and ecological analyses to identify opportunities and constraints to flood management and develop an interim sandbar management plan. Throughout the project process, we coordinated closely with staff from the Department, particularly Mark Hutchinson, Environmental Programs Manager, and Jill Ogren, Hydraulic Planning Unit Lead Engineer.

1.3 Report Preparers

This report was developed by Christina Toms, with supervision from Bob Battalio, PE. James Gregory directed the hydraulic modeling component of the project. To Dang and Eddie Divita performed the coastal analyses under the direction of Bob Battalio. Field data collection was directed by Damien Kunz with assistance from Louis White, PE and Eddie Divita.

1.4 Terminology

Coastal lagoons are complex systems at the dynamic transition between the land and the sea, and accurately describing their environments often requires the use of a specific vocabulary. For reference purposes, the Meadow Creek-Arroyo Grande Lagoon system's features are defined below and labeled in Figure 2.

Lagoon. Cooper (1997) most likely puts it best when describing the challenges of defining a coastal lagoon:

> Precise definition of a coastal lagoon is problematic, and many definitions have been proposed. Considerable overlap between lagoons and estuaries has been identified. As morphodynamic systems, lagoons have been defined as "coastal water bodies which are physically separated, to a greater or lesser extent, from the ocean by a strip of land" (Ward and Ashley 1989). The imprecise definition of coastal lagoons is probably the main problem in the lack of co-ordinated research, as many features variously termed estuaries, blind estuaries, bar built estuaries, embayments, coastal ponds, coastal lakes, bays and sounds may alternatively be regarded as lagoons.

Along California's coastline, the term "lagoon" is typically used to describe the matrix of open water, marsh, and floodplain habitats that is formed when waters from a coastal creek are impounded or dammed upstream by the beach (Clifton et al. 1972). These systems are "typically" open to the ocean during winter-spring (when storm flows breach the beach dam) and disconnected from the ocean during the summer-fall months (when flows gradually impound behind the beach dam). [It is important to note that California coastal lagoons exhibit a broad range of variability in inlet morphodynamics and that this definition of "typical" behavior is a very broad generalization.]

For purposes of this report, we define Meadow Creek Lagoon as the area inundated by flows from Meadow Creek upstream (north) of the Sand Canyon Flapgates. We define Arroyo Grande Lagoon as the area inundated by flows from Arroyo Grande creek downstream (south) of the Sand Canyon Flapgates and up the lower portion of the Arroyo Grande Creek flood control channel.

Stream mouth. Where Arroyo Grande Creek exits its confined channel bounded by the flood control levees. To be contrasted with "lagoon inlet/outlet" (defined below), where the creek/lagoon actually exits the beach.

Lagoon inlet/outlet. Where Arroyo Grande Lagoon exits the beach and flows into the Pacific Ocean. Typically, the inlet/outlet is only open (directly connected to the ocean) during high flows, and otherwise closed (completely disconnected from the ocean) or choked (connected during high tides, disconnected during low tides; usually associated with shallow overflow from the lagoon).

Foredune. Dunes formed by sand-trapping vegetation directly behind (landward of) the beach. Foredunes may occur as discrete scattered mounds, broad and low terraces, or discontinuous or continuous ridges.

Sandbar/Berm. A seasonal or persistent swash bar (wave-deposited sandbar) emergent above high tide or ordinary high water levels seaward of the lagoon.

Beach ridge. A single or compound (multiple berm) beach landform composed of active and relict berms, with or without dune deposits.

Foreshore. The intertidal zone of the beach.

Backshore. The supratidal zone of the beach and foredune. The backshore includes the **swash zone**, where waves run up the beach.

Floodplain. Topographically level areas along the sides of a creek that carry occasional or frequent flood flows. Arroyo Grande Creek is largely disconnected from its floodplain due to the presence of flood control levees immediately adjacent to the active channel.

Thalweg. The deepest portion of a channel.

Geomorphology. The study of landforms, the processes that created them, and the history of their development.

Morphodynamics. Changes in geomorphology on various time scales.

2 ENVIRONMENTAL SETTING

This section describes the environmental setting of the project site, including its evolution since the late 1800s and physical and ecological processes and conditions.

2.1 History Pertinent to Lagoon Hydrology and Geomorphology

The "Five Cities" of Shell Beach, Pismo Beach, Arroyo Grande, Grover Beach, and Oceano are located on a broad, gently sloping alluvial plain (the Cienega Valley) that is bounded by the mountains of the Coast Range to the north, the Nipomo-Arroyo Grande Mesa to the east, the extensive Oceano Dunes complex to the south, and the Pacific Ocean to the west. The flatter portions of this valley have been extensively developed for agricultural, residential, and commercial purposes, which has resulted in significant changes to local hydrology, geomorphology, and ecosystems.

Historic analysis indicates that prior to European settlement much of the Cienega Valley floor was at grade with Arroyo Grande Creek. The low-lying topography of the area made it especially vulnerable to flooding, and the historic record contains multiple accounts of severe floods (1883-84, 1893, 1895, 1907, 1909, 1911, 1914, 1936-37, 1943, 1952, and 2001; see Swanson 2006). Figure 3 displays a T-sheet (historic topographic map) of the area from 1884, before the Southern Pacific Railroad (SPRR) was constructed through the valley. The highly detailed t-sheet displays an extensive, complex backbarrier marsh complex between the beach/ dunes at present-day Pismo Beach and grassland/chaparral habitat farther inland. The marsh is the terminus of Pismo, Meadow, and Arroyo Grande Creeks; a single channel through the marsh drains all three creeks to the ocean through a shared outlet. While it is difficult to comprehensively characterize the morphology based only on sparse historic maps, we expect that the wetland was typically not tidal due to wave and wind transport of sand that perched the outlet channel and seasonally closed the outlet completely. Backbarrier habitats were more likely to be freshwater to brackish marsh. Multiple smaller channels drain from the marsh plain into the main channel in a somewhat dendritic pattern. The t-sheet displays unvegetated mudflats along the edges of portions of the main channel; these mudflats were potentially inundated when the drainage outlet was closed, and exposed when the outlet was open and the system was drained. The backbarrier marsh extends south of the outlet channel, following Arroyo Grande Creek for some distance along the toe of the Oceano Dunes complex. At the outlet, a channel branching to the south ponds water on the beach, seaward of the marsh. This channel also appears to drain some smaller channels that cut through the northern tip of the Pismo dune field to Arroyo Grande Creek. Like many other coastal California lagoon systems, habitats in this area were likely highly dynamic, with frequent habitat conversions driven by episodic events (floods, dune migration, ocean overwash, etc.).

Figure 4 displays a topographic map of the area produced in 1897, before intensive development of the valley began but after the construction of the Southern Pacific Railroad (SPRR). The footprint of the marsh is much the same, though human activity is beginning to impact the system. A spur of the SPRR heading northwest from the main line led to a pavilion at the joined outlet; the alignment of the spur roughly paralleled the present-day alignment of the northern Arroyo Grande Creek levee. The construction of the spur required a portion of lower Arroyo Grande Creek to be re-aligned to the south, and wetlands in the vicinity of the spur were filled. The new, southerly alignment of the lower Arroyo Grande channel would be rendered permanent in the 1960s with the implementation of the Arroyo Grande Creek Flood Control Project (see below). Floods in the early 20th century reportedly destroyed the pavilion (Anderson 2013); it is likely that these same floods also destroyed the railroad spur.

Figure 5 displays a sequence of historic aerial photographs of the site from 1939 until the present-day. Pismo Creek was diverted from the wetland complex in 1911, when major flooding in the basin led local residents to excavate a new ocean outlet for the creek through the dunes west of Pismo Lake (Chipping 1989). The diversion of Pismo Creek removed what was likely a significant source of freshwater, flow energy, and sediment from the system. Arroyo Grande Creek and Meadow Creek continued to flow into the backbarrier wetland complex. In a harbinger of future sedimentation problems in the basin, news reports from this period describe accretion of multiple feet of sediment in the Arroyo Grande floodplain in response to flood events (Chipping 1989).

The development of the Cienega Valley in the mid-1900s fundamentally altered the area’s coastal landscape, and significant proportions of the backbarrier marsh were drained, filled, or otherwise converted to non-wetland uses. The State of California began acquiring the parcels that would become Pismo State Beach and Oceano Dunes SVRA in 1934, and over the next 40 years would develop much of the beach and backbarrier wetland habitats into recreational facilities. A local entity, likely State Parks, had initiated dredging of the lagoon in the vicinity of Pier Avenue by 1939 (Figure 5), and completed dredging and the construction of the adjacent Oceano Campground by 1947. During the same time, State Parks cut the Carpenter Creek outlet through the dunes south of the Pismo Creek outlet, forming an alternate outlet for flows from Meadow Creek. By the 1950s, Oceano Airport and the neighborhood known as “The Island” had been constructed in the wetlands and lowlands west of the joined outlet. Portions of the lower lagoon were dredged, forming the persistent open water basins north and south of the current-day Pier Avenue. Fill material from dredging was likely used to help construct The Island and other surrounding neighborhoods. Around the same time, dune sand was pushed into the northern portion of the marsh to form what is now the Pismo Beach Golf Course (Chipping 1989); constraining Meadow Creek and its associated floodplain habitats (Figure 7). By the 1960s, agricultural development of the Cienega Valley and the implementation of the Arroyo Grande Creek Flood Control Project converted the formerly sinuous creek into a linear channel constrained between parallel flood control levees. The seaward terminus of the Project’s northern levee extended into what remained of the wetland habitats surrounding the joined outlet, separating it into two systems: Meadow Creek Lagoon north of the levee, and Arroyo Grande Lagoon south of the levee. The two systems were joined through flapgates (the Sand Canyon Flapgates) that were designed to limit flow from Arroyo Grande Lagoon upstream into Meadow Creek Lagoon. In 1969, Lopez Dam was constructed primarily to help store water for municipal use throughout the five cities area; a secondary benefit of the lake is its effect on peak flood flows in the system. Since the dam was constructed, the valley was not significantly impacted by the flood events of 1969, 1983, and 1997; flooding in 2001 was due to levee failure along the south side of the creek during a high flow event (Swanson 2006).

In the early 1970s, portions of "The Strand" neighborhood were being constructed directly on top of the dunes to the west of Meadow Creek Lagoon (Figure 5). This coincided with the official establishment of Pismo Dunes SVRA by California State Parks in 1971 (renamed Oceano Dunes SVRA); it remains to this day the only location in the state where vehicles may legally drive on the beach. Construction of The Strand, The Island, and a regional wastewater treatment plant (the South San Luis Obispo Sanitation County District Wastewater Treatment Plant (WWTP), wedged in a former wetland area between the airport, The Island, and the northern Arroyo Grande flood control levee) was largely completed by the mid-1980s (Figure 5). By this point, the area around the now-fragmented lagoon and backbarrier marsh had been largely built out, though development in the Arroyo Grande and Meadow Creek watersheds continues to the present day.

Prior to the early 1990s, the inlet of Arroyo Grande Creek and Lagoon was managed (excavated, or breached) to prevent flooding in the backbarrier lowlands (former wetlands and floodplains). A series of memorandums obtained from SLO DPW indicate that breaching was primarily implemented by CDPR at the request of the County and the South San Luis Obispo County Sanitation District (SSLOCSD, operators of the Oceano wastewater treatment plant) on an annual basis. The lagoon was artificially breached via heavy equipment (backhoes/front end loaders), inducing drainage of Arroyo Grande Lagoon so that Meadow Creek Lagoon could drain through the Sand Canyon flapgates. The letters also describe concerns that natural breaches could lead to beach erosion near the buried WWTP outfall pipe (roughly located immediately north of the alignment of the north Arroyo Grande Creek levee). Artificial breaching was halted in 1993-1994 when the Coastal Commission declared that the breaches required a Coastal Development Permit. In 1999, SSLOCSD applied for a Regional General Section 404 (federal Clean Water Act) permit to breach Arroyo Grande Creek straight to the ocean, and to construct a diversion structure on the beach that would prevent the inlet from migrating to the north. The intent of the application was to permit work to protect the SSLOCSD wastewater outfall line, which discharges into the ocean just north of Arroyo Grande Creek. The permit was not pursued because the creek mouth began to migrate south, and permitting agency requests for additional studies and information were beyond the capability of the SSLOCSD. This report constitutes the first effort to re-evaluate the need and means of inlet management.

2.2 Effects of Site Development on Flooding and Lagoon Breaching

The intensive development of the Cienega Valley in the mid-1900s resulted in dramatic changes to the physical and ecological conditions and processes in the backbarrier wetland complex. Many of these changes contribute to the flood risk in the areas around the present-day lagoons. Among the most relevant changes were the following:

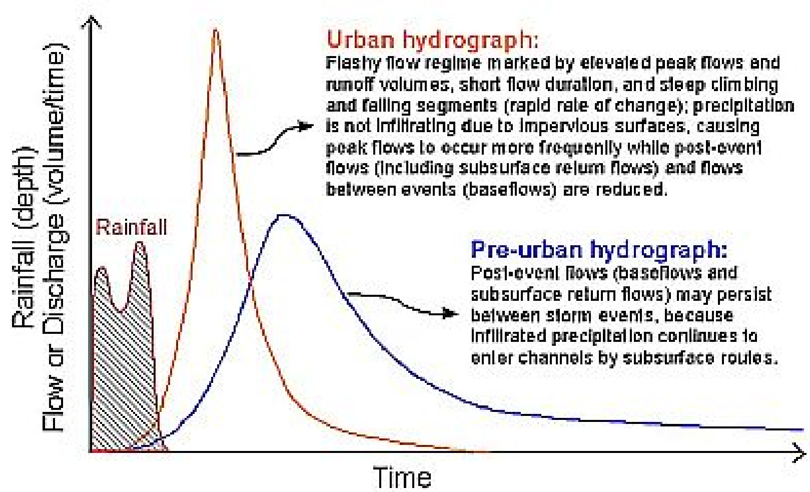
- **Placement of regional infrastructure, homes, recreational amenities, and businesses in low-lying, flood-prone areas.** The prior manual breaching of the lagoon facilitated development of much of the former backbarrier wetland complex. This development has put people and structures directly in the drainage path for most of the Cienega Valley. Many of these areas, such as the airport, the WWTP, The Island, The Strand, and various amenities of Oceano State Beach have base elevations that are either within or are close to the historic flood elevation range. Figure 6 displays the historic habitats from the 1897 t-sheet overlaid on a current aerial photograph.
- **Decreased frequency of large, scouring flows.** Though the development of the Arroyo Grande and Meadow Creek watersheds has likely made these systems more "flashy" (that is, prone to intermittent high flows and water levels with short durations, see below), the diversion of Pismo Creek and construction of Lopez Dam have reduced peak flow velocities from major storm events relative to historic conditions.[1] The US Army Corps of Engineers has estimated that construction of Lopez Dam has decreased the flow rate of a 2-year event to 25% of what it would be without the dam, and reduced the rate of a 100-year event by half (Waterways 2010). It is also possible that the Carpenter Creek outlet serves as a high-flow bypass for lower Meadow Creek; this is discussed in greater detail below in Section 3.2. While the decrease in large flood peaks is traditionally perceived as benefitting flood management in the lower basin, it has also significantly decreased opportunities for scour and "flushing" of sediments to the ocean. In natural (not anthropogenically impacted) lagoon systems, major flood flows often serve as a "reset" button on lagoon/marsh habitats, facilitating the establishment of new, hydraulically efficient creek channels and ocean outlets. When these flows become less frequent, accreted sediments can build up in channels and floodplains, decreasing channel depths (and flood passage capacity) and making it easier for dense thickets of riparian vegetation (primarily willows) to establish and persist. This effect is enhanced by increased sediment yields from developed watersheds (see below). More importantly to this study, sedimentation can reduce water storage capacity and result in higher water levels and flood risk for more frequent rainfall events. In this sense, the flood control project loses effectiveness over time, requiring mechanical breaching of the outlet to limit water levels to below flood stage. This is explained further, below.
- **Reduced flood conveyance in creek channels.** Intensive urban development (the growth of the Grover Beach, Oceano, and Arroyo Grande communities) coupled with agricultural conversion of the Arroyo Grande floodplain has led to increased sediment yields to Meadow and Arroyo Grande Creeks. The construction of flood control infrastructure such as levees disconnected the creeks from their floodplains, so sediment from storm flows either accretes in the channels themselves, or in the backbarrier marsh. (See Swanson 2006 for an in-depth discussion of geomorphic changes to lower Arroyo Grande Creek.) Coupled with the lack of scouring flows (above), sediment accretion has made the creek-marsh system much less hydraulically efficient than its pre-development

1 The construction of the dam on Pismo Lake has likely also affected storm pulses, but to a lesser degree than the diversion of Pismo Creek and the construction of Lopez Dam.

condition. In maps from the late 1800s, the lower Meadow Creek channel is mapped as open water 50 to 100 feet wide in most locations. By the 1950s, much of the historic channel was clogged with sediment and/or vegetation; by the 1970s, the only channel that remained was a narrow one that appeared to be dredged roughly parallel to Highway 1. No channel is currently visible. A similar situation exists in Arroyo Grande Creek. Multiple reports (Swanson 2006, Waterways 2010) discuss the high rates of sedimentation in the lower creek, which as a result has seen its capacity decrease by over 80% since the flood control project was implemented. The high sedimentation rates and lower base flows encourage vegetative growth in a positive feedback loop: as the sediment flushes less sediment, more vegetation (particularly willows, which have taken over much of the former backbarrier emergent marsh upstream of MCL) can establish, which further reduces flow velocities and increases sedimentation rates. This process has effectively "cemented" the creek's morphology as a shallow, braided, and likely highly aggraded channel-floodplain system. The extensive willow thickets also attract beavers, whose dams further restrict system hydraulics.

- **Relative increases in peak flow velocities from small storm events.** Urban development can alter watershed hydrology by increasing the proportion of impervious surfaces and routing surface runoff through hydraulically efficient drain pipes, culverts, and other structures. The development of much of the lower Arroyo Grande and Meadow Creek watersheds has likely made the hydrograph of small storm events more "flashy" by increasing peak runoff volumes, decreasing the time it takes for a given event to reach its peak, and decreasing the duration of flow (Graphic 1). In other words, while overall watershed practices have reduced flowrates in local creeks (and reduced scour of the creek mouth/inlet), local runoff contributes to lagoon water levels (and thus flood risk). These altered hydrographs increase the risk of flooding from small storm events, creating challenges for local flood management.

Graphic 1. The effects of urbanization on flood hydrographs. From EPA 2012.



- **Effects of the Sand Canyon Flapgates on lagoon water levels.** The Sand Canyon Flapgates contribute to the stable water levels in MCL, which has facilitated the lagoon's use by beavers, who then build dams that further perch water levels. The flapgates have also effectively turned Meadow Creek Lagoon into a reservoir upstream of Arroyo Grande Lagoon. This hydraulic separation has likely reduced the degree to which flows in Meadow Creek can affect scour of the inlet at Arroyo Grande Lagoon. The hydraulics of this system are discussed in depth below in Section 3.2**.**

- **Beach and dune management activities.** Most dunes in the immediate project vicinity are not very mobile, as they are colonized by robust stands of non-native, invasive European dunegrass (*Ammophila arenaria*) that prevent dune movement and migration. The exception to this rule is the dune field seaward of The Strand neighborhood and in front of the mouth of Arroyo Grande Creek. Homeowners in The Strand exist in an uneasy equilibrium with the dunes in front of their homes: to provide protection from the ocean, sand fencing is occasionally placed along the dunes to encourage the establishment of dune vegetation, which helps trap blowing sand. However, the trapped sand causes the dunes to grow, and when the dunes get too big, they block the views from Strand homes. Sand from the dunes is then mechanically moved closer to the shorelines so that views are restored. As discussed in further detail in Section 3.1.1 below, these activities interfere with natural cycles of dune growth, erosion, and migration, potentially impacting the morphology of beaches further downcoast. The vehicular traffic on the shore may also compact beach sands, potentially inhibiting the scour of high creek discharges and progressively muting drainage from the system. We have no data to confirm this hypothesis at this time, but recommend considering the effects of these existing activities on the shore morphology,and creek discharge, as these activities could be contributing to the potential for floods.

  As mentioned earlier, prior breaching facilitated development within the estuarine flood plain. This breaching also likely inhibited the growth of the beach berm and dunes in the breach location. Since breaching was prohibited in the mid-1990s, it is likely that the elevations of the beach berm and dunes have increased. This has likely increased the extent and depth of AGL as well as incrementally increased in the size of MCL (relative to breached conditions), improving their ability to support estuarine ecosystems. However, the higher berm and less efficient southerly breach location result in higher lagoon water levels in the fall, thereby increasing the flood risk.

Existing physical conditions and processes are discussed in greater detail below in Section 3.

3 EXISTING CONDITIONS

This section summarizes existing conditions at the site, including topography, bathymetry, hydrology, and biological communities.

3.1 Topography and Bathymetry

The topography and bathymetry of Arroyo Grande and Meadow Creek Lagoons can be seen in Figure 8. Like many coastal California lagoons, AGL and MCL are perched relative to the tides (tidal range of 0 to +5 ft NAVD; see Section 3.2 below), and for the most part are not intertidal systems. This is because the ocean waves build up the beach via waves running-up onto the shore and depositing sand on the back beach, and predominate onshore winds build coastal dunes. The crest of the break in slope just inland of the high tide elevation contour, called the beach berm, is related to this process and creates a sill that reforms over time after it is scoured or excavated. The only portion of the lagoon system that has elevations within the intertidal range is the dredged portion of MCL immediately upstream and downstream of Pier Avenue. Much of the Island neighborhood is at elevations of +9 to +10 ft NAVD, which is the same elevation as much of the beach berm that contains AGL.

3.1.1 Beach Profiles and Shoreline Conditions

Figure 9 and Figure 10 display the elevations of beach profiles that were extracted from DEMs (Digital Elevation Models) that reflect topography from May 2010 and December 2011, respectively.[2] The profiles are mapped from the wet/dry line to allow for easy comparison between profiles. Both figures demonstrate that in general, the beach berm in front of AGL slopes downward from north to south (downcoast).

May 2010. In May 2010, the dunes at the mouth of Arroyo Grande Creek (XS1) were relatively high, with crest elevations of up to about +15 ft NAVD. Moving downcoast, beach berm elevations decreased from about +13 ft NAVD (XS2) to a minimum of about +10 ft NAVD (XS6). The inlet at the time was experiencing shallow overflow, and had an invert elevation of approximately +7.5 ft NAVD. South of the lagoon, the beach was narrower, and berm elevations ranged from approximately +8 to +9 ft NAVD, with a backbeach-dune scarp inflection (where the backbeach and foredunes meet) elevation of about +15 ft NAVD. When interpreting the 2010 profiles, it is important to note that the profiles south of the lagoon are less influenced by scour from breach events, as well as the buffering effect of the lagoon on wave overwash. When waves overtop the berm in front of AGL, they slow down and seep into the sand on the berm's

2 December 2011 data is from ESA PWA field surveys; May 2010 data is from the NOAA-OPC California Coastal Mapping Project.

backslope before draining into the lagoon. In contrast, when waves overtop the berm south of the lagoon, they run up the shoreline until they reach the toe of the dunes. This causes local scour at the dune toe, and the scoured sand is deposited on the beach as the wave retreats to the shoreline. Sand from the higher portions of the dune can then collapse from undercutting, moving back into the formerly scoured portion of the dune toe. In this way, the profiles south of the lagoon are fundamentally different from the profiles seaward of the lagoon, and potentially illustrate what the profiles in front of the lagoon might approximate in the absence of the sand management near the Strand.

December 2011. The beach profiles from December 2011 are limited to areas that were surveyed by the ESA PWA field crew, and as such do not extend south of the lagoon. As expected for a winter profile, much of the beach berm in front of AGL in Dec 2011 was lower than the summer profile, ranging between +8 to +12 ft NAVD, with an inlet elevation of about +6 ft NAVD. The December 2011 surveys indicated the presence of a low "saddle" in between higher portions of the beach berm, north of the actual outlet. It's unclear how much of the magnitude of differences between beach berm elevations in 2010 and 2011 were due to inter-annual or inter-seasonal differences in wave action, littoral sand transport, and/or other factors. If the May 2010 profile represents a profile that would have continued to grow over the summer, it's possible that elevations in late fall 2010 were even higher, potentially contributing to the Christmas 2010 floods. The relationship between beach topography and wave action is discussed further below and in Section 3.2.

Factors Governing Beach Berm Morphology. Conceptually, the elevation of the beach berm changes in response to wave action and creek scour. The beach berm builds in the fall as long wavelength, low height waves (low steepness defined by wave height divided by length) move sand into the beach. Wet season rains flood the backbarrier lagoon until the water level exceeds the berm elevation and induces overflow to the ocean. Typically, a relatively large rainfall event induces a more vigorous overflow, which can then scour the beach berm and drain the back-barrier wetlands (see Section 3.2.1 below for a more detailed discussion of the lagoon fill-breach-drain cycle). Beach berm elevations recover as the discharge flowrate recedes; however, the rate of recovery diminishes as the beach berm elevation increases due to less frequent wave runup overtopping and less sediment deposition (Battalio et al. 2006). The rate of recovery is also diminished in the portions of the berm near the most recent inlet location. Since the berm near the inlet is lower, it takes longer to build as more sand has to be deposited from wave action. Groundwater flows can be greater at the relict inlet location as well, further retarding berm growth. Other factors such as the presence of coarse sediment, reduced sediment compaction, and local beach morphology may also contribute to the persistence and formation of low berm locations. As a result, low points in the berm (swales, depressions) tend to persist in areas where an inlet was historically located. This location bias is particularly strong and persistent where mechanical breaching is regularly conducted, which can effectively "train" the mouth morphology. Major changes in inlet morphology and location are typically driven by major storm/runoff events, which can scour inlets in new locations (Figure 5). Relict inlet swales/depressions typically persist until the next year; in the absence of major runoff events, they can last multiple years. While lagoon mouths typically migrate and breach the beach berm over a range of locations, many systems also tend to have a dominant outlet location, which is reinforced over time. In this way, natural and mechanical breaches, as well as other management activities such as dune construction and vehicular traffic, can influence outlet morphology and backbarrier hydrology. Ocean conditions, which are inherently variable and subject to climatic fluctuations such as El Nino (ENSO) and the Pacific Decadal Oscillation (PDO), can also induce variability in the beach berm elevations and flood potential.

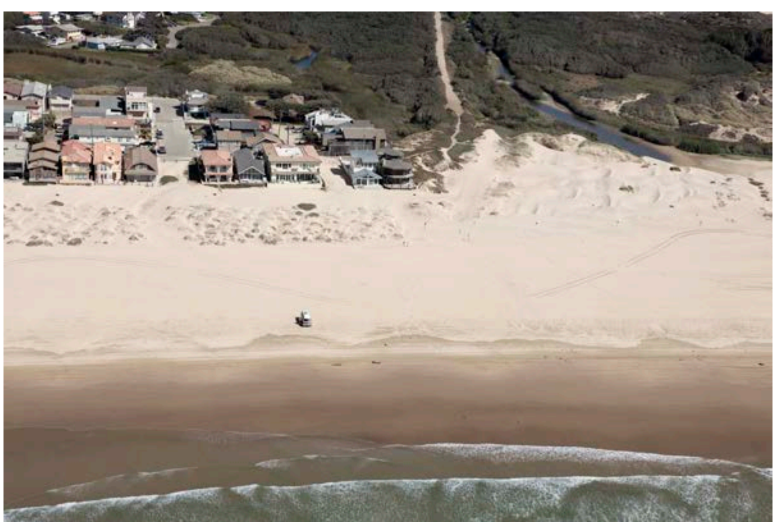
Dune Management at the Arroyo Grande Creek Mouth. As mentioned earlier in Section 2, a history of dune management in front of the Strand and at the mouth of Arroyo Grande Creek may be influencing the elevations of the beach berm in front of Arroyo Grande Lagoon. Oblique aerial photographs dating back to 1972 from the California Coastal Records Project are especially helpful at illustrating how the beach in front of The Strand and Arroyo Grande Lagoon has changed over the past 40 years:

Date unknown, 1972: The 1972 photograph displays limited development in The Strand, and mature vegetated foredunes in front of the homes. The outlet of AGL is actively managed, and heads straight out to sea, in line with the mouth. Most of the ponded lagoon space is in the lower creek channel, which is maintained relatively free of vegetation.

May 4, 1979: By 1979, the Strand was much more built out, and some of the dunes, particularly near the south end, appear to have been leveled off. The lagoon has formed a backbeach runnel, and the outlet (not shown) is well to the south of the mouth.

June 1987: The Strand is completely built out, and the wastewater treatment plant has expanded. Only minimal dune vegetation is observed in front of the Strand. The outlet is still being managed to head straight out to sea. Vegetation management in the lower creek appears to have waned.

Sept. 2, 2002: Active management of the outlet had ceased by 1994, and by 2002, signage had been installed in front of the Strand and the lagoon, likely to protect western snowy plover habitat. A dune in the northernmost portion of the mouth appears enlarged compared to earlier photos, potentially indicating increased wind-blown sand transport to the mouth.



October 11, 2004: Ten years after the cessation of regular breaching, a sizeable dune field has grown at the creek mouth that deflects the outlet to the south. Exclusion fencing installed in front of the Strand has facilitated the growth of small patches of dune vegetation. Mature emergent wetland vegetation has established at the toe of the dunes, in the edge of the lagoon.

September 24, 2010: The effects of the exclusion fencing (now gone) can be seen in the large patches of vegetated foredunes fronting the Strand. The vegetation facilitates dune growth by capturing additional wind-blown sand. Portions of the extensive dune field at the creek mouth have mature dune vegetation, and the outlet (not shown) is well to the south.

The 2012 aerial photograph (Figure 5) displays the sand fencing that is presently used to manage wind-blown sand in front of the Strand neighborhood. In addition, staff from have indicated that in recent years, State Parks has graded a "bowl" near the Pier Avenue off-road vehicle access point, and deposited this sand along the foreshore such that it can move downcoast.

Though available information does not allow for a definitive assessment of the effects of management activities on Arroyo Grande Lagoon beach/dune morphodynamics, we hypothesize that:

1. The dunes in front of the homes are farther seaward and more steep than typical dunes in the area, which is raising the beach berm in front of Arroyo Grande Lagoon, with the effect diminishing with distance southward. This effect could be compounded by further grading/sand placement near Pier Avenue.
2. The beach profiles farther south are representative of "natural" (i.e. unmanaged) beach elevations in the area.
3. The dune management in front of the Strand, coupled with a lack of active breaching since 1994, has resulted in higher berm elevations, and associated higher water levels in AGL.
4. The beach berm elevation is inherently variable owing to the variability of ocean and rainfall conditions, with "high berm" conditions inducing higher lagoon water levels that increase the flood risk in the fall when rains arrive prior to breaching.
5. The cumulative effects of flood control measures throughout the basin (see Section 3.2 below) has reduced scouring that would occur during breaches, and reduced flood storage capacity within the system.

In the aggregate, the changes made to the lagoon system are quite extensive, and have progressively encroached on the lagoon over time. These changes, coupled with limited available data, make it difficult to precisely characterize the lagoon hydrology, particularly whether it is in a state of dynamic equilibrium or a progressive evolution. However, we conclude that the berm elevations that result in flooding are within a range that can be expected to recur, and hence, future flooding is likely under existing conditions.

3.2 Hydrology

As discussed above, the hydrology of the Arroyo Grande – Meadow Creek Lagoon system is significantly altered by human activity. This section describes the fluvial and tidal hydrology at the site. The watershed/fluvial hydrology of Arroyo Grande and Meadow Creek is described in detail in Waterways (2010) and Chipping (1989), respectively, so Section 3.2.2 below focuses on the specific hydrologic analyses that were implemented for this project.

3.2.1 Lagoon Fill-Breach-Drain Cycles

Lagoons in coastal California exhibit a broad range of morphologic and hydrodynamic diversity, from systems that are almost always open to tidal action (e.g. Russian River Estuary in Sonoma County) to systems that close for extensive periods of time in the summer (e.g. Mission Creek Lagoon in Santa Barbara County). Many small lagoons, such as AGL, have inlets that close in the summer due to low watershed flows. This causes water to impound behind the beach berm, forming a mostly freshwater pond perched relative to the tides. Occasionally, wave action will overtop the beach berm, and fill the lagoon even more. This overtopping can cause brackish (and often stratified) conditions to develop in the lagoon, though the salt water often quickly seeps out the berm face. It can also sometimes trigger a breach. When winter rains arrive, watershed runoff causes water surface elevations in the lagoon to rise above those of the beach berm, and the system breaches and drains. Only when (or if) the inlet thalweg scours to intertidal elevations and the fluvial discharge abates can ocean water flood directly enter the lagoon and make it a brackish system. Once storm flows recede, wave action moves sand into the inlet, the beach berm re-builds itself, and water once again begins to pond behind the beach berm. Once the inlet closes, salt water can remain in the bottom of the lagoon, with extensive upstream migration possible due to density and momentum of wave overtopping flows, with limited mixing of fresh surface waters. As in the summer, though, this salt wedge usually seeps out through the beach face over time.

In some systems, such as Arroyo Grande Lagoon, the outlet is frequently in a “shallow overflow” state, called a drainage outlet, where water from the lagoon drains through a small, shallow channel to the ocean (Figure 11). These channels can cause lagoon hydrology to be almost “steady state”, where the amount of water coming in from the watershed is balanced by lagoon outflows, thus causing little relative change in lagoon water levels. According to the Department, AGL frequently has a shallow overflow channel across the broad, gently sloped beach. It is unclear if the presence of this channel is in any way influenced by sand compaction from the movement of vehicles accessing Pismo Dunes SVRA. Future time series monitoring of inlet morphology will be helpful in assessing how the shallow overflow channel influences lagoon hydrodynamics.

3.2.2 Fluvial and Lagoon Hydrology

Arroyo Grande Creek drains approximately 157 square miles of coastal mountains, hills, mesas, and valleys. Lopez Dam, which impounds the watershed’s upper 70 square miles, is located in the creek’s upper watershed, at the confluence of Arroyo Grande Creek and Lopez Creek (Figure

12). The remaining 87 square miles of watershed, including Tar Spring and Los Berros Creeks, flow into Arroyo Grande Creek downstream of Lopez Dam. Meadow Creek has a much smaller watershed of less than 11 square miles, and drains the low coastal hills north of the five cities. Both creeks have a typically coastal California (Mediterranean) climate, with winter rains that arrive in pulses and mostly arid summers.

The Department maintains a network of gages that monitor rainfall and water levels throughout the AGL-MCL system. The gages used in this project's analyses are summarized in Table 1. We used data from these gages to assess the response of lagoon water levels to rainfall events, as well as model the potential response of water levels to inlet management. Appendix A contains a technical memo we produced for the Department in May 2012 that describes our "first cut" at modeling the hydrology and hydraulics of the coupled lagoon system. Our modeling methods and assumptions have since been revised (see Section 3.2.3 below), but the memo nonetheless provides useful background information about the system's hydrology.

TABLE 1
SLOC DPW GAGE SUMMARY

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
795	Oceano	October 1986	Rainfall

ESA PWA acquired data for these gages from the Department and for select time periods plotted water levels against rainfall. We selected these periods because they best illustrate the breach-drain-fill cycle at Arroyo Grande Lagoon, and the response of water levels in Meadow Creek Lagoon to these cycles.

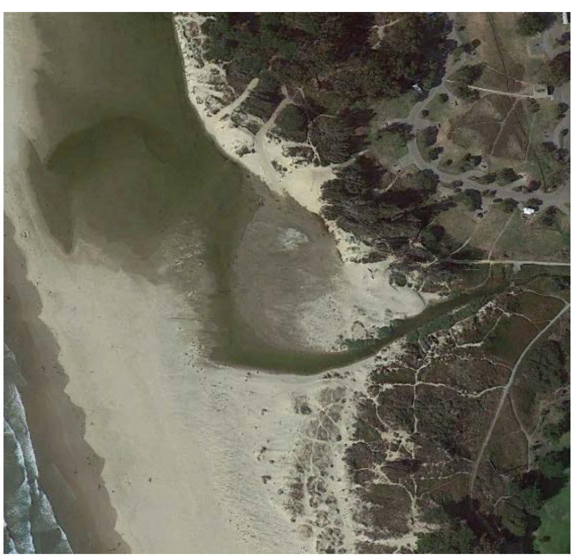
December 2010. The December 2010 storm was notable for the extreme amount of precipitation it dropped in the lower Arroyo Grande Valley below Lopez Dam. The first rains of the December 2010 storm event arrived on December 17 and by December 21 the watershed received 6.48" of cumulative rainfall, with 5.4" of that falling on December 18 and 19. Based on the NOAA Water Atlas, a storm causing 5.4" of rainfall within 48 hours has an estimated recurrence interval of 50 years, indicating that this was an unusually strong rainfall event (Perica et al. 2011). The peak cumulative rainfalls for additional durations, and the respective recurrence intervals for those events, are listed in **Error! Reference source not found.**Table 2.

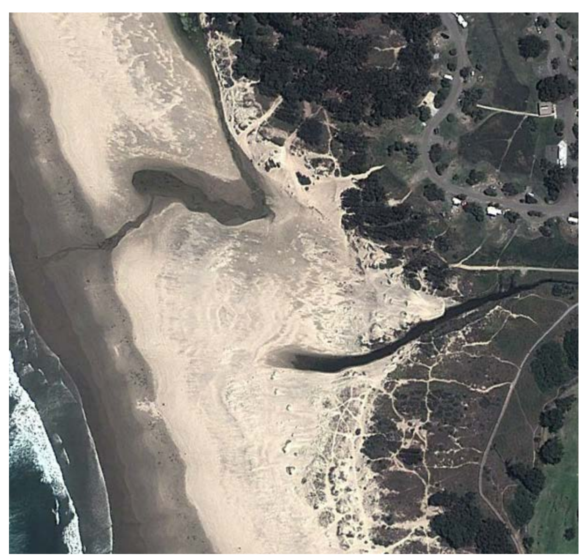
TABLE 2
PEAK CUMULATIVE RAINFALLS AND RECURRENCE INTERVAL
FOR THE DECEMBER 2010 STORM EVENT

Storm Duration	Inches of Precipitation (December 2010 Event)	Recurrence Interval (NOAA Water Atlas)
24 hr	3.2”	10 yr
48 hr	5.4”	50 yr
72 hr	6.5”	25+ yr

At the time, there were no gauges in MCL, so the storm can only be described anecdotally and with data from AGL (Figure 13). The data indicate that prior to the arrival of the storm system on December 17th, water levels in AGL were around +9.5 ft NAVD. Anecdotal reports describe a saturated watershed that quickly turned precipitation into storm runoff, rapidly raising water levels in MCL to more than +12 ft NAVD before AGL could breach (J. Ogren, pers. comm.). Homes in the Island neighborhood begin to flood around approximately +10 ft NAVD, so many homes were flooded with multiple feet of water. The data indicate that AGL did not breach until December 19th, when water levels rose above +10 ft NAVD. The lagoon rapidly drained, and after a brief period of rapid water surface elevation (WSE) oscillations driven by drainage and wave overtopping, water levels in AGL stabilized at about +7.3 ft NAVD. Our analysis of other flooding events (see below) indicates that at the time, water levels in MCL most likely also stabilized at a similar elevation.

The December 2010 flood reportedly “blew out” the Carpenter Creek outlet (M. Hutchinson, pers. comm.), which is not gauged. It is unclear what proportion of flows from the Meadow Creek watershed exited at Carpenter Creek instead of flowing downstream into MCL. Aerial photographs collected since the December 2010 storm indicate that water continues to flow out of the Carpenter Creek outlet, even during the summer and fall when surface flows are generally at their lowest (see photographs below).





Carpenter Creek outlet: Aerial photographs from September 17, 2011 (L) and May 15, 2012 (R) show the Carpenter Creek outlet (bottom) and the Pismo Creek outlet (top; merged with the Carpenter Creek outlet in the 2012 photo). Photos from 2002-2010 show an outlet that is either completely dry, or with much less water than the amount seen here after the December 2010 storm. Photos from Google Earth.

March 2011. Following the devastating December 2010 floods, installed two new gages in MCL: the upstream gage at Pier Avenue, and the downstream gage at the Sand Canyon flapgates. Prior to the next storm's arrival in March 2011, WSEs in lower MCL and AGL were at approximately +7.3 ft NAVD. Though the Sand Canyon flapgates are two 48-inch culverts with invert elevations at approximately +6.5 ft NAVD, the similarity of the water levels indicate that they were not fully sealed, and that water was able to move between AGL and lower MCL. The flapgates have a metal-metal closure surface, so some leakage through a closed gate is normal. The similarities between water levels in AGL and lower MCL indicate that backflow from AGL into MCL could be occurring under certain conditions, but this needs to be investigated further. Water levels in upper MCL were at about +8.6 ft NAVD, more than half a foot higher than the lower lagoon. These two observations – the similarity in water levels between lower MCL and AGL, and the head difference between upper and lower MCL – would persist in almost all the lagoon water level data analyzed as a part of this project, except during storm events that would close the Sand Canyon flapgates. It is not clear what is driving the head difference in MCL, though Department staff have indicated that persistent beaver dams or a sandbar uncaptured by recent bathymetric surveys may be to blame.

The next major storm to arrive was in March 2011, where over 3 inches of rain fell over 4 days (roughly between a 1-yr and 2-yr storm [Perica et al. 2011]). The arrival of rains on March 18th caused water levels to rise, and on March 20th, a particularly large slug of rain caused water levels to spike at all three lagoon gages (Figure 14). Water levels in AGL went from about +7 to +9.8; at lower MCL, they rose from about +7.5 to +9. Since lower MCL peaked at +9 while AGL rose to +9.8, the Sand Canyon flapgates were closed with minimal leakage, with no apparent backflow from AGL into lower MCL (data from subsequent storms would further support this hypothesis). AGL breached at +9.8 ft NAVD, and water levels rapidly decreased as the lagoon drained. Water levels in lower MCL also decreased, implying that the flapgates opened, but this drainage was accompanied by oscillations in the data that could be attributed to inflow due to high total water levels (TWLs) during high tides. At upper MCL, water levels peaked slightly later than at AGL and lower MCL, and did not drain until March 21st. Water levels at upper MCL drained to their former level of +8.6 ft NAVD, more than a foot above levels in lower MCL and AGL.

Water level data throughout much of the rest of 2011 is difficult to analyze due to gage malfunction, particularly at the lower MCL station. We therefore used the 2012 data to analyze how the lagoons behave while transitioning from the summer-fall dry season into the winter-spring wet season.

2012-2013. Throughout most of early-mid 2012, water levels in lower MCL and AGL tracked each other similarly, though lower MCL peaks would never reach as high as AGL peaks in response to precipitation events (Figure 15). Early 2012 provided some examples of times when water levels in AGL (and lower MCL) would rise without precipitation inputs. It's not clear if these increases were due to wave overtopping, or a temporarily closed inlet that caused water to back up behind the beach berm. At upper MCL, water levels would rapidly rise in response to storm events (but rarely above +9 ft NAVD), and then gradually decrease over the course of a week or two.

Throughout the summer of 2012, AGL and lower MCL tracked each other closely through the flapgates, ranging between +7.3 to a little over +8 ft NAVD. Upper MCL stayed relatively constant, at around +8.5 ft NAVD (plus or minus a tenth or two throughout the summer). Anecdotal reports indicate that AGL had a shallow overflow channel for much of the summer (M. Hutchinson, pers. comm.), so water level variation in AGL-lower MCL was driven by more water entering the lagoon (from either Arroyo Grande Creek or wave overtopping) than was leaving the lagoon (through the shallow overflow channel).

On October 11th, the AGL inlet closed, and water began to impound behind the closed beach berm. Water levels in both lower MCL and AGL rose until October 16th; after then, water levels in AGL continued to rise, but levels in both upper (+8.5) and lower (+8.3) MCL stayed constant. Overnight on November 10th, AGL breached at an elevation of about +9.3, most likely artificially as a result of human activity. As soon as AGL water levels dropped below +8.3 ft NAVD, lower MCL began to drain, indicating that the flapgates opened. Though water levels in AGL and lower MCL dropped to +7.5 ft NAVD in a matter of hours, levels in upper MCL remained unchanged. Over the next few weeks, the lagoon inlet would continue to stay open/choked, until late November/early December when another storm system would cause AGL levels to rise high enough to fully seal the flapgates. In mid-December and early January, wave overwash on high tides would cause twice-daily water level spikes in AGL and MCL, though water levels at MCL would not get as high as in AGL, potentially due to flapgates closing on a flood tide and draining on a receding tide. Throughout all of these events, water levels in upper MCL remained virtually unchanged. Water levels in upper MCL did increase in response to precipitation events, but only slightly, and very, very gradually.

Our analysis of the AGL-MCL gage record has led us to the following conclusions about system hydrology and hydraulics:

1. **The primary driver of water levels in lower Meadow Creek Lagoon appears to be water levels in Arroyo Grande Lagoon**, not precipitation in the Meadow Creek watershed. Water levels in lower MCL and AGL track each other very closely until they reach +8.3 ft NAVD, at which point lower MCL appears to stabilize while AGL can continue to rise. This could potentially indicate complete flapgate closure at +8.3 ft, or backflow from lower MCL into upper MCL across a drainage divide. Precipitation in the Meadow Creek watershed can occasionally cause water levels in both upper and lower MCL to rise (see data from Jan 6-7, 2012), but the precise set of conditions under which this occurs is not clear. *If backflow from AGL to lower MCL through the flapgates is confirmed by future work, limiting it could help reduce the flood risk around MCL if water levels between upper and lower MCL were equalized (see below).*
2. **Water levels in upper Meadow Creek Lagoon appear to be relatively unaffected by water levels in the lower lagoon**. When AGL experienced a major breach in early November 2012 that caused water levels in lower MCL to drop by a foot in a matter of

hours, water levels in upper MCL were not measurably affected. This pattern is consistent throughout 2012; the only factors that seem to influence water levels in upper MCL are precipitation events – and even then, there are many rain events in the record that have no discernable effect on upper MCL water levels. Beaver activity or some other morphological feature has effectively divided MCL into two separate reservoirs. *Flood risk around MCL could be reduced if water levels within the lagoon could consistently equalize to the lower elevations typically observed in lower MCL.*

3. **Carpenter Creek may be acting as an active flood bypass for Meadow Creek Lagoon.** Precipitation in the Meadow Creek watershed has to flow somewhere, and if significant proportions of it are not flowing into the lagoon, they may be leaving the system through Carpenter Creek. This is consistent with observations by the Department that the Carpenter Creek outlet was cleared out by the 2010 flood, and evidence from aerial photographs taken since 2010. In addition, recent activities by California State Parks to remove vegetation from the outlet (M. Hutchinson, pers. comm.) could also increase the amount of water that can flow through and bypass the lagoon. *Maintaining Carpenter Creek as a flood bypass could help reduce the flood risk around upper MCL, by reducing the potential for water to back up around the lagoon.*
4. **The Sand Canyon flapgates may not close at their invert elevation of +6.5 ft NAVD.** The Sand Canyon flapgates are dual 48” flapgates with an invert at +6.5 ft NAVD, yet water level data indicates that they may not close until water levels reach +8.3 ft NAVD. *Managing the flapgates so that they more effectively close at +6.5 ft NAVD could help to reduce flood risk in lower MCL by reducing the amount of water that enters the lagoon from AGL. This reduction, however, would likely be minimal if only the small area around the flapgates reflected the lower MCL gage data (and the rest of the lagoon reflected the upper MCL gage data).*

Figure 16 displays an elevation profile of the AGL-MCL system, from the Pacific Ocean, through the Sand Canyon Flapgates, up to near Pier Avenue. The figure displays the approximate elevations of the thalwegs through AGL and MCL, as well as the typical water levels that were encountered throughout the 2012 dry season. The implications of the AGL-MCL gage record are discussed further below and in Section 4, Opportunities and Constraints.

3.2.3 HEC-RAS Modeling

Throughout 2012 and 2013, we developed a preliminary HEC-RAS model of the coupled Meadow Creek Lagoon – Arroyo Grande Lagoon system, for the purposes of characterizing the relationship between the inlet/outlet of AGL and water levels (and thus flood risk) in MCL. We implemented two rounds of HEC-RAS modeling – one in spring 2012, and a second, revised round in summer 2013.

First Round of HEC-RAS Modeling. The methods and results of our first round of HEC-RAS modeling are detailed in a previous deliverable to the County (Appendix A), and summarized below.

- **Model Domain.** ESA PWA adapted an existing HEC-RAS hydraulic model of AG Creek developed by Waterways (2011). The original model, which contained AG Creek from the mouth to approximately 1,000 feet upstream of Fair Oaks Avenue, and Los Berros Creek from AG Creek to approximately 600 feet upstream of Century Lane, was expanded to include Meadow Creek Lagoon and AG Lagoon. The upstream limit of the model was truncated on AG creek at 22nd Street, excluding Los Berros Creek from the hydraulic model. The updated model domain is summarized in Table 3.

TABLE 3
HEC-RAS MODEL DOMAIN

Reach	Extent
Arroyo Grande Creek	Confluence with Meadow Creek Lagoon to the 22nd Street bridge
Arroyo Grande Lagoon	Ocean outlet to confluence with Meadow Creek Lagoon[1]
Meadow Creek Lagoon	Confluence with Arroyo Grande Creek to approximately 2,300 feet upstream of Pier Avenue[2]

[1]Ocean breach geometry modeled as outflow weir
[2]Includes culvert and flap-gate configuration connecting Oceano and AG lagoons

The expanded elements of the model, which include the Meadow Creek and AG Lagoons, the culverts connecting Meadow Creek Lagoon to AG creek, and the breach geometry at the AG lagoon outlet, were developed using HEC-GeoRAS, a GIS based tool that allows for the transfer of georeferenced topographic and hydraulic feature information between GIS and HEC-RAS. The topographic data used to extract cross-section topography was developed from survey data collected by ESA PWA and Cannon Engineers (2011) and tied into LiDAR data and existing contour information as described in Appendix A.

- **Model Calibration and Boundary Conditions.** The hydraulic model was run for the storm event that occurred over January 20-22, 2012 and calibrated to measured data at gauges on Arroyo Grande Creek and Meadow Creek Lagoon. The model contains two upstream boundary conditions requiring inflow hydrographs: 1) on AG Creek at 22nd Street, and 2) at the upstream end of Meadow Creek Lagoon. The gauge on AG Creek at 22nd Street was used to estimate inflows at the upstream limit of this reach using a rating curve developed by the SLO County Public Works Department and provided to ESA PWA in 2012. For flow into Meadow Creek Lagoon, the change in storage can be used as a surrogate for inflow during periods where the lagoon was not draining. Model calibration demonstrated general agreement between modeled and measured water levels, with the exception of Pier Avenue water levels, which appeared to be affected by the afore-mentioned drainage divide between Upper and Lower Meadow Creek Lagoons, and the potential backflow of water upstream through the Sand Canyon Flapgates from Arroyo Grande Lagoon. The model did not consider flows through the Carpenter Creek outlet.
- **Breach Scenarios.** In order to characterize how various configurations of the AG Lagoon breach influence water levels in Meadow Creek Lagoon, model runs were constructed for two flooding events: one on March 20-21, 2011 and another for the Christmas 2010 event that flooded low-lying homes around Meadow Creek Lagoon. For both events, boundary inflows were estimated using the same methods as for the calibration event. The March 2011 event modeled unsteady hydrographs with peak flows of 247 cfs in Meadow Creek, and 942 cfs in Arroyo Grande Creek. The December 2010 event modeled unsteady hydrographs with peak flows of 106 cfs in Meadow Creek, and 1381 cfs in Arroyo Grande Creek. The Meadow Creek hydrograph for the December 2010 event was developed by scaling the estimated flows in Arroyo Grande Creek by the ratio of the drainage areas of the two creeks.

- **Model Results.** The first round of HEC-RAS modeling indicated the following:
  - For storm events similar to the one experienced in March 2011 (roughly a 1- to 2-yr storm), an inlet invert elevation of +9.5 ft NAVD or below would likely reduce the flood potential around Meadow Creek Lagoon.
  - For more significant storm events such as the December 2010 storm, it was less clear what inlet invert elevation would reduce flood potential, as the HEC-RAS model was unstable at inlet elevations below +7 ft NAVD.
  - Increasing the storage volume in Meadow Creek Lagoon would likely reduce the flood risk for relatively smaller storms. It is not clear that additional storage in MCL would provide additional protection against flooding from the type of significant storm experienced in December 2010.
  - Modeling refinements, particularly to the input Meadow Creek hydrograph, could help improve the utility of the model.

Second Round of HEC-RAS Modeling. In summer 2013, we implemented various refinements to the HEC-RAS model, based in part on the recommendations described in Appendix A and an analysis of water level data through the winter of 2012-2013. These refinements included:

- Modeling Meadow Creek Lagoon as two separate flood basins, Upper MCL and Lower MCL, based on observed gage data through 2013.
- Allowing water in the model to flow upstream through the Sand Canyon Flapgates from AGL to MCL, up until water levels in AGL reached +8.3 ft NAVD.
- Adjustments to the physical configuration of the AGL outlet geometry to improve model stability for a wider range of breach elevation scenarios.

The results of these refinements were mixed. Separating MCL into two lagoons based on a sill elevation observed in the topo data made it difficult for the model to account for storage upstream in Meadow Creek Lagoon; the model would tend to overestimate spillage from the upper lagoon and generate inaccuracies from observed data. Adjusting the flapgate operation had little observed effect on modeled results, which is likely related to the multiple other assumptions about system hydrology that are inherent in the model.

The adjustments to the modeled AGL outlet were more helpful, and indicated that for a storm event similar to the December 2010 event, drainage from Meadow Creek Lagoon was much improved when AGL had an inlet invert elevation of +8 ft NAVD. The model estimated that only incremental improvements in drainage could result from inlet elevations below +8 ft NAVD, which is consistent with the fact that total water levels (see below) associated with high tides are typically between +6 and +8 ft NAVD and that the AGL lagoon inlet appears to only infrequently (after storm events) scour to below +7-7.5 ft NAVD (judging from the minimum AGL water levels seen in Figure 15).

3.2.4 Waves and Tidal Hydrology

Aside from fluvial hydrology, tidal and coastal processes are among the other primary drivers of flood hydrodynamics at Arroyo Grande and Meadow Creek Lagoons. This section discusses the tidal characteristics of the site as well as wave action, total water levels, and the relationship between coastal processes and beach berm morphology.

Tides. Like all coastal California beaches, the beach at Arroyo Grande Lagoon has mixed diurnal tides, or two daily high and low tides of unequal value. Tidal datums for the local area are provided below in Table 4.

TABLE 4
TIDAL DATUMS ALONG THE ARROYO GRANDE LAGOON SHORELINE

Datum	Elevation (ft NAVD)
Mean Higher High Water (MHHW)	5.25
Mean High Water (MHW)	4.54
Mean Tide Level (MTL)	2.75
Mean Sea Level (MSL)	2.72
Mean Low Water (MLW)	0.96
Mean Lower Low Water (MLLW)	-0.08

Notes: Data from NOAA CO-OPS Station # 941-2110, Port San Luis.

Waves. Coastal lagoon systems are formed by the action of waves acting to build up a berm along the beach. This berm traps stream flow from the upland watershed, forming a ponded lagoon. These lagoons are highly dynamic systems that can change quickly in response to shifting wave and watershed conditions. Over the course of the year the beach berm will grow or shrink and the lagoon may open or close depending on wave condition and stream flows. Water levels within the lagoon are closely linked to the elevation of the beach berm. When the lagoon mouth is closed the berm crest acts as a sill, and the lagoon water levels will rise until they overtop or nearly overtop the berm crest. When the lagoon mouth is open, a channel will form where the berm erodes due to the scouring effect of flow from the lagoon into the ocean.

High water levels occur within coastal lagoons when rainfall runoff increases. The highest elevations occur when there is a large rainfall event while the beach berm elevation is high, before breaching. Waves can contribute to both the growth and erosion of the beach berm, depending on the frequency and height of the waves incident to the beach. The USACE Shore Protection Manual lists criteria for determining whether particular wave conditions will cause accretion or erosion based on the beach slope, grain size and offshore wave height and length (USACE 1984). Based on these criteria, we observe that steeper waves (larger amplitude relative to wave length) tend to cause erosion while flatter waves lead to accretion. We compare this criterion with wave data collected at the SCRIPS wave buoy #46218, located off of Point Conception. The record for this buoy shows that the steepest waves tend to occur during the winter and spring season, while waves in the summer and fall are generally flatter. This leads to our conceptual understanding, also supported by observations of numerous other lagoons and beaches in Central California, that for beaches along the California coast waves typically act to build up the berm elevation except for during very large storm events. Due to the strong seasonality of storm systems striking the California coast we find that beach berms generally accrete gradually during the spring, summer and fall seasons and then may experience punctuated erosion during a few winter storm events each year, and lower through the spring before beginning to recover.

Coastal Conditions During the December 2010 Storm Event. The flooding which occurred at Meadow Creek Lagoon in December 2010 was a result of an unusually intense rainfall event occurring early in the winter season, before the large beach berm that accreted during the previous summer had a chance to erode. There were several small rain events in the two months leading up to the flood event, with a cumulative rainfall of ~6 inches, however these small storms were not accompanied by erosive wave conditions and none of these early season storms created sufficient watershed discharge to breach the lagoon. Consequently the beach berm remained high, and water levels within both Arroyo Grande and Meadow Creek Lagoons were perched well above mean higher water during the weeks leading up to the December storm (Figure 13).

A comparison of the aerial photos in Figure 5 dated 6/17/2009 and 8/23/2010 shows the growth of the beach berm leading up to the flood event. In 2009 the lagoon stretches ~200 ft from the toe of the dune towards the shore, however in 2010 the berm has encroached inland, leaving only 120ft of open lagoon between the berm and the dune. In addition, a LiDAR survey flown in by the California Coastal Conservancy in May 2010 shows the beach berm crest elevation at 12-13.5 ft NAVD (Figure 9). This is nearly 3 feet higher than the berm crest surveyed on December 1, 2011 by ESA PWA (Figure 10). The aftermath of the flood event can be seen in the image dated 9/17/2011 (Figure 5). In this image, taken a full 9 months after the flood event, the remnant breach at the creek mouth is still visible. This is the location where the energetic flow from the creek punched through the beach berm. By the time of the image, the elevations of the beach berm have mostly recovered, closing the northern breach and redirecting the lagoon towards its more typical breach alignment located farther to the south of the creek mouth. However, the photo indicates that limited wave overwash is still able to enter the lagoon in the location of the former breach, indicating that this area is still lower than much of the rest of the berm.

Quantified Conceptual Model. We developed a quantified conceptual model (QCM) of the processes which affect the growth and erosion of the beach berm at Arroyo Grande Lagoon. The QCM is used to illustrate the relative importance of wave and watershed forces in building and eroding the beach berm over time. The QCM was developed based on historic monitoring data and published parameterizations of the key physical processes driving the berm elevation. The QCM considers offshore wave conditions, tide elevation, and watershed discharge. The model has been tuned based on a limited number of topographic surveys and a 4-year long continuous dataset from the Arroyo Grande Lagoon water level gage. Details about the QCM setup are provided in Appendix B.

The QCM provides a useful tool for understanding the role that different processes could have potentially played in shaping the beach berm and influencing lagoon water levels. The model demonstrates that preceding events and wave conditions can potentially drive elevated or lowered berm elevations that cannot be easily explained just by considering the current conditions or from the water level record. For example, the model results indicate the growth of an elevated berm crest during the summer leading up to the flood event in December 2010. This conclusion is supported by the May 2010 LiDAR data collected by NOAA (Figure 9), which indicate the presence of a relatively high berm in front of Arroyo Grande Lagoon. The predicted berm elevations from the model show the berm tracking closely with AGL water levels through the winter and spring of 2010. Then, during the fall of 2010, the beach experiences a series of high wave run-up events which can contribute to the formation of an elevated berm crest. In other years, November and December brought about the return of erosive waves, which lower the berm elevation and facilitate breaching of the berm with storm flows. However, the model indicates that erosive waves in early winter 2010 were likely smaller than usual, and as a result the high summer berm crest likely persisted into late December. This elevated berm was likely problematic when the December storms arrived, because it increased the elevation to which water levels in Arroyo Grande Lagoon would have to rise in order to breach the beach berm and facilitate the opening of the Sand Canyon Flapgates, and the drainage of Meadow Creek Lagoon. In the time it took for water levels in Arroyo Grande Lagoon to breach the berm, water levels in Meadow Creek Lagoon rose to flood levels due to the lack of flood storage volume in the full lagoon.

3.3 Biological Communities

Habitats at Arroyo Grande and Meadow Creek Lagoons encompass a broad range of costal/estuarine wetland communities, including open water, dune, emergent wetland, and riparian thicket. Figure 18 presents a map of habitats in and around Arroyo Grande Lagoon, and Figure 19 presents a map of Meadow Creek Lagoon habitats that was prepared by Terra Verde Environmental Consulting (2012). The Terra Verde report provides detailed descriptions of plant, fish, and wildlife communities on the site; the material in this section is based on that report as well as our own observations of the site over the past year and a half.

3.3.1 Beach

Beaches in the project area are a highly dynamic environment that is subject to change on daily, seasonal, and intra-annual scales. Though some of this change is driven by natural processes, such as wind, waves, and creek storm flows, human activities such as use of the beach by cars, trucks, and off-road vehicles also create disturbance. As a result, the unconsolidated sand on the beach shifts too frequently to support many vascular plants.

Beach food webs are supported by subsidies from adjacent habitats. Among the most important of these are plankton, which feeds suspension feeding sand crabs and clams low on the beach, and buoyant kelp wrack, which feeds deposit feeders (beach-hoppers) near the high tide line. These abundant and diverse intertidal invertebrate animals support a variety of fish during high tides, and large numbers of shorebirds between fall (July-October) and spring migration (March-May). Lower beach invertebrates may be suppressed by freshwater seeping through the beach face immediately below the lagoon.

The ample supply of food and gentle beach slopes have resulted in the local beaches providing roosting and foraging habitat for a broad variety of shorebird species. The project area is listed by the USFWS as Critical Habitat for the Western snowy plover (*Charadrius nivosus nivosus*). The beach also provides roosting habitat for gulls, terns, and their allies. However, use of the beach by all bird species is limited by the disturbance of vehicular traffic accessing the Oceano Dunes SVRA.

3.3.2 Coastal Strand and Dune

Coastal strand and dune is found along the western edges of both AGL and MCL, between the unvegetated beach and open water lagoon areas. Coastal strand and dune vegetation traps blowing sand during strong winds, building low hummocks near the shoreline and taller dunes further inland. These systems are typically more stable inland (often landward of a foredune ridge) with increasing numbers of plant species further from the beach.

At Meadow Creek Lagoon, coastal strand and dune habitat includes broad areas dominated by non-native, invasive species: iceplant (*Carpobrotus edulis*) mat and European beach grass (*Ammophila arenaria*) swards (TerraVerde 2012). The dense growth of these species minimizes migration and movement of the dunes, "cementing" them in place and preventing the establishment of native dune species. On the contrary, the foredunes at the mouth of Arroyo Grande Creek are much more dynamic, and are sparsely vegetated by species such as American dune grass (*Elymus mollis* spp. *mollis*), sea rocket (*Cakile maritima*), beach-bur (*Ambrosia chamissonis*), and others. In wetter areas near the lagoons, a variety of wetland plants may occur along with typical coastal strand and dune plants (e.g. saltgrass, *Distichlis spicata*).

Dunes support roosting by many of the same bird species that use the beach, particularly Western snowy plover, which prefer to nest in sparsely vegetated foredunes. Accordingly, the dunes at the mouth of Arroyo Grande Creek are roped off to protect any potential nesting that may occur.

3.3.3 Emergent Wetland

Emergent wetland habitat within Meadow Creek and Arroyo Grande Lagoons is dominated by two vegetation communities: bulrush (*Schoenoplectus californicus*) marsh and Pacific silverweed (*Potentilla anserina*). Bulrush marsh dominates much of MCL as well as the emergent marsh areas around AGL. These areas are more or less constantly inundated with water, and support associated species such as Olney's three-square bulrush (*Schoenoplectus americanus*) and broad-leaved cattail (*Typha latifolia*). Silverweed marsh is limited to an area along the eastern edge of MCL, and is inundated relatively less frequently. It includes species such as sand dune sedge (*Carex pansa*), salt grass, and marsh baccharis (*Baccharis glutinosa*).

At MCL, emergent wetland habitats are highly stable due to the lack of scouring flows or other disturbances that would displace or bury emergent vegetation. Emergent wetland habitats at AGL are more dynamic, as they are subject to scouring flows from Arroyo Grande Creek as well as wave overwash from the Pacific Ocean.

The emergent marsh supports a broad range of birds, reptiles, and amphibians, which are described at length in the 2012 TerraVerde report. Special-status species that utilize emergent wetland habitats include California red-legged frog (CRLF, *Rana draytonii*) and Western pond turtle (WPT, *Actinemys marmorata*). Emergent wetland also supports fish and other species that live in the open water areas of MCL and AGL. The tall wetland plants shade the water column, creating cooler temperatures (which can help support higher dissolved oxygen levels), and directly contribute productivity to the aquatic food web. The relatively small amount of emergent marsh along the fringes of AGL could limit the food web support the lagoon can provide to fish and other aquatic species. Finally, emergent marsh in both MCL and AGL helps to improve water quality by facilitating the removal or sequestration of pollutants such as nitrogen, phosphorus, heavy metals, and complex organic compounds.

3.3.4 Riparian Thicket

As previously discussed, the infrequency of scouring flows in both Meadow Creek and Arroyo Grande Lagoons has facilitated the establishment of dense riparian thickets in lower AG Creek as well as the fringes of MCL. These thickets encourage the further accretion of sediment in the creek channels and support a broad variety of birds, mammals, reptiles, and amphibians, which are described at length in the 2012 TerraVerde report. The riparian thickets are comprised primarily of arroyo willow (*Salix lasiolepis*), with other species including California wax myrtle (*Morella californica*), coast live oak (*Quercus agrifolia*), and twin berry (*Lonicera involucrata*). Portions of the thickets are classified by TerraVerde as “coastal brambles” and are dominated by California blackberry (*Rubus ursinus*). Poison oak (*Toxicodendron diversilobum*) is common in both the willow and blackberry thickets.

One species of note in the riparian areas is the robust resident population of American beaver (*Castor canadensis*), which has been known to construct dams within lower AG Creek as well as lower MCL. Staff from the Department report that after beaver dams in these areas are removed, they are quickly rebuilt by the beavers, in some cases within a day (M. Hutchinson, pers. comm.). These dams may be the root cause of the persistent higher water level elevations in upper MCL relative to lower MCL.

3.3.5 Open Water Lagoon

Though they are hydraulically connected through the Sand Canyon flapgates, the open water communities in Arroyo Grande and Meadow Creek Lagoons are quite different due to differences in hydrology and water quality. Though AGL is a perched lagoon that is primarily freshwater, wave overwash creates ephemeral brackish conditions that support estuarine species such as Pacific staghorn sculpin (*Leptocottus armatus*), three-spine stickleback (*Gasterosteus aculeatus*), and the federally endangered tidewater goby (*Eucyclogobius newberryi*). Yearly surveys by CDPR fisheries biologists indicate that the tidewater goby population may be locally extirpated in AGL by large flood events, but there are multiple records of goby re-colonizing the lagoon. For example, while no gobies were found in the lagoon in 2011, after the December 2010 and March 2011 flood events (Rischbeiter 2011), surveys by TerraVerde and Rischbeiter in 2012 indicated that gobies were abundant.[3] The CDPR surveys have also noted the persistence of federally threatened south-central California coast steelhead (*Onorhynchus mykiss*) smolts in the lower creek/lagoon; the 2011 surveys found for the first time young of year (YoY), indicating that steelhead were successfully spawning in the lower reaches of the creek (Rischbeiter 2011). The

3 Rischbeiter 2012 states “It has not been determined if tidewater goby ‘recolonized again’ following a repeated extirpation during the December-March 2011 floods, or if they had persisted through those floods and simply had gone undetected until late in 2011 due to low numbers.” In either case, the numbers of observed tidewater goby in the lagoon were estimated in the hundreds of thousands by Sept. 2012, the highest numbers for this species ever recorded in Arooyo Grande Lagoon since regular monitoring commenced in 2003.

presence of YoY continued in 2012 (Rischbeiter 2012). This spawning is notable given that the middle reach of Arroyo Grande Creek (between the lagoon and the upper watershed's hillslopes often runs dry, indicating that lower creek and lagoon flows are primarily supported by shallow groundwater. The lower creek and lagoon are both listed as critical habitat for tidewater goby (USFWS 2005) and south-central California coast steelhead (NMFS 2005).

The extent of aquatic habitat in AGL is primarily driven by whether or not the inlet is open or closed (closed inlet = more ponding of water behind the beach berm), as well as aggradation of the lagoon bed (more aggradation = shallower depths). The morphology of the lagoon can influence water quality, particularly stratification and its effects on dissolved oxygen. Though no water quality data was collected as part of this study, a review of historic annual photographs indicates that AGL frequently experiences summer algal blooms, indicating that the lagoon is eutrophic (artificially enriched with nutrients, particularly nitrogen and phosphorus). This eutrophication is most likely driven by agricultural runoff that enters Arroyo Grande Creek from the extensive farms in the Cienega Valley, as well as "nuisance" flows from urban areas. In the last 20 years, the lagoon has tended to form a long, narrow backbeach runnel pinned between the beach and the tall Oceano Dunes. In our experience, such lagoons are likely to be shallow, well-mixed, and warm, with infrequent salinity-driven stratification caused by wave overtopping of the beach berm (this marine water likely seeps out quickly through the beach face, though, so salinity-driven stratification is likely to be short-lived). In such systems, aquatic habitat is typically more favorable for fish in the upstream reaches of the lagoon, where deeper depths and shading from emergent wetland and riparian vegetation support cooler water temperatures and higher dissolved oxygen levels. The results of annual fisheries surveys by CDPR support this hypothesis, as greater fisheries diversity/numbers (including listed species) have been observed in the upper lagoon reaches near the mouth, and lower diversity/numbers have been observed in the downstream reach near the inlet (Rischbeiter multiple years).

In contrast with AGL, MCL is a wholly freshwater lagoon with a fish community dominated by non-native species such as centrarchids (bluegill, *Lepomis macrochirus*, and largemouth bass, *Micropterus salmoides*), golden shiner (*Notemigonus crysoleucas*), and western mosquitofish (*Gambusia affinis*). Crayfish (*Pacifastacus* spp.) and bullfrogs (*Lithobates catesbiana*) are also abundant. The presence of non-native fish communities is most likely due to a history of stocking for fishing events, as well as the release of bait fish (Smith 1976). Native species such as three-spine stickleback are present in limited numbers, especially in the shallower portions of the lagoon closer to the flapgates (TerraVerde 2012).

Open water portions of both MCL and AGL lagoons support a suite of migratory and resident wading birds, waterfowl, and shorebirds, which are described in detail in the TerraVerde report.

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4 CONSTRAINTS AND OPPORTUNITIES

Given the information presented above in Sections 2 and 3, there are multiple constraints and opportunities for flood management at Arroyo Grande Lagoon. Both help define the parameters of the interim sandbar management plan described in Section 5. There are a number of constraints and opportunities that are not addressed here, because these are beyond the scope of interim sandbar management.

4.1 Constraints

Constraints to flood management at Meadow Creek and Arroyo Grande Lagoons include:

1. **Base flood elevations.** Homes and infrastructure around Meadow Creek Lagoon were built on top of the former backbarrier lagoon, placing them in the direct path of flooding. These structures have very low base flood elevations relative to typical water level elevations in MCL, AGL, and the Pacific Ocean (Figure 16). This fundamental constraint will only become more severe as sea levels rise, increasing the base elevation to which AGL and MCL can drain.
2. **Historic flood management.** The development of the area around Meadow Creek Lagoon was facilitated by a) the construction of the Arroyo Grande Creek flood control levees and installation of the Sand Canyon Flapgates in 1959, and b) mechanical breaching of the Arroyo Grande inlet between 1960 and 1980. Now that artificial breaching is largely not permitted by regulatory agencies, the conditions that facilitated development are no longer present, which has likely increased the flood risk of the developed areas.
3. **Aggraded nature of creek/lagoon system.** The development of portions of Meadow Creek Lagoon, coupled with the decreased frequency of scouring flood flows (due to Lopez Dam construction in 1969), increased sediment delivery (from watershed urbanization), and the growth of dense emergent wetland and riparian vegetation communities has resulted in a highly aggraded creek/lagoon system that is choked with fine sediment. This system has no clear flow paths for floodwaters, especially upstream of MCL, and the high hydraulic roughness of lower MCL may impede efficient drainage to the Sand Canyon Flapgates.
4. **Flows through the Sand Canyon flapgates, and the Meadow Creek Lagoon drainage divide.** Water level data suggests that the Sand Canyon flapgates may not fully shut until water levels in AGL reach +8.3 ft NAVD, instead of their invert elevation of +6.5 ft NAVD. Flows between lower MCL and AGL track each other closely until water levels in AGL reach +8.3 ft NAVD. At that point, water levels in lower MCL tend to stabilize, while water levels in AGL can continue to rise. Water does not appear to drain out of lower MCL until water levels in AGL drop below +8.3 ft NAVD. These conditions most likely help to maintain water levels in MCL higher than they would be otherwise, limiting flood storage space in the lagoon. This effect is potentially compounded by the drainage divide (beaver dams/sandbar?) in MCL, which maintains water levels in upper MCL at about +8.5 ft NAVD seemingly regardless of drainage in lower MCL.

5. **Arroyo Grande Lagoon inlet elevation.** The invert elevation of the Arroyo Grande Lagoon inlet is the ultimate control on system drainage – water throughout MCL and AGL can drain only to this elevation, and no lower. Under existing conditions, water levels (and, by proxy, inlet invert elevations) in AGL appear to only rarely drop below +7 ft NAVD, almost 2 feet above MHHW (Figure 13, Figure 14, Figure 15) and only 3 feet below the base flood elevations in the Island neighborhood. As discussed earlier, the shape and size of the inlet are largely determined by the frequency/magnitude of scouring flood flows, and wave action on the beach. Wave action in the absence of scouring flows can construct a high beach berm that results in high lagoon WSEs when the inlet is closed or overflowing. Given the existing wave climate and trends in lagoon WSEs, it therefore may not be feasible for the beach to maintain an inlet with an invert elevation below +6 ft NAVD. Sea level rise and attendant increases in total water levels will likely increase this typical invert elevation (+7 ft NAVD) in the future, raising it closer to the area's base flood elevation (+10 ft NAVD).
6. **Effects on lagoon habitats.** Any inlet management regime that establishes a target maximum water level in Arroyo Grande Lagoon must consider how that level will affect the depths and distribution of aquatic habitat in the lagoon that support special-status species such as steelhead and tidewater goby. In general, higher water levels lead to greater depths and increased extents of inundated habitats.4 In addition, inlet management regimes that would directly breach the lagoon must consider the potential impacts to tidewater goby and steelhead, and incorporate necessary impact avoidance/minimization measures.

4.2 Opportunities

There are multiple opportunities for flood management at Meadow Creek and Arroyo Grande Lagoons. The first three opportunities described below are beyond the scope of interim sandbar management; the fourth is the focus of this report and is further developed in Section 5.

1. **Removing the apparent drainage divide between upper and lower Meadow Creek Lagoon.** Water levels in lower MCL are consistently lower than water levels in upper MCL; frequently on the order of about one foot. Removal of the drainage divide between the upper and lower portions of Meadow Creek Lagoon could potentially drop water levels across the entire lagoon to the levels typically seen in lower MCL. This could increase the flood storage capacity in MCL enough such that smaller storms result in a decreased flood risk relative to existing conditions. Existing topographic data indicate that lowering base water levels in Meadow Creek Lagoon from +8.5 to +6.5 ft NAVD would create approximately 40 acre-feet of additional flood storage space in Meadow Creek Lagoon. To more accurately define the benefits of this opportunity, more detailed hydraulic analysis would be necessary, particularly assessment of the actual storm inflows to MCL, the extent of the area represented by the lower MCL gage, the relationship between storm return rates and necessary storage, and the influence of alterations to flapgate operation (below).

4 This assumes the bed is static, which it is not (flood events can deposit sediment in the lagoon as well as scour it out), but averaged over time, this tends to be the case.

2. **Potentially retrofitting the Sand Canyon Flapgates if they are found to not adequately seal below +8.3 ft NAVD.** As described earlier, flows between lower MCL and AGL track each other closely until water levels in AGL reach +8.3 ft NAVD, at which point existing data seem to indicate flapgate closure. While it is unrealistic to expect metal-sided flapgates to ever fully seal, they should be inspected and, if possible, retrofitted so that they close at an elevation below their current closure threshold. This would help create flood storage space in MCL, particularly if it were coupled with actions to eliminate the drainage divide between upper and lower MCL (above). An increase in flood storage space in MCL would decrease the likelihood that relatively smaller runoff events could cause water levels in MCL to rise to flood elevations.
3. **Monitoring and maintenance of the Carpenter Creek outlet.** If, as it appears, the Carpenter Creek outlet is serving as a high-flow bypass for lower Meadow Creek, this function should be maintained and, if possible, enhanced. A more thorough assessment of the conditions under which Carpenter Creek breaches to the ocean and bypasses flows from Meadow Creek would help the Department understand the role of the outlet in influencing flood conditions in Meadow Creek Lagoon.
4. **Modifications to the current sand management regime along the shoreline.** Existing sand management activities by California State Parks in the vicinity of Arroyo Grande Lagoon could be affecting the growth and elevations of the beach berm in front of the lagoon, thereby influencing its breach dynamics. Obtaining additional information about these sand management activities, and assessing their potential effects on the berm and lagoon inlet, could help identify sand management measures that could reduce the likelihood of elevated beach berm development.
5. **Inlet/sandbar management.** Active management of the Arroyo Grande Lagoon inlet could help improve the predictability of the system's flood response to storm flows, and could help reduce the flood risk around Meadow Creek Lagoon. The relatively highly managed/manipulated nature of the beach at AGL may make inlet management more palatable there relative to other, less actively managed beaches. Inlet management could also be incorporated into other beach/ecosystem management/enhancement activities, such as dune restoration and vegetation management. The inlet could be managed in multiple ways:
    a. **Pre-breaching**, where the beach berm is managed at a maximum given elevation. When water levels in AGL rise above this elevation, the lagoon will breach, and if water levels in AGL sink below those in lower MCL, the flapgates will open and Meadow Creek Lagoon will drain.
    b. **Breach priming**, in which coarse material (cobbles and gravels) is placed in the beach berm in a trench located roughly in line with the mouth of lower Arroyo Grande Creek (through the small dune field). The increased permeability of this trench relative to compacted sands at the existing southern outlet could encourage breaches to form at the trench. This could create a more hydraulically efficient outlet closer to the mouth, that could hasten drainage of AGL (and, potentially, MCL) under flood conditions.
    c. **Active breaching**, in which Arroyo Grande Lagoon is artificially breached during floods or when floods are potentially imminent. This action is closest to the way in which the inlet was historically managed.

    All inlet management options must consider the potential for special-status estuarine species, particularly steelhead and tidewater goby, to be impacted by inlet management activities. Typically, during flood conditions, estuarine fish that poorly tolerate marine conditions (such as tidewater goby and not-yet-osmoregulated steelhead smolt and YoY) will search out habitat that (1) stays inundated, even after a breach event, and (2) provides velocity refugia from high flows, so that fish are not washed out from the lagoon into the ocean. Therefore, inlet management should be implemented in a way that mimics “natural” breaching as much as possible, and that provides habitat with adequate depths and refugia for estuarine fish. Inlet management is discussed in further detail in Section 5 below.

5 INTERIM SANDBAR MANAGEMENT PLAN

Section 4.2 above described three potential inlet/sandbar management methods that could potentially reduce the flood risk around Meadow Creek Lagoon: pre-breaching, breach priming, and active breaching. For purposes of this report, we are selecting the first option, pre-breaching, as the basis for the interim sandbar management plan. We are focusing on this method for the following reasons:

1. Pre-breaching would result in breach dynamics being as close as possible to existing conditions (wherein flood flows trigger breaching), and entail the lowest level of intervention, limiting the potential for tidewater goby, steelhead, and other estuarine fish to be caught off-guard (i.e. outside high flow refugia) once breaching commences. For safety reasons, active breaching would most likely be implemented outside storm windows, which runs the risk of catching fish off-guard and outside refugia.
2. The potential effects of pre-breaching on water levels can be most effectively modeled by HEC-RAS; monitoring of pre-breaching results can be fed back into the model for further calibration.
3. The breach priming method is relatively untested, and would require further research into beach permeability and other factors that are outside the scope of this study.

The following sections describe the elements of the interim sandbar management plan.

5.1 General Provisions

It should be understood that this sandbar management plan is *interim* and *experimental*, and as such should not necessarily be considered a permanent solution to the flooding problems around Meadow Creek Lagoon. As noted in the “Opportunities” section above, implementing a multi-pronged approach to flood management could reduce the flooding frequency around MCL. The low-lying topography of the area and the flooding constraints described above make the areas around MCL extremely vulnerable to flooding, and it is likely that under certain conditions (e.g. storm events such as those observed in December 2010), flooding will occur around MCL regardless of how the inlet is managed due to the sheer volume of water that drains to the lagoon system.

Ideally, the sandbar management plan should be implemented within an adaptive management context, in which the results of implementation are closely monitored and analyzed, and lessons learned from the results are applied to future management actions. Monitoring and adaptive management of the interim sandbar management is discussed more in Section 5.4 below.

Sections 5.2.3 through 5.2.5 below are based on resource protection measures that were originally developed for a formal, permitted outlet channel management at the Russian River Estuary (SCWA 2012). These conditions should be discussed with the above-referenced resource agencies (and, if necessary, revised) well before sandbar management may be necessary (i.e. over the summer dry season).

5.2 Potential Resource Agency Protection Measures

There are multiple conditions under which sandbar management may be necessary:

- If, similar to the summer-fall 2010, there is an extended period of constructive wave action that builds a particularly high beach berm (above +9 ft NAVD) in front of Arroyo Grande Lagoon
- If water levels within Arroyo Grande Lagoon and/or Meadow Creek Lagoon approach +7.5 ft NAVD (half a foot below the estimated allowable invert elevation [+8 ft NAVD] that preliminary modeling indicates would reduce flood risk for larger, less frequent storm events)
- If a significant precipitation event is predicted for the Arroyo Grande Creek and Meadow Creek watersheds (e.g. a "Pineapple Express" or similar storm), especially early in the rainy season when the lagoon outlet is closed or subject to shallow overflow

One of the most critical elements of interim sandbar management is monitoring lagoon water levels ***well before*** they reach the preliminary (roughly estimated) threshold of +7.5 ft NAVD, so that the beach berm can be lowered without directly breaching the lagoon. Obviously, recognizing these conditions require continued monitoring of lagoon water levels, beach topography, and, if possible, wave action along the local shoreline. If one or more of the above conditions are met, and the Department decides that sandbar management would be prudent, they will alert the relevant regulatory agencies, which we presume will consist of many or all of the following: California Coastal Commission, US Fish and Wildlife Service, National Marine Fisheries Service, California Department of Fish and Wildlife, California State Parks and the Regional Water Quality Control Board.

5.2.1 Topographic and Bathymetric Surveys

Prior to sandbar management, staff from should perform a topographic and bathymetric survey of Arroyo Grande Lagoon and its vicinity, including the dune field west of the mouth and the entire beach/beach berm west of the backbeach runnel. The topographic and bathymetric survey should include the establishment of beach profiles that extend perpendicular across the beach from the toe of the dunes east of the backbeach runnel to approximately MLLW in the Pacific Ocean. The location of these profiles should be documented using GIS so that the profiles can be re-surveyed after construction and after the lagoon eventually breaches. The beach profiles do not have to be in the same location as the ones described in Section 3.1.1 of this report, as these profiles were extracted from raster data (i.e. profiles in other locations can easily be extracted from the historic data). Other topographic data that should be surveyed include the extent (wetted area) of the lagoon, the lagoon thalweg, and the geometry of any low points (past inlet locations) in the beach berm.

These data are necessary to evaluate the impacts of sandbar management on lagoon morphology and breach morphodynamics, as well as the interactions between management activities and wave action. They are critical to implementation of the adaptive management described in Section 5.4 below.

5.2.2 Water Quality Monitoring

If feasible, water quality profiles should be collected in Arroyo Grande Lagoon prior to sandbar management, so that these data can be compared with post-breach conditions. Previous water quality monitoring in Arroyo Grande Lagoon appears to have been limited to discrete profiles collected concurrent with fisheries data (Rischbeiter, multiple years). More regular water quality monitoring will help the Department and other agencies understand the relationships between lagoon inlet management, water quality, and habitat suitability in the lagoon for tidewater goby, steelhead, and other estuarine fish. Work in other coastal California estuaries has identified inlet morphodynamics as a primary driver of lagoon water quality and habitat conditions (PWA 1994, 2^{nd} Nature 2006, WWR 2008, WWR 2010, PWA 2010, Behrens 2012, CSP 2012, ESA PWA 2013).

For purposes of guiding sandbar management, the primary constituents of concern are temperature, salinity, and dissolved oxygen. Profiles should be collected in the Arroyo Grande Lagoon thalweg at the following locations (Figure 2):

- Upstream of the Sand Canyon Flapgates,
- At the Sand Canyon Flapgates,
- Halfway between the Sand Canyon Flapgates and the historic (southern) inlet
- In the southern end of the lagoon before, it transitions into the inlet channel

We expect that these profiles would be collected concurrent with the topographic surveys described in Section 5.2.1. The Department and CSP might also want to consider installing sondes in Arroyo Grande and Meadow Creek Lagoons to collect time series data of water quality at multiple depths. Time series data allow for a more detailed understanding of seasonal and diurnal changes in water quality, particularly stratification/destratification and eutrophication which are among the primary drivers of estuarine habitat conditions.

5.2.3 Biological Resource Protection

Given the timing of the rainy season, it is most likely that sandbar management would be necessary outside the nesting season of western snowy plover and other shorebirds (roughly March through September). Nonetheless, pre-construction surveys should be implemented to avoid or minimize impacts to birds, plants, and other wildlife that utilize AGL and its adjacent habitats. These surveys should:

- Identify special-status plants and butterflies (or larval host species) and nesting birds present within 150 feet of the general location of the sandbar management area, including access routes
- Be conducted by a qualified biologist no more than 30 days prior to commencement of the lagoon management period

If no special-status plants, butterflies, larval host species, or nesting birds are encountered, no further surveys would be required for at least 30 days, unless additional measures are required by regulatory agencies. Additional pre-construction surveys, specifically for nesting birds, shall be conducted such that no more than 30 days will have lapsed between the survey and sandbar management activities.

If special-status plants, larval host species for special-status butterflies, or nesting birds are encountered, the location shall be documented and species-specific avoidance and minimization measures shall be prepared by the qualified biologist in coordination with the Department and appropriate resource agencies. The avoidance and minimization measures shall be implemented to prevent the loss of the species or abandonment of active nests, but shall also take the goals of sandbar management (i.e. flood protection concerns) into consideration.

Since pre-breaching does not actually directly breach the lagoon, and tidewater goby and steelhead are presumed to be present in Arroyo Grande Lagoon, pre-implementation fish surveys of AGL should not be necessary. In consultation with biologists from CSP and USFWS, the Department should consider actions that would minimize the impacts of breach events (whether “pre-breached” or not) on tidewater goby and steelhead populations in AGL, especially the addition of structural complexity (e.g. coarse woody debris) to the downstream portions of the lagoon. In its recent/current state, AGL has relatively little structural complexity once it turns south from the creek mouth and forms a backbeach runnel. This lack of complexity could potentially limit the availability of velocity refugia for tidewater goby and steelhead, putting them at a increased risk of mortality during breach events. It is possible that in order to develop a more permanent (permitted) sandbar management plan, resource agencies will require a formal protection/enhancement plan for tidewater goby, steelhead, and other estuarine fish.

Worker Training. Worker environmental awareness training should be included to inform construction personnel of their responsibilities regarding sensitive biological resources that are present within 150 feet of the general sandbar management area and access route. The training should comply with the following measures:

- The training should be developed by a qualified biologist familiar with the sensitive biological resources that are known or have the potential to occur in the area.
- The training shall be completed by all construction personnel before any work occurs in the sandbar management area, including construction equipment and vehicle mobilization. If new personnel are added to the proposed project, the Department should ensure that new personnel received training before they start working.
- The training shall provide educational information on the special-status species that are known or have the potential to occur in the area, how to identify the species, as well as other sensitive biological resources (e.g. sensitive natural communities, federal and state jurisdictional waters). The training shall also review the required conditions to avoid

impacts on the sensitive resources, and penalties for noncompliance with resource protection requirements.

5.2.4 Cultural Resource Protection

Based on the site's history of prior breaching activities, sand and dune management, and off road vehicle use, pre-breaching is not expected to impact cultural resources. The pre-breaching plan will document that the extent of construction is well within prior disturbances. Construction period activities to check for cultural resources are anticipated.

5.2.5 Public Safety

Following sandbar management, the Department should install semi-permanent signage notifying beach users of beach/lagoon conditions, the potential for safety hazards from beach erosion or lagoon breaching, and emergency contact information. Signage should be posted and maintained at key locations, such as the end of the northern Arroyo Grande Creek levee, the Pier Avenue and Grande Avenue SVRA entrances, and 100 feet on either side of the lowered beach berm.

5.3 Pre-Breaching Method

Once the conditions in Section 5.2 are met, and the Department decides to proceed with sandbar management, pre-breaching should be implemented as follows:

5.3.1 Timing

Again, sandbar management activities will most likely be necessary late in the dry season, when the AGL outlet is closed/overflowing and before the arrival of the first winter rains. Sandbar management should be implemented within one week of predicted rainfall, so that wave action has minimal time to re-build beach berm elevations before precipitation begins. The Department should limit sandbar management activities that require the use of heavy equipment to between local sunrise to local sunset.

5.3.2 Location, Dimensions, and Equipment

To minimize potential impacts to sensitive foredune habitats in the dune field near the Arroyo Grande Creek mouth, sandbar management should initially focus on the southern extent of the beach berm in the general location of the recent (last 5 years) inlet.

Preliminary HEC-RAS modeling so far (Section 3.2.3) has identified +9.5 ft NAVD as an estimated minimum inlet invert elevation for storms in the 1- to 2-year range, and +8 ft NAVD for larger storms. Inlet management should therefore target this elevation range as the post-construction thalweg elevation. For smaller anticipated storm events, an elevation closer to +9.5 ft NAVD would be appropriate; for larger events, an elevation closer to +8 ft NAVD would be appropriate. Lowering the inlet to elevations closer to +8 ft NAVD carries with it an increased risk of more frequent breaching/overtopping that could impact habitat conditions within the lagoon, therefore, the lower end of the elevation range should only be targeted if it's deemed necessary for flood control. It is also important to note that a lower inlet thalweg is more likely to fill with sand from wave action than a higher inlet. Future monitoring, modeling, and adaptive management (see Section 5.4 below) as well as discussions with regulatory/resource agencies will help to refine the target inlet elevation. Ultimately, we anticipate that the target inlet elevation will be partially determined by water surface elevations in the lagoon, as under no circumstances should the Department lower the inlet thalweg below existing lagoon water levels (this would result in an artificial breach). Artificial breaching under non-storm conditions could result in potentially significant impacts to lagoon ecology and listed species. Therefore, the inlet should be excavated such that at least half a foot of freeboard exists between the lagoon water level and the inlet thalweg post-construction.

The beach berm should be lowered to the target elevation such that a trapezoidal cross-section (perpendicular to the ocean) is cut across the beach. Initially, we recommend that the invert of the trapezoid be approximately 200 ft wide at the thalweg, with 1:1 side slopes extending to grade (Figure 20A). This width is based on a rough estimation of the dimensions of past inlets observed in historic aerial photographs. This trapezoidal "wedge" should be cut across the beach between the lagoon and the ocean (a distance of approximately 200 feet; will vary year to year – see Figure 20B). Further monitoring and adaptive management will indicate if these dimensions need to be refined.

The sandbar should be lowered using either an excavator or front-end loader, so that excavated sand can be easily placed into a dump truck for transport. Excavated sand should be placed to the south of the recent inlet location, in the direction of net longshore transport, to help minimize re-deposition on the lowered beach berm. However, if waves are from the south during the pre-breaching period, the sand may be placed higher up on the beach against the dunes and with maximum separation from the lagoon and breach. The Department should coordinate with CSP to determine if this sand can be used to potentially create sparsely vegetated foredune habitat for western snowy plover within the non-vehicular areas of Oceano Dunes SVRA (Pismo Dunes Natural Preserve).

5.3.3 Expected Morphological Endpoints

Our description of expected morphological endpoints is based on our previous experience in California coastal lagoons, particularly ones like Arroyo Grande Lagoon that are situated on broad, gently sloping beaches and are prone to shallow overflow and/or choked conditions.

Once the Arroyo Grande Lagoon sandbar is lowered, watershed runoff will eventually cause water levels in the lagoon to rise above the elevation of the lowered sandbar, triggering a breach. If the breach occurs at high tide, the relatively lower head difference between the lagoon and the ocean could trigger the formation of a shallow (overflow channel that would drain the lagoon to the ocean until either (1) water levels between the two equilibrated or (2) wave action would move enough sand into the inlet for it to close, allowing water to once again begin ponding behind the beach berm. These same conditions might also form if the breach is driven by a relatively slow/steady runoff event. If the breach occurs at a low tide, the higher head difference between the lagoon and the ocean could potentially cause headcutting down through the beach berm, draining Arroyo Grande Lagoon to a relatively lower water level than if the breach occurred at a high tide. These conditions could also form if the breach was more energetic due to faster/flashier runoff events that sent larger volumes of water into the lagoon within a short time period. Breaches during neap tide periods would likely have the least potential to deeply scour through the beach berm. However, it should be noted that a deeply scouring breach may be the natural result of a strong rainfall event. By timing the pre-breach excavation for the rainfall event, the effect of the pre-breaching will be to mitigate rather than amplify the scour potential.

Once runoff recedes, wave action will eventually move sand into the inlet. Initially, this can cause the inlet to be choked (open at high tide, but then closed during low tide). Eventually, as more sand moves into the inlet, it converts from choked to either fully closed or shallow overflow conditions. Throughout 2012, AGL experienced shallow overflow conditions, even in the summer when base flows were low. Department staff reported that this was perceived as an unusual occurrence, as anecdotal evidence as well as aerial photographs indicate that the lagoon inlet typically closes completely during the summer months (M. Hutchinson, pers. comm.). More research is needed to understand the conditions under which shallow overflow of the beach berm occurs, and the effects this overflow has on sand deposition in the inlet and the growth/erosion of the beach berm.

The residual depths (and resulting habitat conditions) in the lagoon after the breach are largely dependent upon (1) the depth to which the inlet incises, (2) the timing and rate of runoff entering the lagoon from the watershed, (3) the timing and rate at which the inlet closes. For example, if the inlet incises deep within the beach berm, it will take longer to close, and if post-breach rates of runoff are low, it could take longer for the lagoon to regain its pre-breach water levels than if the inlet closed quickly and experienced higher rates of runoff. It is important to note that the quantitative conceptual model approximates how these competing factors interact with one another to govern lagoon hydrology and geomorphology, which is why it is important to implement monitoring and adaptive management (Section 5.4) so that this model can be refined for future applications.

5.4 Monitoring and Adaptive Management

Ideally, once the beach berm is lowered, the actual breach event could be captured in pictures/video, but the unpredictability of breach events makes this unlikely unless continuous time-lapse photography is deployed. Once the lagoon does breach, there are a number of physical elements in the lagoon/inlet that should be monitored on a short-term and long-term basis to facilitate adaptive management of the interim sandbar management plan. The goals of monitoring and adaptive management are as follows:

- Assess the effects of the interim sandbar management plan on flood risk, breach timing, and drainage
- Gain a better understanding of the locally specific relationships between precipitation, AGL and MCL water levels, wave action, and breach geometry
- Further calibrate and refine the HEC-RAS and quantitative conceptual models for applications in future sandbar management efforts

These efforts are described below, and should be reviewed with relevant regulatory agencies prior to implementation of the interim sandbar management plan.

5.4.1 Topographic and Bathymetric Surveys

After the sandbar is lowered, the Department should implement an as-built survey (including photographs) to capture the post-construction topography and bathymetry of the lowered area. Once the system eventually breaches, additional surveys should re-occupy the beach profile locations established prior to construction (Section 5.2.1) as well as the new thalweg, inlet, and wetted lagoon edge. If possible, the re-formation of the beach berm after the breach (wave-driven transport of sand into the inlet) should also be surveyed, so that inlet closure can be better understood and potentially incorporated into the HEC-RAS model.

This information, coupled with water level data from Arroyo Grande and Meadow Creek Lagoons, will allow the Department to compare the breach/drain dynamics to those that were estimated by the HEC-RAS and quantitative conceptual models (Section 5.4.3).

5.4.2 Water Levels and Water Quality Monitoring

We presume that the existing gages (at Pier Avenue, lower Meadow Creek Lagoon (upstream of the Sand Canyon Flapgates), and Arroyo Grande Lagoon (downstream of the Sand Canyon flapgates) will continue to be monitored in the long-term. Data from before, during, and after the breach should be utilized to assess the performance of the HEC-RAS and quantitative conceptual models, as described below.

Water quality profiles of temperature, salinity, and DO should also be collected in Arroyo Grande Lagoon after the breach, in the same locations described in Section 5.2.2.

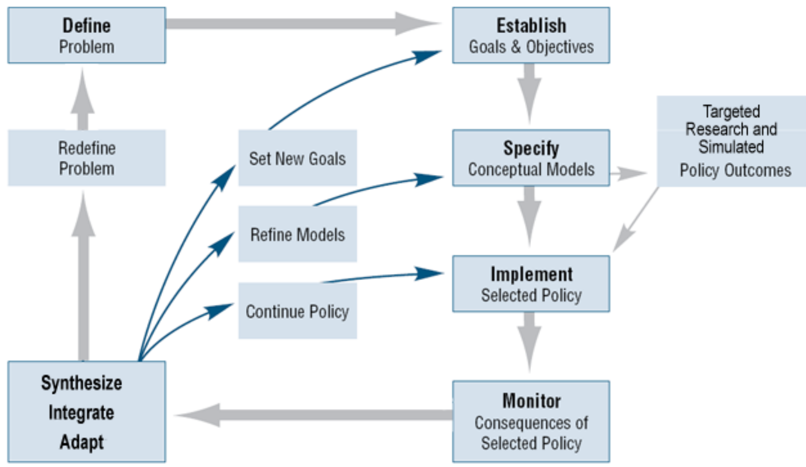
5.4.3 Model Refinement and Adaptive Management

Adaptive management is the process of learning from restoration and management actions, then using this knowledge to inform and adapt future actions (CALFED 2000). While this project does not have the scope to develop a complete adaptive management plan, the process of adaptive management input to sandbar management can be described generally as:

1. Define measurable flooding and resource protection objectives (Section 1.1).
2. Articulate a conceptual model (or models) of the process linkages that explain how the management actions address the flooding and resource protection ecological objectives (Section 3.2).
3. Identify key uncertainties in the conceptual model(s) (Section 3.2 and Appendix A).
4. Articulate hypotheses for each of the key uncertainties (Section 3.2 and Appendix A).
5. Design experiments to test the hypotheses. Effectively, the “experiment” in this case is the interim sandbar management plan (Section 5.3).
6. Implement a monitoring and adaptive management plan for the interim sandbar management plan (Section 5.4).

Adaptive management is an iterative process. Once monitoring results are available (from Step 6), the adaptive management process circles back to reassess the objectives (Step 1) and conceptual models (Step 2), etc. Graphic 2 below is commonly used to visualize the adaptive management process:

Graphic 2: The adaptive management process, as defined by CBDA 2009.



In the case of interim sandbar management, pre- and post-breach data describing AGL and MCL water levels, AGL topography and bathymetry, wave action, and AGL inlet morphodynamics should be synthesized to refine the HEC-RAS and quantitative conceptual models. These refined models can be applied to future sandbar management efforts, particularly the identification of (1) lower inlet invert elevations that could help avoid or minimize flooding during larger, more infrequent storm events and (2) the potential limits of inlet management to affect flooding under a range of storm conditions.

The results of the first few rounds of interim sandbar management (including any insight gained from model refinement and adaptive management) should be compiled into reports for distribution to CSP and the relevant resource agencies for review, comment, and future application.

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Figures

List of Figures

SOURCE: Aerial- ESRI Ditgital Globe

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Figure 1
Location Map

SOURCE:Aerial-NAIP 2012

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Figure 2
Site Map

SOURCE: 1884 T-Sheet

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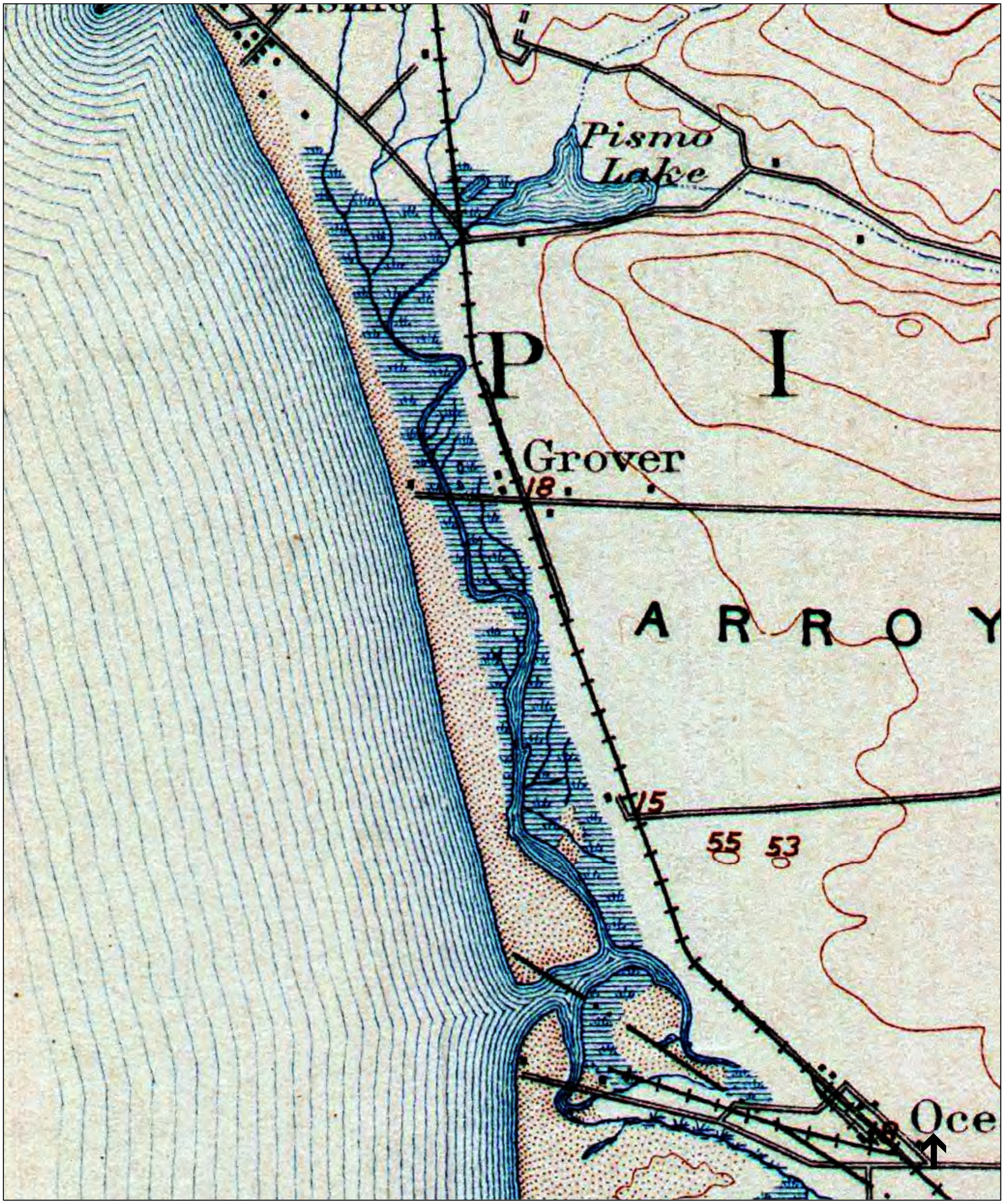
Figure 3
1884 T-sheet



SOURCE: U.S. Coast Survey 1897

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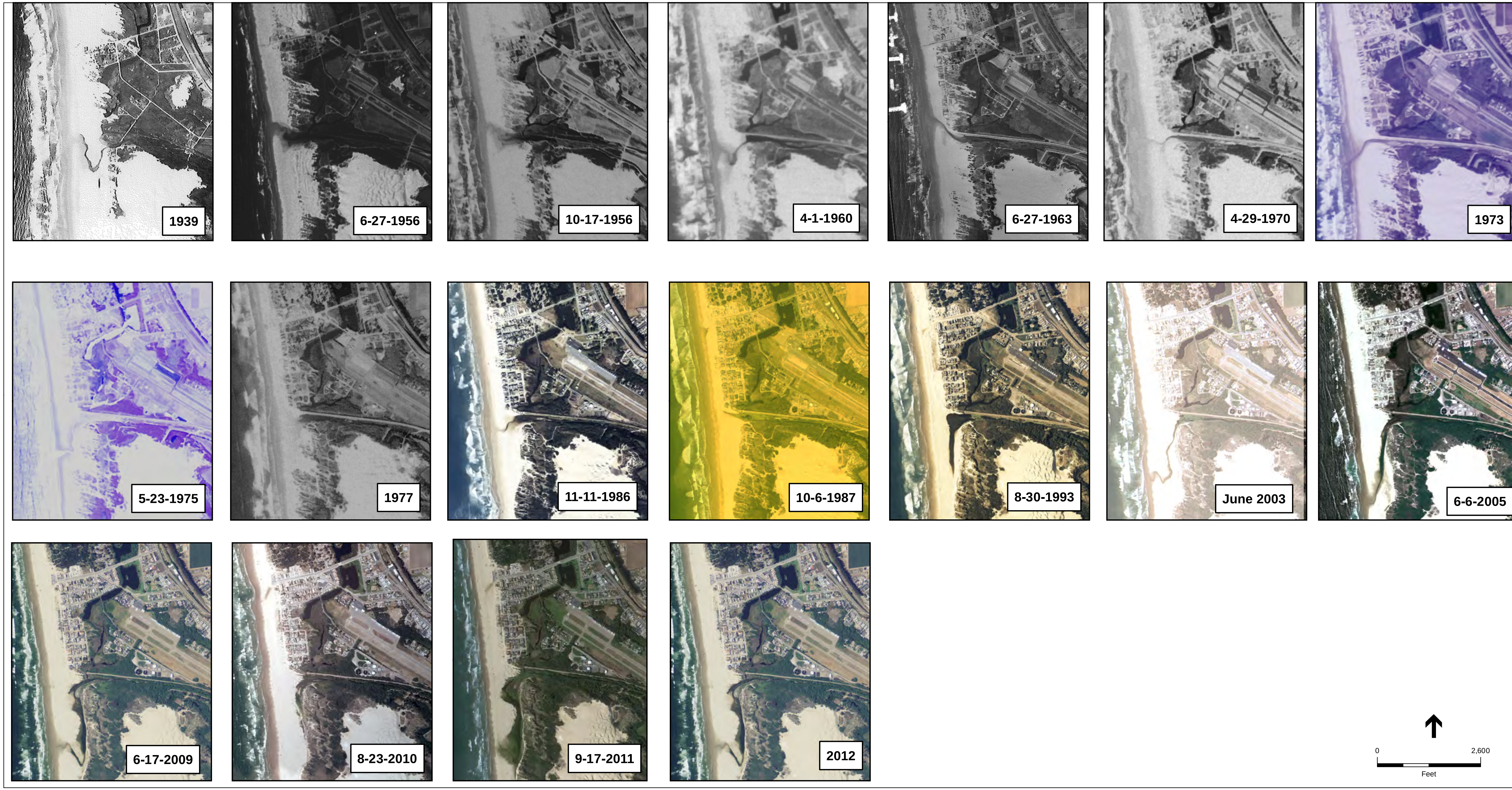
Figure 4

1897 T-sheet



SOURCE: County of San Luis Obispo (1939), USGS (1956-1993), USDA (2003-2010, 2012), Google Earth (2011)

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Figure 5

Historical Air Photo Sequence, 1939-2012

SOURCE: U.S. Coast Survey 1987, 2012 NAIP Imagery

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Figure 6

Overlay of 1897 Habitats on 2012 Airphoto

SOURCE:U.S. Coastal Survey 1956

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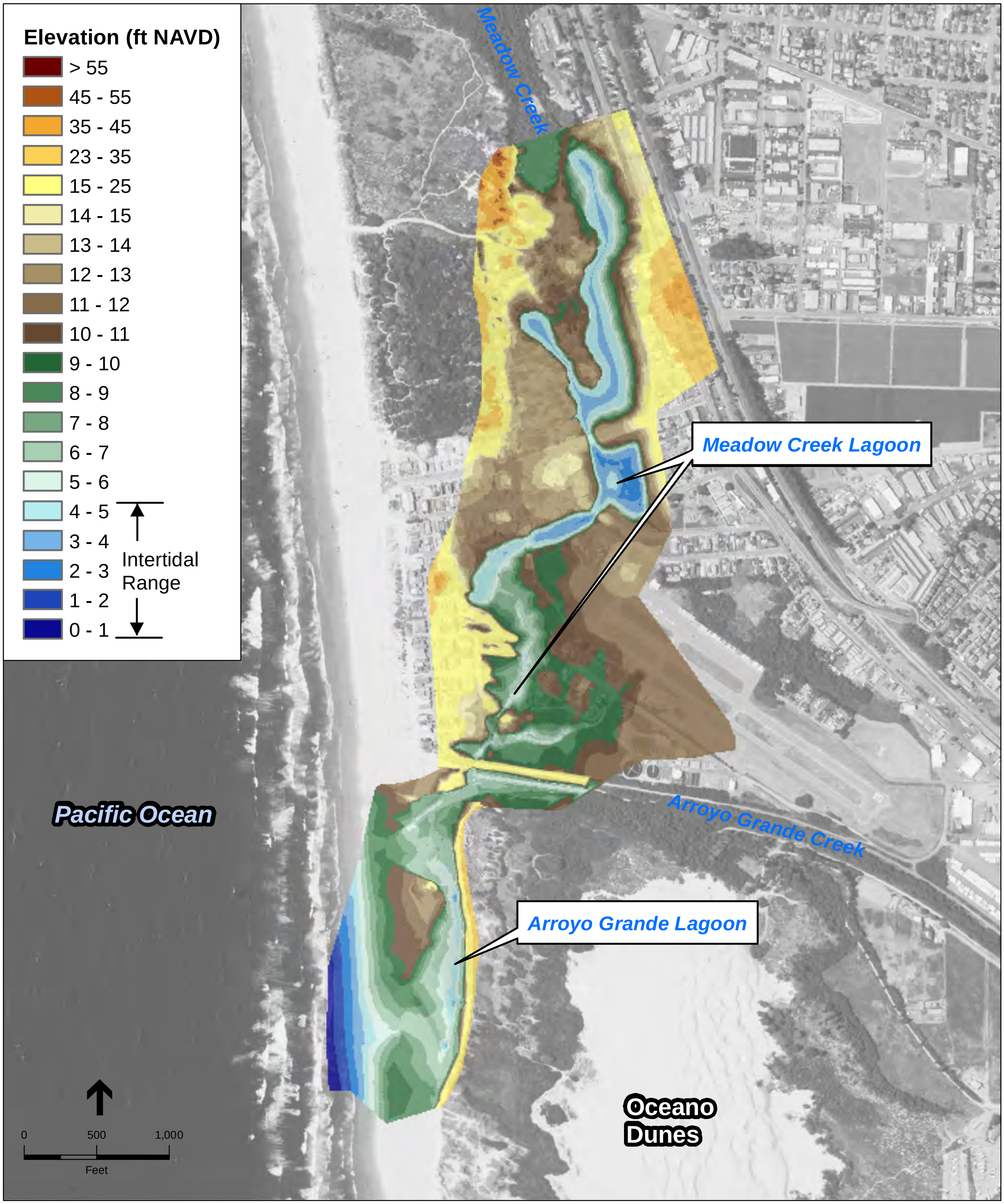
Figure 7
1956 Aerial Photo



SOURCE: ESA PWA 2011 (survey data), Cannon Engineering 2011 (survey data), NOAA 2010 (LiDAR), NAIP 2012 (air photo)

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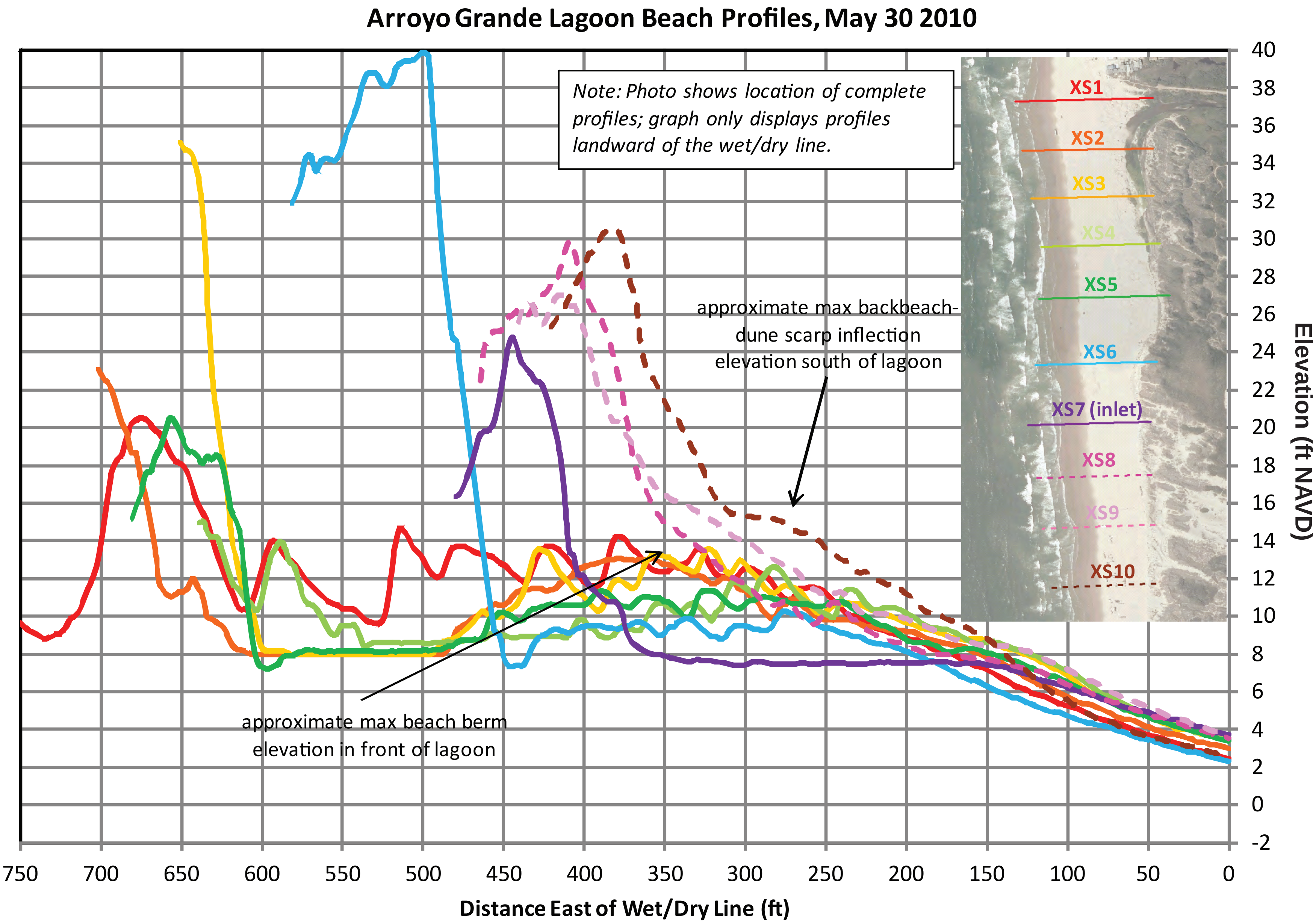
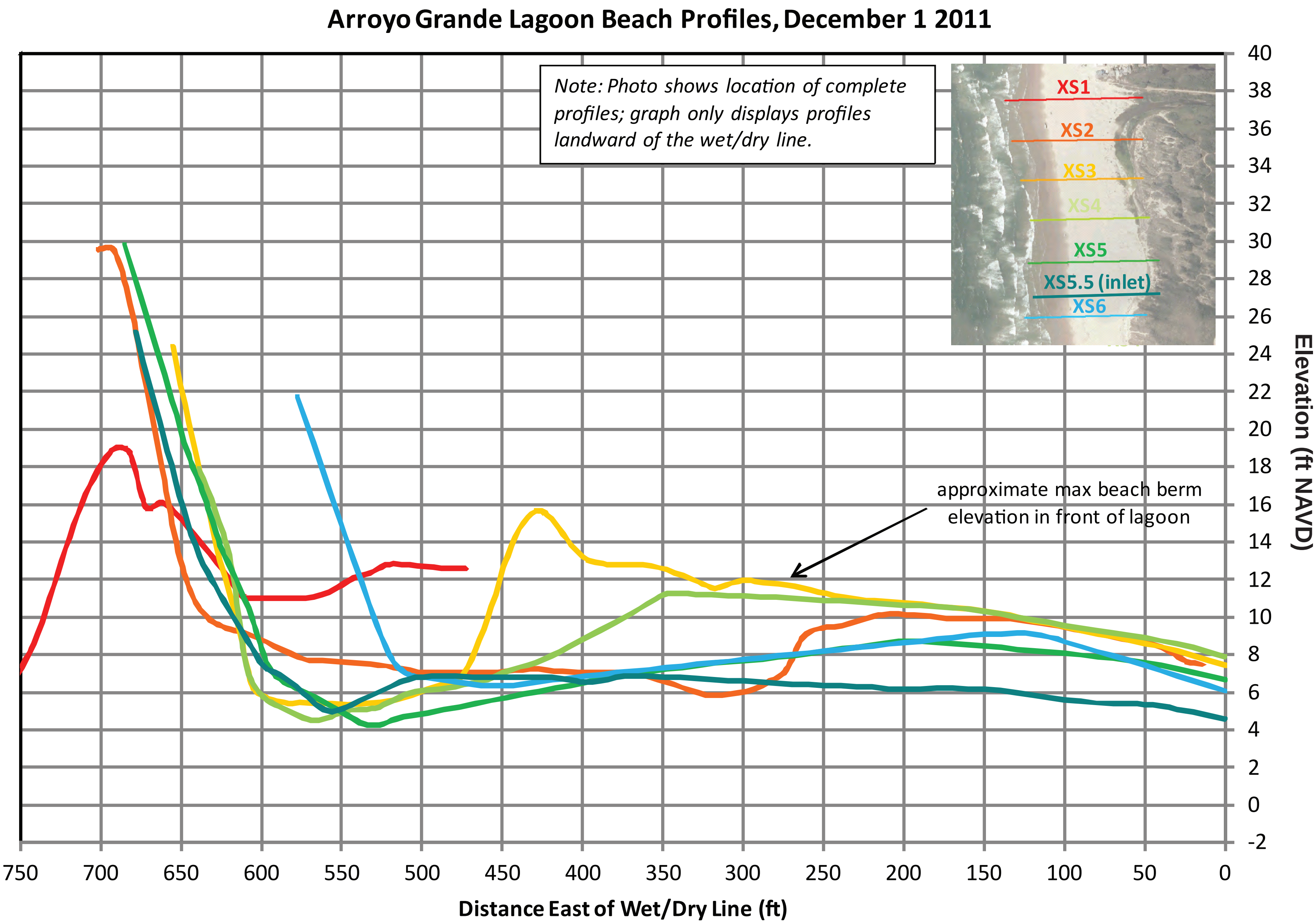
Figure 8
Topography and Bathymetry



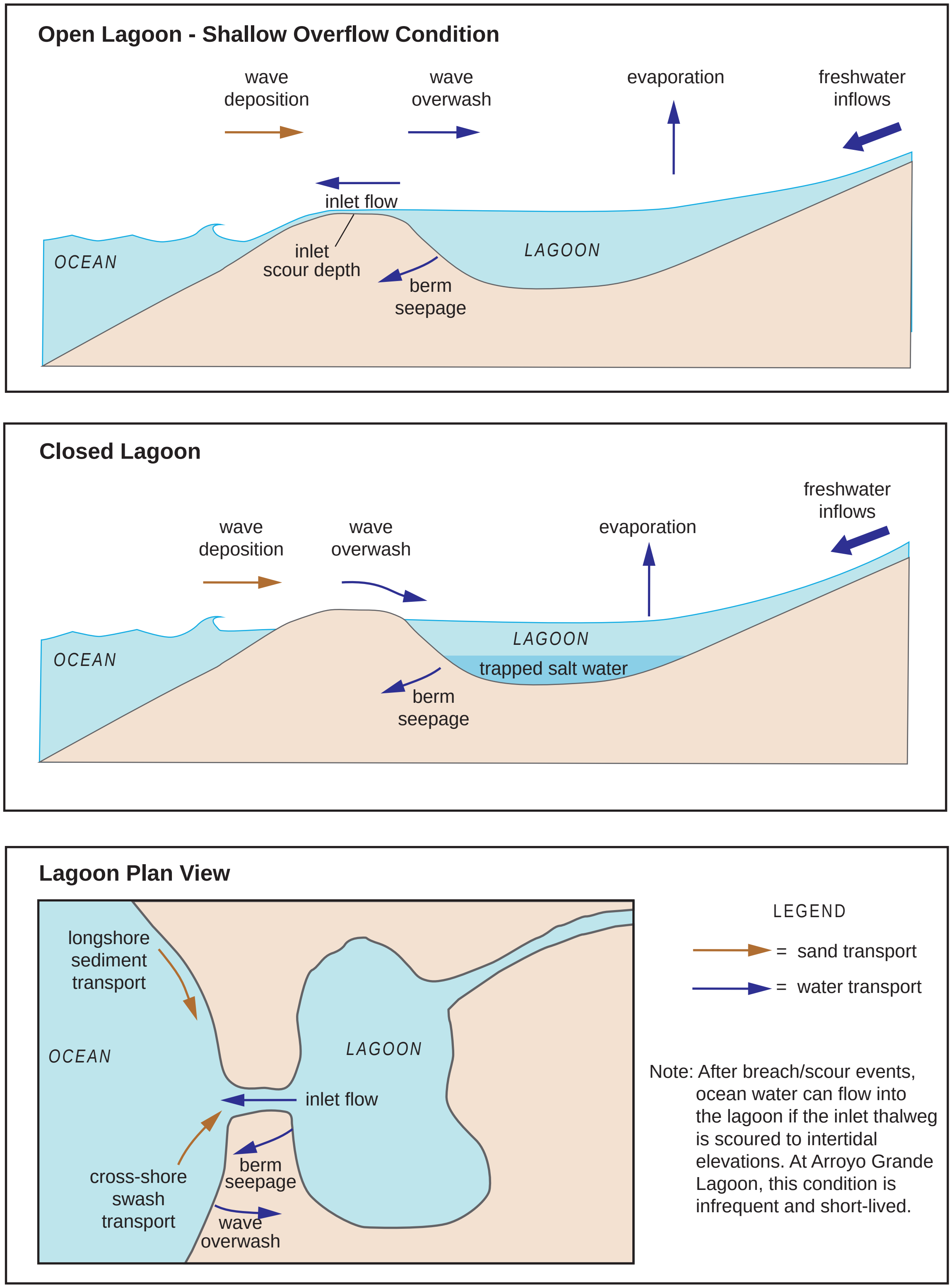
SOURCE: ESA, 2013

Figure 9
Beach Profiles, May 2010



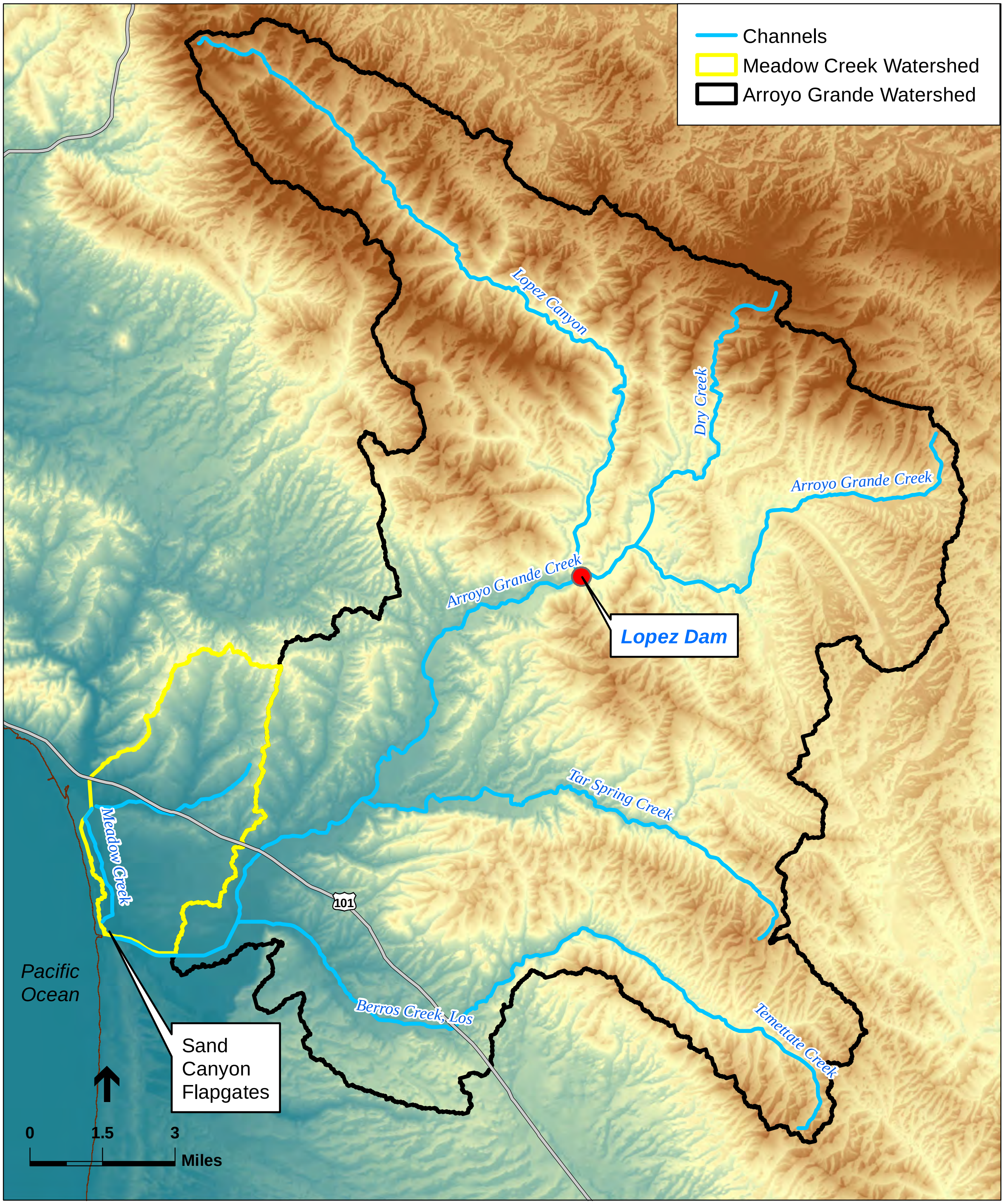
SOURCE: ESA, 2013

Figure 10
Beach Profiles, Dec 2011



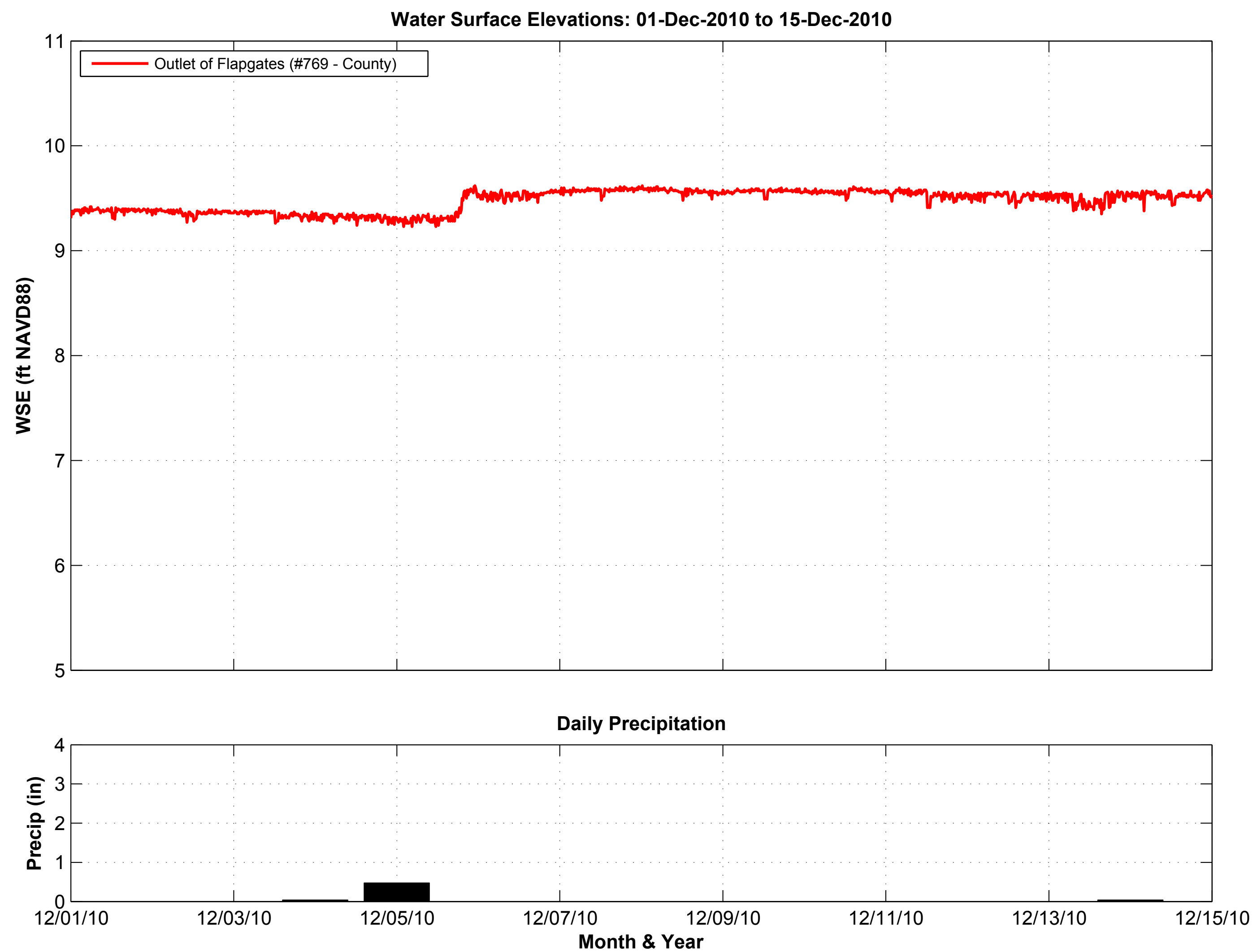
SOURCE: ESA, 2013

Figure 11
Open and Closed States
Arroyo Grande Lagoon



SOURCE:USGS DEM (2009)

Figure 12
Watershed Map



SOURCE: ESA, 2013

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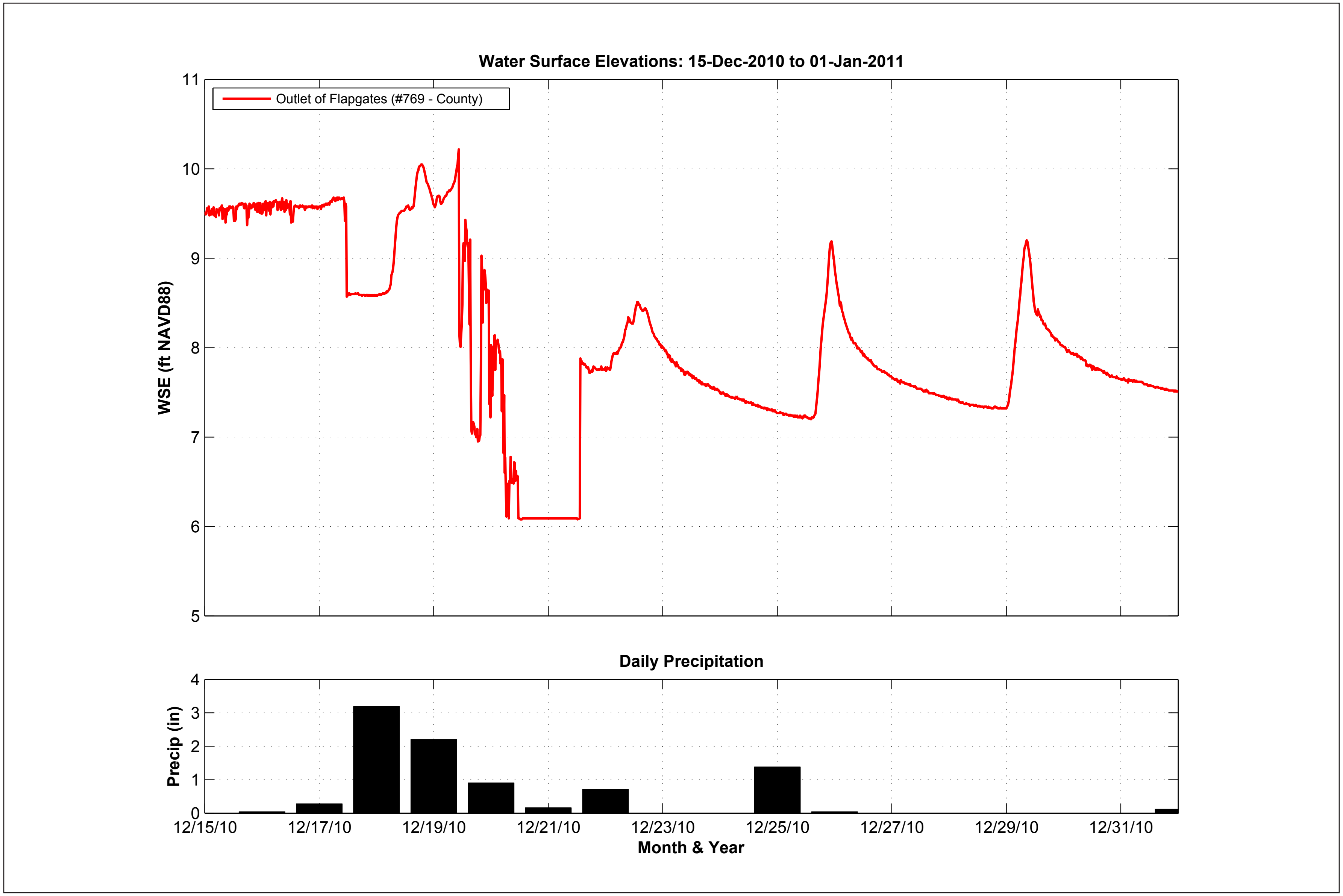
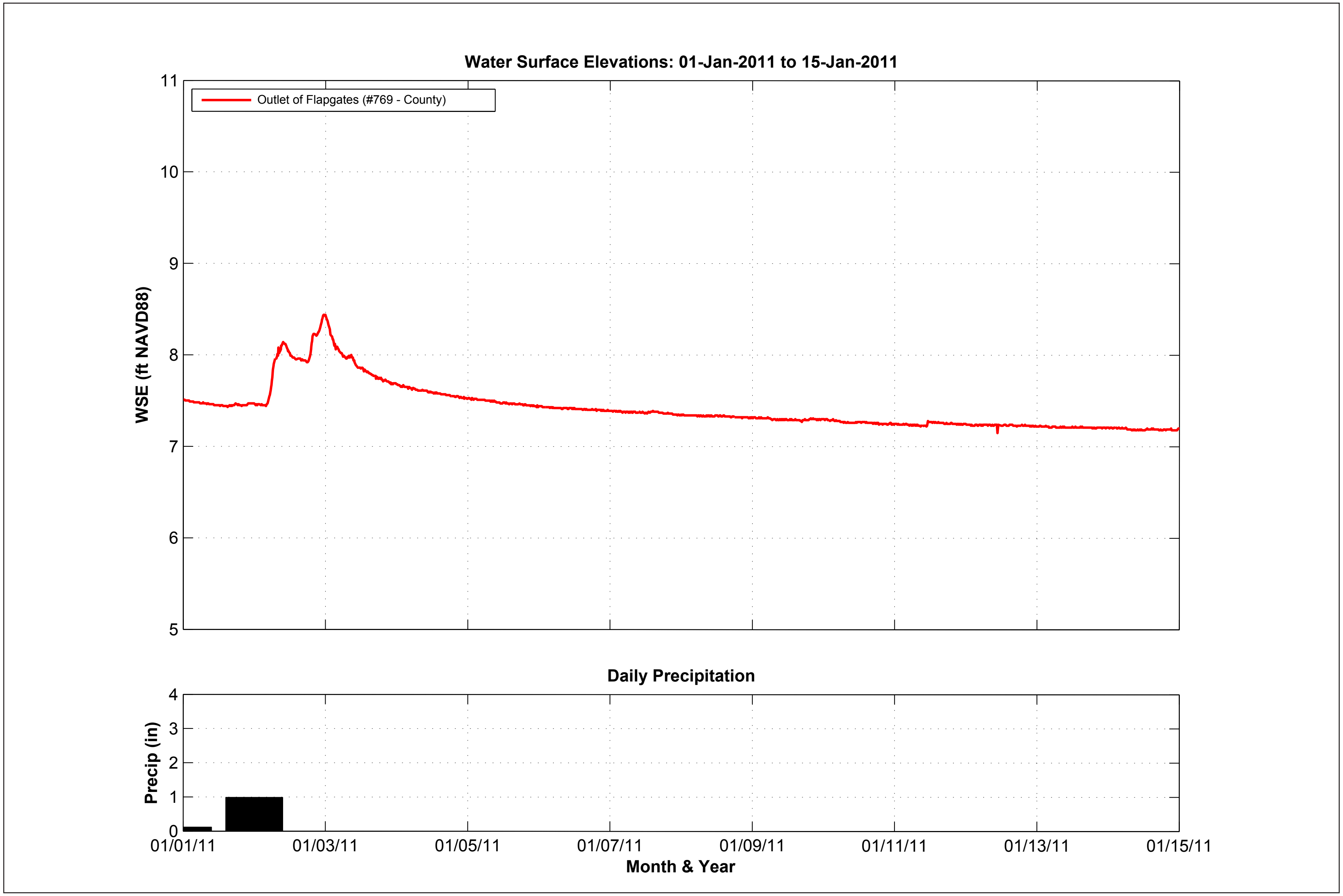
Figure 13A
Christmas 2010 Storm Hydrology
December 01-15, 2010



SOURCE: ESA, 2013

Figure 13B
Christmas 2010 Storm Hydrology
December 15, 2010- January 01, 2011



SOURCE: ESA, 2013

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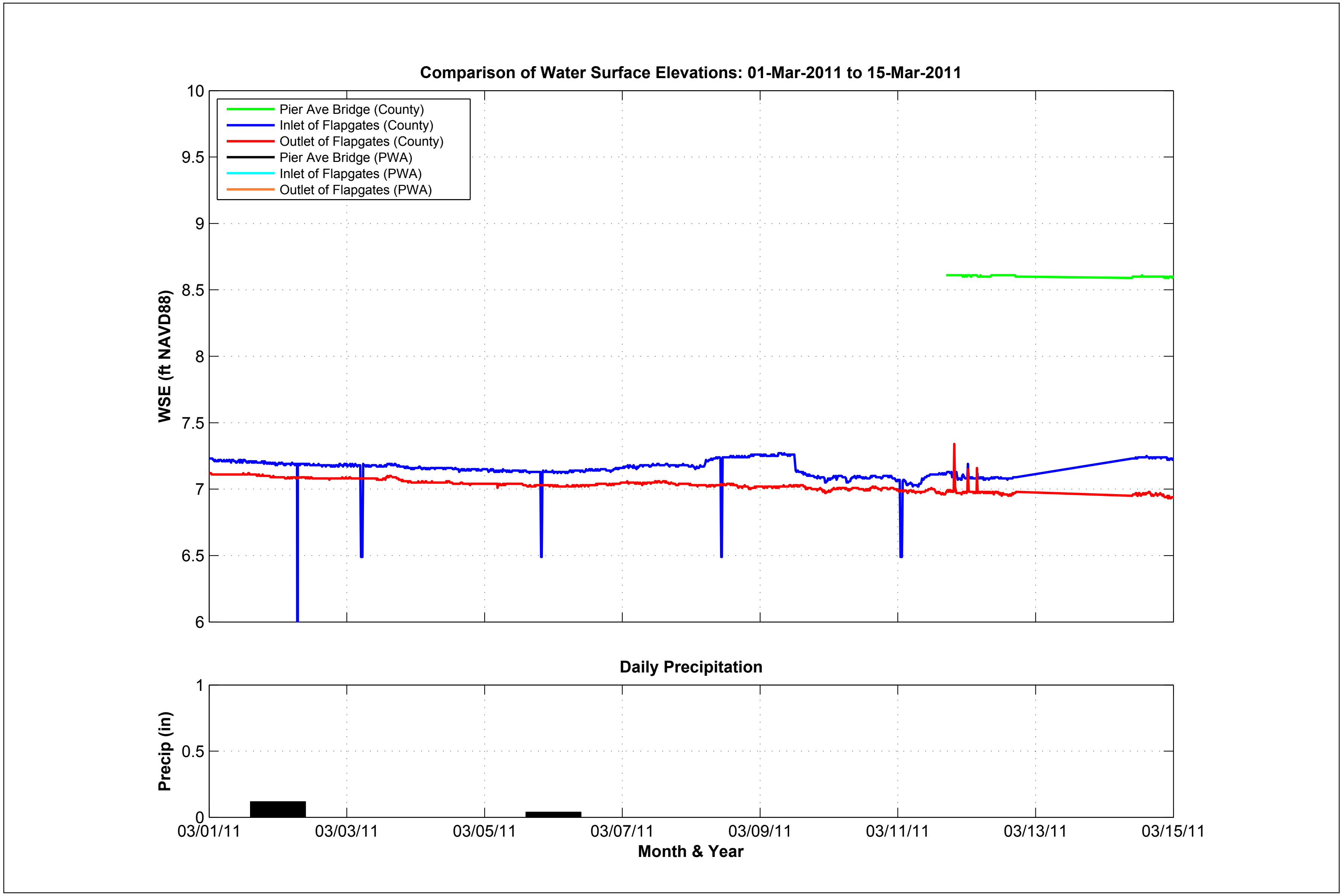
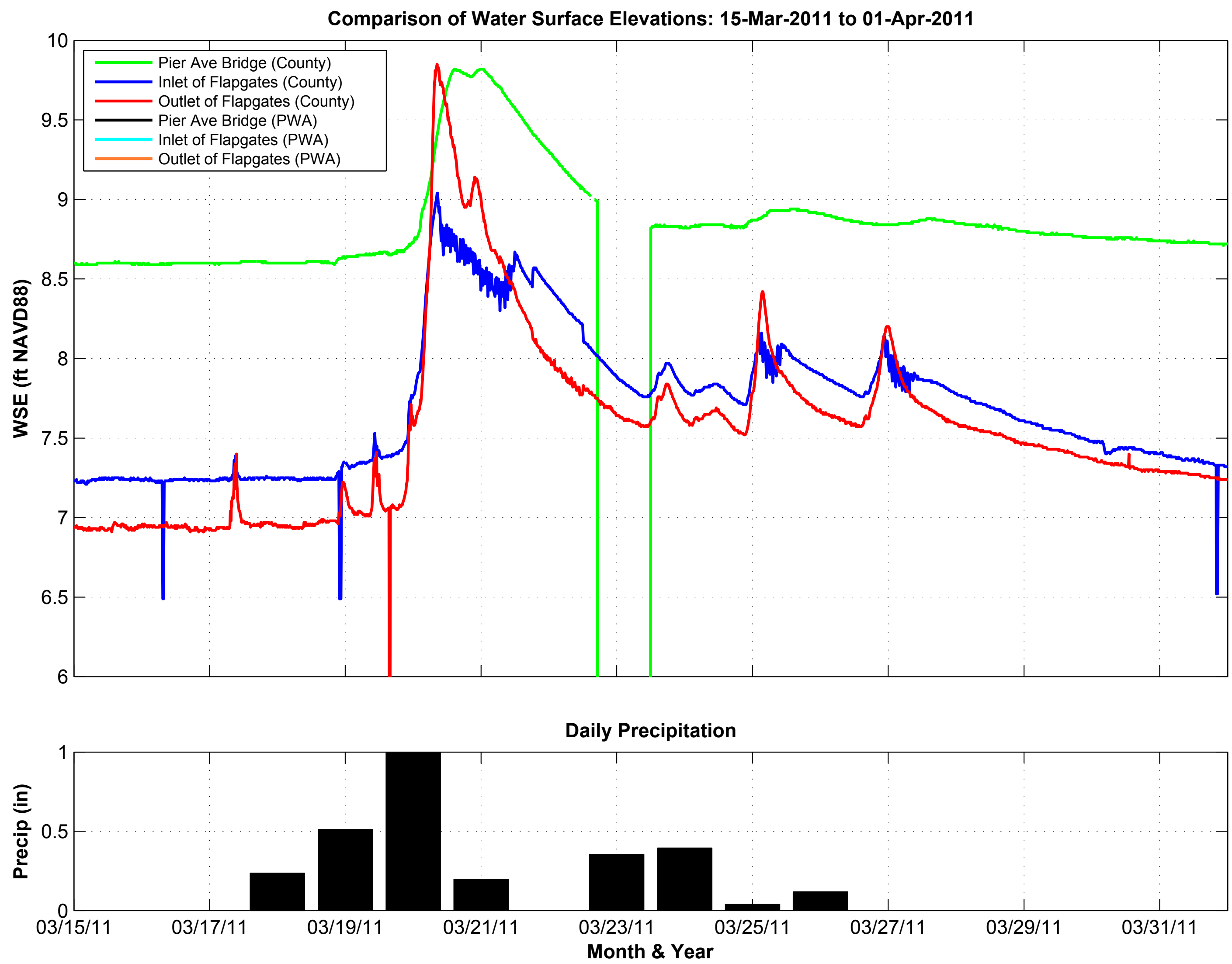
Figure 13C
Christmas 2010 Storm Hydrology
January 01- January 15, 2011



SOURCE: ESA, 2013

Figure 14A
March 2011 Storm Hydrology
March 01-15, 2011



SOURCE: ESA, 2013

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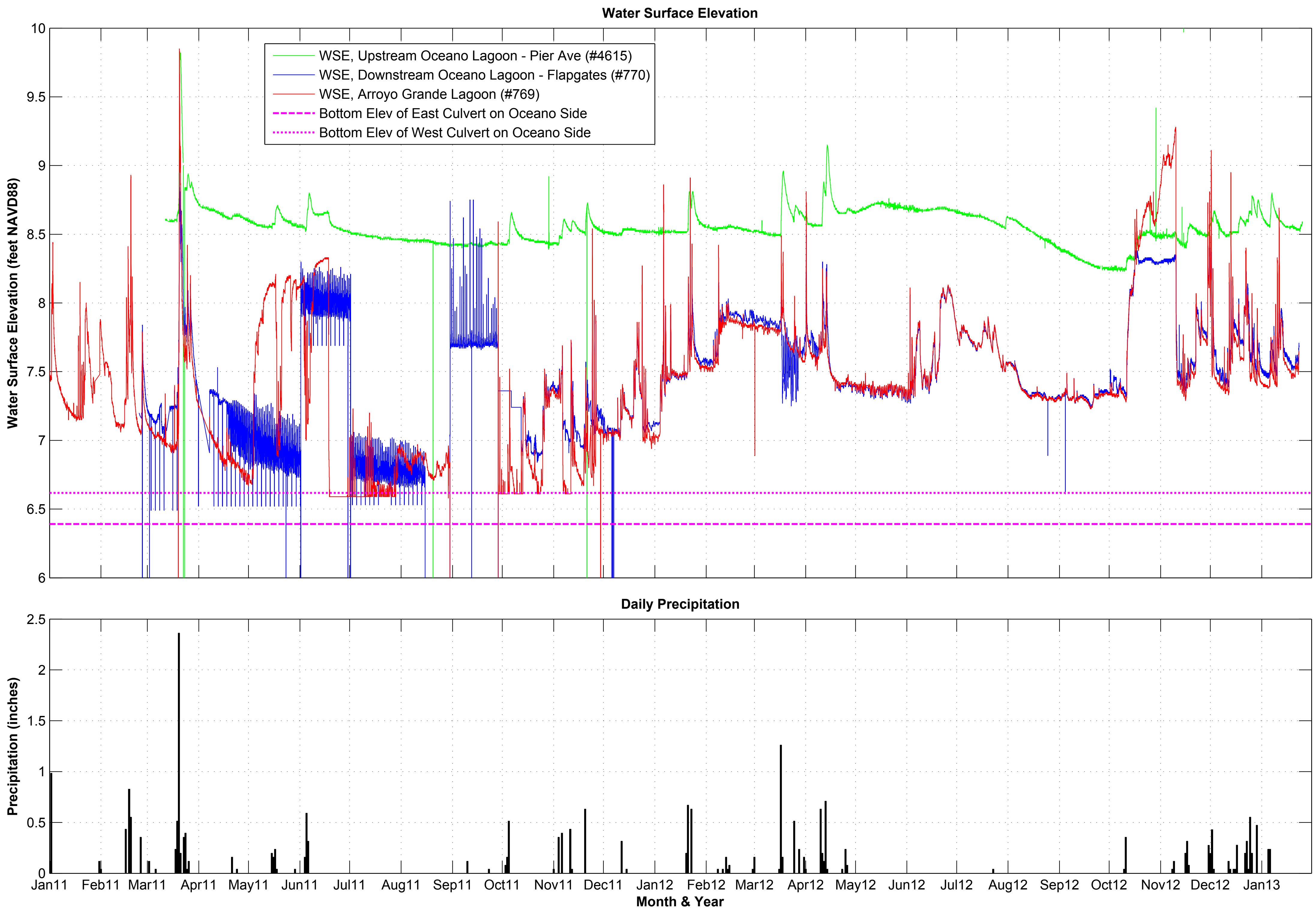
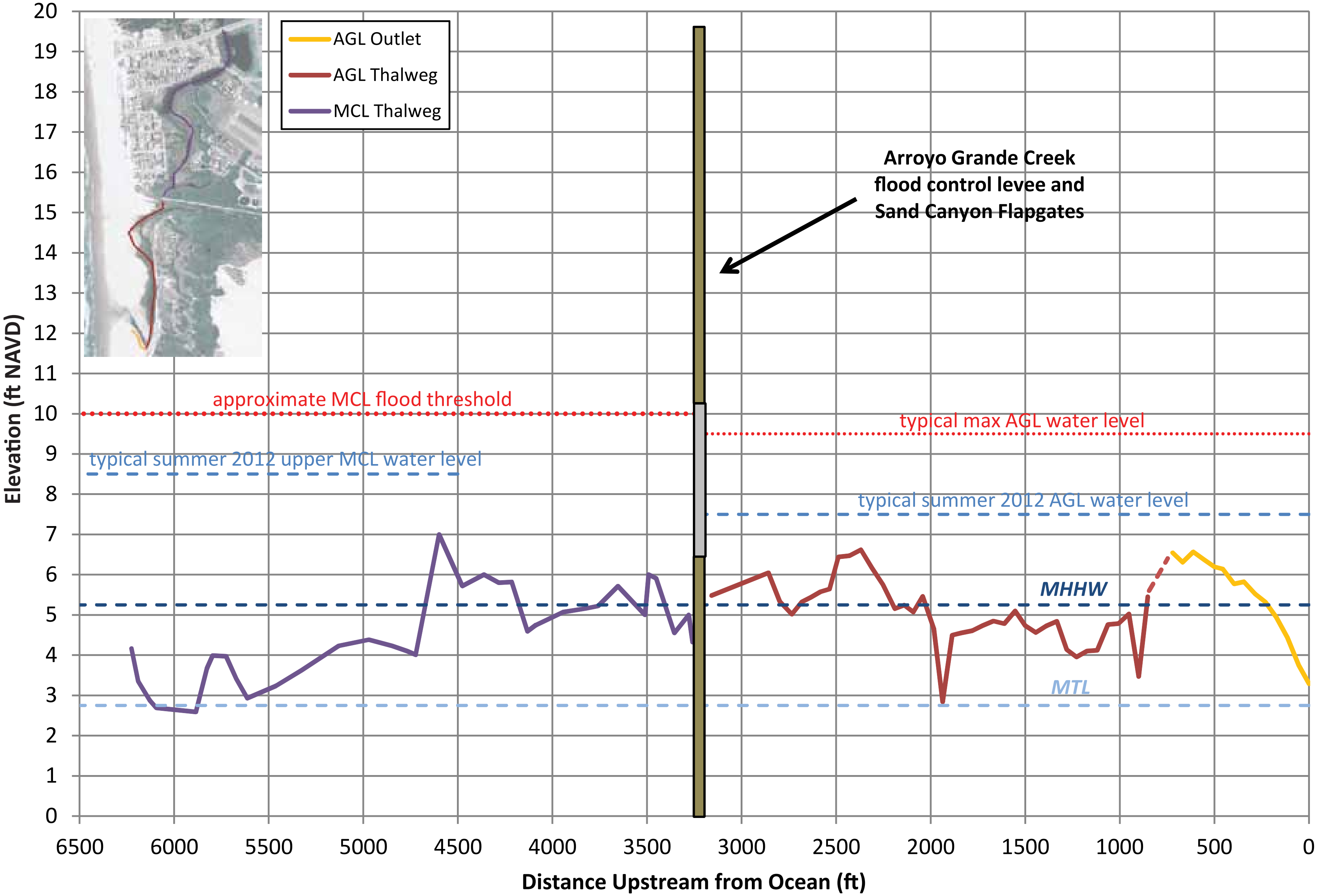
Figure 14B

March 2011 Storm Hydrology
March 15-April 01, 2011



SOURCE: ESA, 2013

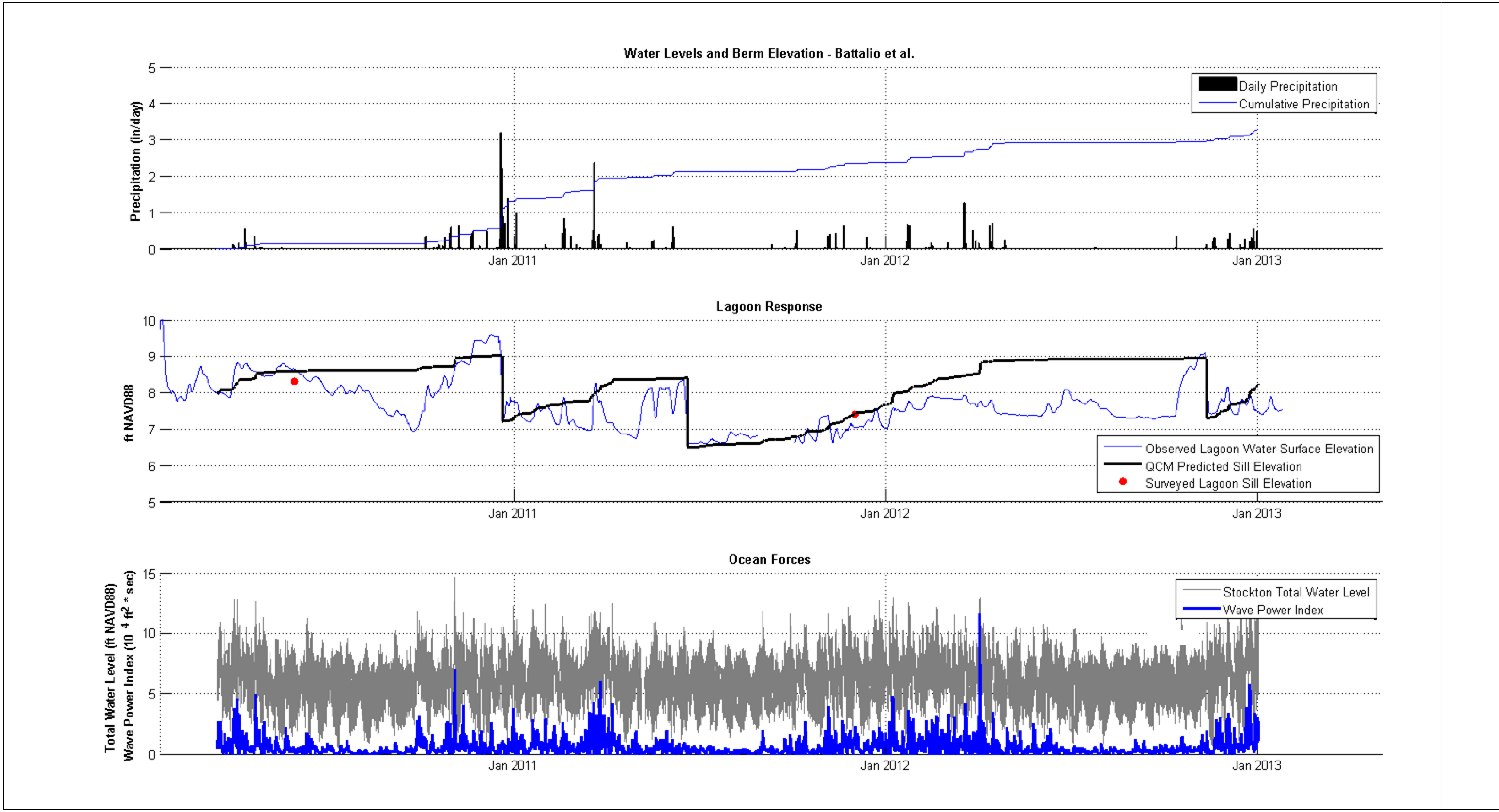
Figure 15
2012 Hydrology



SOURCE: ESA, 2013

Note: Meadow Creek Lagoon thalweg elevations are approximate due to limited data.

Figure 16
Arroyo Grande Lagoon - Meadow Creek Lagoon Elevation Profile

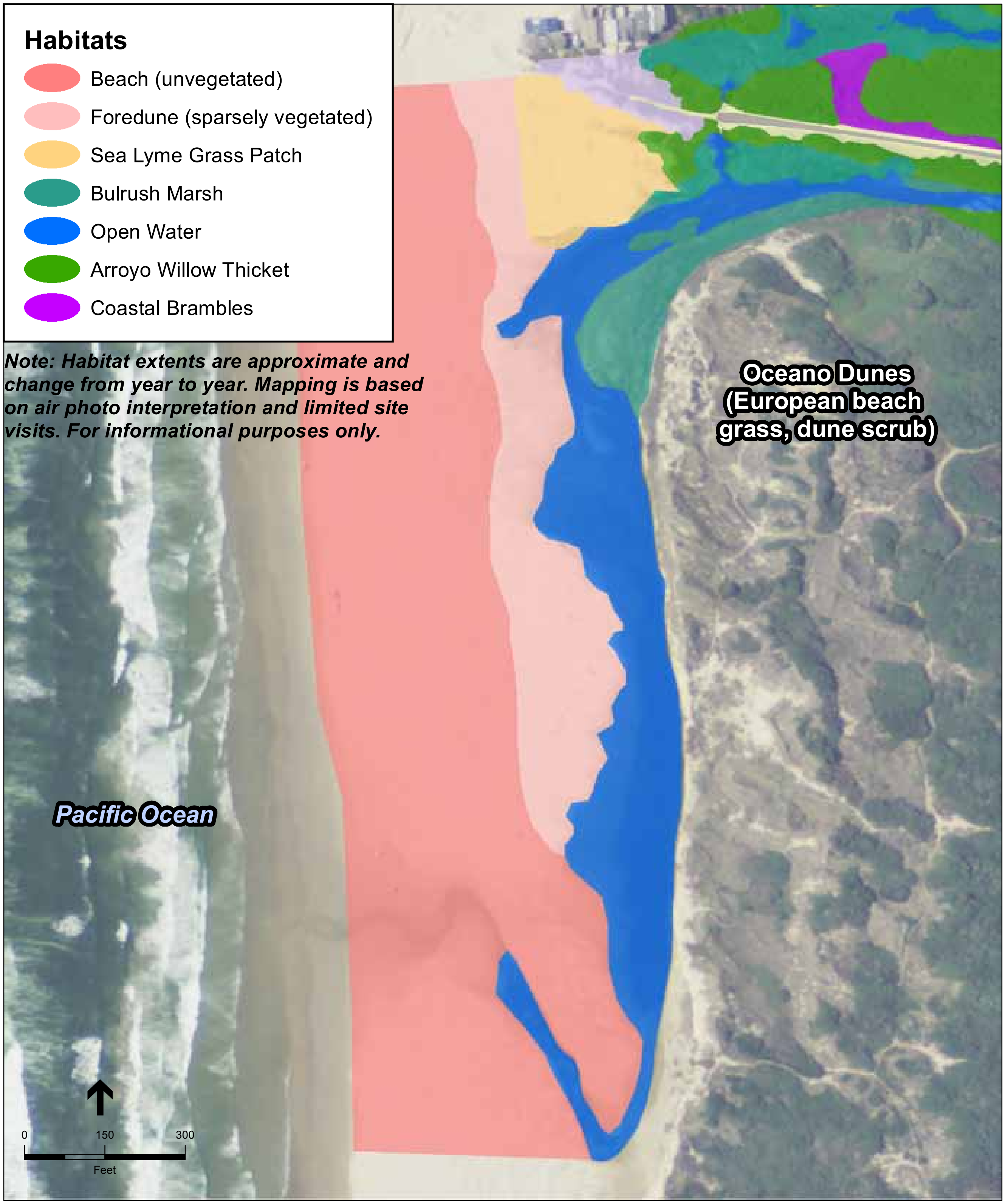


SOURCE: ESA 2013

Arroyo Grande Lagoon Interim Sandbar Management Plan . D211720

Figure 17

Quantified Conceptual Model Results



SOURCE: ESA PWA 2013 (AGL data), Terra Verde 2012 (MCL data), NAIP 2012 (air photo)

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Arroyo Grande Lagoon Interim Sandbar Management Plan . D211720

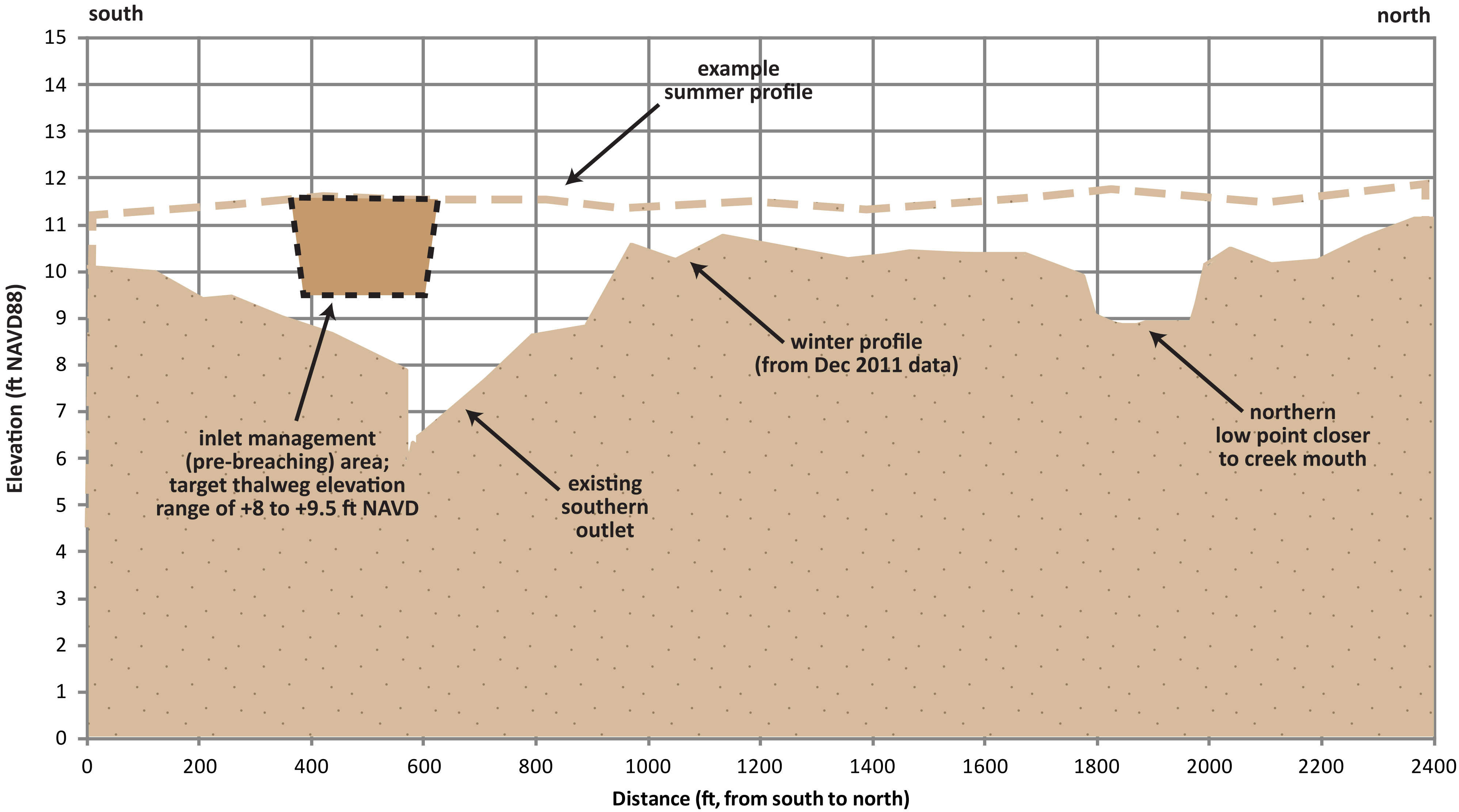
Figure 18
Arroyo Grande Lagoon Habitat Map

SOURCE: Terra Verde 2012

Arroyo Grande Lagoon Interim Sandbar Management Plan . D211720

Figure 19

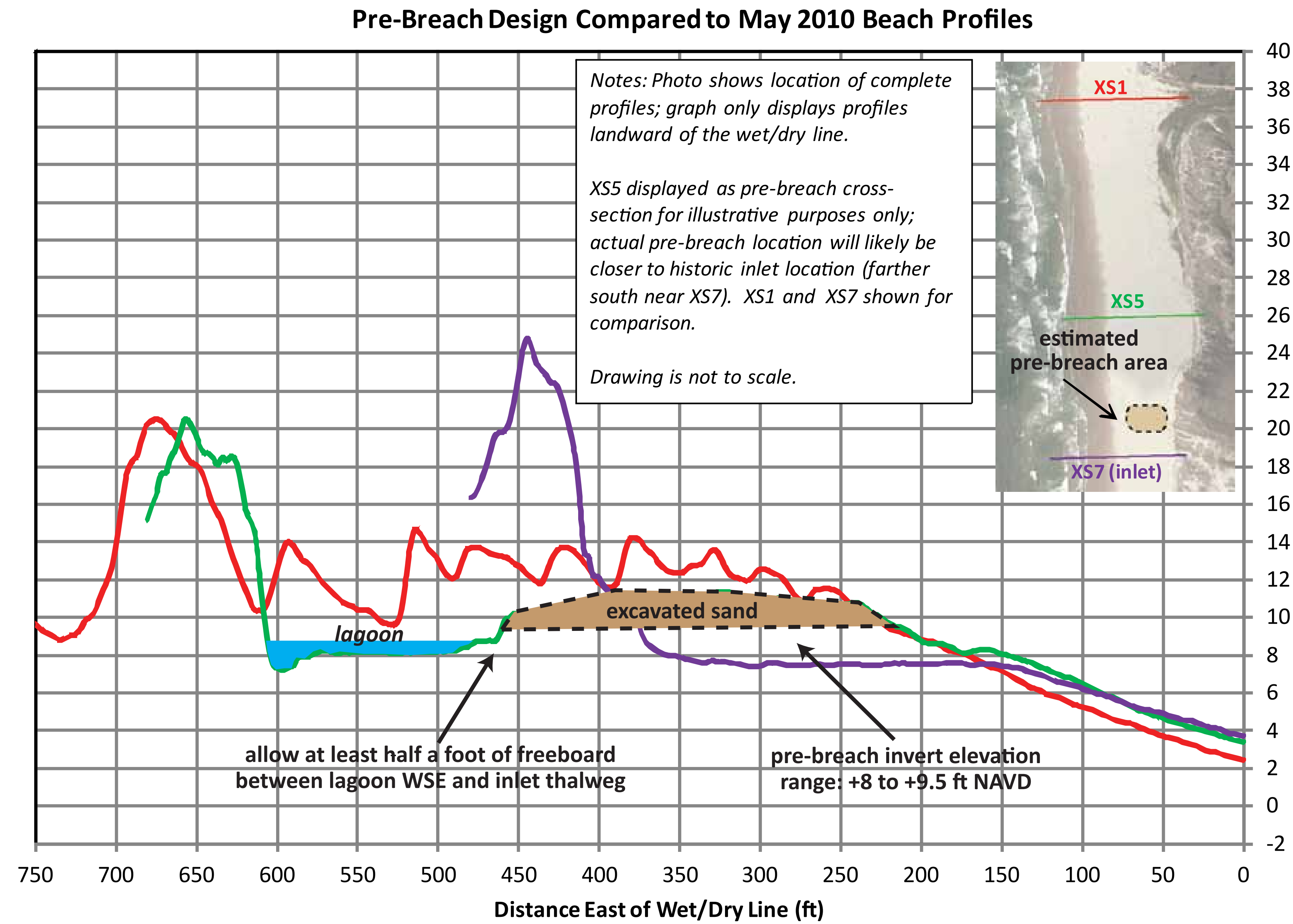
Meadow Creek Lagoon Habitat Map



Note: Drawing is not to scale and is for illustrative purposes only.

SOURCE: ESA, 2013

Figure 20A
Interim Sandbar Management Plan Details



SOURCE: ESA, 2013

Figure 20B
Interim Sandbar Management Plan Details

Appendix A

Technical Memo:
Preliminary Meadow Creek – Arroyo Grande Creek Hydrologic and Hydraulic Analyses
May 23, 2012

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memorandum

date 5/23/2012

to Mark Hutchinson, SLO DPW

from Christina Toms, ESA PWA

subject Preliminary Meadow Creek - Arroyo Grande Creek Hydrologic and Hydraulic Analyses

Introduction and Project Understanding

As part of an interim sandbar management plan under development for San Luis Obispo (SLO) County, ESA PWA has conducted preliminary hydrologic and hydraulic analyses of the Arroyo Grande (AG) and Meadow Creek systems at their confluence near the mouth of AG Creek. This memorandum provides the results of the hydrologic and hydraulic analysis to date.

The goal of the Arroyo Grande Lagoon Interim Sandbar Management Project is to identify a suite of sandbar/outlet management options that reduce the risk of flooding in the developed low-lying areas that surround Meadow Creek Lagoon. The purpose of the preliminary hydrologic and hydraulic (H+H) analyses is to identify the H+H conditions that can lead to potential flooding events. Meadow Creek enters Meadow Creek Lagoon (also referred to as Oceano Lagoon) which drains through culverts fitted with flap gates into a back-beach lagoon at the downstream end of AG Creek (Figure 1). The culvert flap gates prevent AG Lagoon from backwatering into Meadow Creek Lagoon and allow Meadow Creek Lagoon to drain as water levels recede in AG Lagoon. When the outlet between AG Lagoon and the Pacific Ocean is open, water can drain out of AG Lagoon, which can lead to drainage of water from Meadow Creek Lagoon. If the outlet is closed, the beach berm can create a backwater that inhibits drainage.

The work described in this technical memo is preliminary in nature and is not meant to define beach berm management objectives for Arroyo Grande Lagoon. Rather, the purpose of the preliminary hydraulic analysis is to develop a “first cut” of characterizing how the beach outlet of AG creek could influence water levels in Meadow Creek Lagoon, and to investigate how Meadow Creek Lagoon could respond to various AG Creek outlet configurations. The Meadow Creek Lagoon – Arroyo Grande Lagoon system is a poorly studied and understood system, and we have had to implement a broad range of analyses and assumptions in order to develop functionally descriptive hydrologic and hydraulic models of the system. Many of these analyses were outside our original scope of work, which assumed that a minimal amount of effort would be necessary to grow the original hydraulic model of AG Creek into a coupled model that described the entire lagoon system. The details of these analyses are presented below.

This memo is organized into the following sections: (1) a description of the hydrologic analyses used to develop inputs to the hydraulic model, (2) a description of the methods used to develop the hydraulic model, (3) the preliminary results of two modeled breach scenarios, and (4) recommendations for proposed modeling refinements. The work described in this memorandum was completed by James Gregory, Shinuo Deng, Damien Kunz, Christina Toms, and Louis White with oversight by Bob Battalio. James Gregory and Shinuo Deng implemented the hydrologic analyses and hydraulic modeling. Damien Kunz led ESA PWA's field data collection efforts, and Louis White led the development of a combined digital terrain model.

Hydrologic Analysis

An overview of the project location and AG and Meadow Creek watersheds is shown in Figure 1. A hydrologic analysis of the Meadow Creek watershed was conducted to characterize the watershed rainfall-runoff response for modeling various flow events. The SCS curve number method (NRCS 1986) was used to estimate peak flow and lag time parameters to generate synthetic hydrographs for runoff generated in the Meadow Creek watershed. The watershed was delineated in GIS and a composite runoff curve number was estimated using data collected for landuse, and soil type.

Landuse data was obtained as a gridded GIS raster at 100-foot resolution from the National Land Cover Database of 2006 (NLCD 2006). This information was merged with soil data for San Luis Obispo County obtained from the NRCS Soil Survey Geographic (SSURGO) database[1]. The land use types from the SCS curve number method were matched to the appropriate NLCD land use category for each soil type, and an area-weighted composite curve number for the watershed was estimated.

To estimate lag time for use in constructing a synthetic hydrograph, the following equation from the curve number method was applied:

$$t_{lag} = \frac{2.587 * L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{1900 * H^{0.5}}$$

Where:

t_{lag} = the time between the start of the hydrograph and the hydrograph peak (hours)
L = the length of the longest flow path in the watershed (feet)
CN = the watershed curve number
H = the average basin slope (%)

Basin slope was estimated using a 10-meter resolution digital elevation map obtained from the USGS[2]. The land use categories, basin slope, basin soils, and estimated curve number are shown in Figure 2. The hydrologic parameters estimated for the Meadow Creek watershed are summarized in Table 1.

[1] http://soils.usda.gov/survey/geography/ssurgo/
[2] http://seamless.usgs.gov/

Table 1. Meadow Creek hydrograph parameters for the SCS curve number method

Watershed	Drainage Area (mi^2)	Curve Number	Length of Longest Flowpath (ft)	Basin Slope	Lag Time (hours)
Meadow Creek	10.64	70.4	35,000	3.01%	10.75

This analysis builds on the SCS curve number modeling for the Arroyo Grande Creek watershed developed by SLO County Public Works (2011) and can be used for estimating the volume and timing of runoff from the Meadow Creek watershed. It should be noted that watershed area south of Highway 101 is highly urbanized and the more complicated flow routing is not captured by this analysis. This may influence the magnitude and timing of runoff from the Meadow Creek watershed as runoff from the more urbanized drainage would be expected to runoff and enter the lagoon quickly, while flow from the upper watershed is likely to more slowly drain to the lagoon. Comparisons of modeled flows to stage readings in the Meadow Creek Lagoon suggest the need to refine this model to capture these processes if simulating rainfall-runoff events.

Hydraulic Analysis

Existing Conditions Model

For this study, ESA PWA adapted an existing HEC-RAS hydraulic model of AG Creek developed by Waterways (2011). The existing model and the ESA PWA model are vertically referenced to the North American Vertical Datum of 1988 (NAVD88). The original model, which contained AG Creek from the mouth to approximately 1,000 feet upstream of Fair Oaks Avenue, and Los Berros Creek from AG Creek to approximately 600 feet upstream of Century Lane, was expanded to include Meadow Creek Lagoon and AG Lagoon. The upstream limit of the model was truncated on AG creek at 22nd Street, excluding Los Berros Creek from the hydraulic model. The updated model domain is summarized in Table 2.

Table 2. ESA PWA HEC-RAS model domain

Reach	Extent
Arroyo Grande Creek	Confluence with Meadow Creek Lagoon to the 22nd Street bridge
Arroyo Grande Lagoon	Ocean outlet to confluence with Meadow Creek Lagoon[1]
Meadow Creek Lagoon	Confluence with Arroyo Grande Creek to approximately 2,300 feet upstream of Pier Avenue[2]

[1]Ocean breach geometry modeled as outflow weir

[2]Includes culvert and flap-gate configuration connecting Oceano and AG lagoons

The expanded elements of the model, which include the Meadow Creek and AG Lagoons, the culverts connecting Meadow Creek Lagoon to AG creek, and the breach geometry at the AG lagoon outlet, were developed using HEC-GeoRAS, a GIS based tool that allows for the transfer of georeferenced topographic and hydraulic feature information between GIS and HEC-RAS. The channel lengths, and cross-section alignments and topography were set up in GIS and commuted to HEC-RAS using GeoRAS. The original model extents upstream of 22nd street were removed for this analysis and cross-sections downstream of 22nd street were not changed from the original model. The topographic data used to extract cross-section topography was developed from survey data collected by ESA PWA and Cannon Engineers (2011) and tied into LiDAR data and existing contour information as described below.

Topographic Surface Data

Existing grades at the project site were measured and characterized during two topographic field surveys of the Arroyo Grande Lagoon (December 1 and 2, 2011) and Meadow Creek Lagoon (January 4-6, 2012). Topographic surveys were performed using a combination of total station survey, utilizing laser level and stadia rod, and Real Time Kinematic (RTK) techniques. Measurements of spot elevations and hydrographic soundings were organized in cross sections across the lagoons, beach profiles to approximately subtidal elevations, and contour mapping of breaklines, such as the lagoon perimeter and other grade breaks. The Arroyo Grande Lagoon was open during the period of survey, although no significant change in water surface elevation was observed. Vertical and horizontal control was established by the County in cooperation with Cannon Engineers. Elevations are presented in feet relative to NAVD88. The horizontal coordinate system used for data analysis is the California State Plane System, Zone 5, in feet.

A triangular irregular network (TIN) model was developed using AutoCAD Civil 3D to approximate the existing grade of the Arroyo Grande Lagoon, beach, and Meadow Creek Lagoon. The survey data described above was used in combination with additional bathymetric survey of the Meadow Creek Lagoon provided by Cannon Engineers. Spot elevations, soundings, and breaklines were used to approximate the actual topographic and bathymetric relief of the site geomorphology. The TIN model was intended to provide a basis for modeling, including hydraulic cross sections and development of stage storage relationships.

Although the upstream extent of survey and modeling provided in the original scope of work was to the Pier Avenue Bridge, the storage in the lagoon north of the bridge likely plays a significant role in the hydraulics of the system. Therefore, the TIN model was extended to the northernmost portion of Meadow Creek Lagoon up to the California State Parks' field yard (approximately 2,000 feet). Existing LiDAR data (NOAA 2011) and aerial imagery (USDA 2010) was used to define the upland topography and the approximate perimeter of the lagoon. The depth of the lagoon was estimated based on the measured lagoon bathymetry on the south side of the Pier Avenue Bridge; we assumed the lagoon thalweg north of Pier Avenue to be 4 feet NAVD88.

The extent of the model, cross-section alignments, and the topographic surface developed for the modeling are included in Figure 3.

Model Calibration

The hydraulic model was run for the storm event that occurred over January 20-22, 2012 and calibrated to measured data at gauges on AG Creek and Meadow Creek Lagoon. San Luis Obispo County maintains several stream gauges that were used for this analysis. The gauges used are summarized in Table 3.

Table 3. SLO County gauge summary

Gauge ID	Location	Gauge Type	Current Datum
4165	Meadow Creek Lagoon at Pier Avenue	Water Level	NAVD88
769	Meadow Creek Lagoon on upstream side of flap gates	Water Level	NAVD88
770	Arroyo Grande Creek on downstream side of flap gates	Water Level	NAVD88
734	Arroyo Grande Creek at 22nd Street	Water Level	NAVD88

The water level gauges on AG Creek at 22nd Street and Meadow Creek Lagoon on the upstream side of the flap gates were used to develop boundary conditions for inflow at the upstream end of these features. The water level gauge on AG creek downstream of the flap gates was used as a calibration point to compare the model results and adjust the input parameters to match the gauge measurements.

Boundary Conditions

The model contains two upstream boundary conditions requiring inflow hydrographs: 1) on AG Creek at 22nd Street, and 2) at the upstream end of Meadow Creek Lagoon. The gauge on AG Creek at 22nd Street was used to estimate inflows at the upstream limit of this reach using a rating curve developed by the SLO County Public Works Department and provided to ESA PWA in 2012.

For flow into Meadow Creek Lagoon, the change in storage can be used as a surrogate for inflow during periods where the lagoon was not draining. The gauge records on either side of the flap gates indicate that water levels in AG Creek were higher than or equal to the water level in Meadow Creek Lagoon until approximately 09:00 on January 21. Flow into Meadow Creek Lagoon for this period was estimated using a stage-storage curve developed for the lagoon and assuming the change in storage was equal to the inflow until the AG creek levels dropped, allowing the lagoon to drain. Once the lagoon begins to drain, the change in storage is equal to the inflow minus the outflow. Outflow was estimated in a separate HEC-RAS model run wherein only the culverts were modeled and the measured stage from gauges 770 and 769 were used as the upstream and downstream boundaries, respectively. This estimated outflow was added to the change in storage in the lagoon to estimate total inflow from 09:00 on January 21 to the end of the simulation at 05:00 on January 22.

The downstream boundary of the model represents the AG Lagoon breach configuration at the time of the January 2012 storm. ESA PWA survey data was used to represent the shape of the breach which was included in the model as an overflow weir controlling the water levels in AG Lagoon. It was assumed that the ocean levels were fixed at a mean higher-high water of 5.25 feet NAVD estimated from the nearby Port San Luis tide gauge.

Calibration Results

The results of the modeling show a general agreement with the timing and magnitude of water levels measured on the downstream side of the Meadow Creek Lagoon culverts as shown in Figure 4. The model predictions show water levels consistently higher by approximately 0.3-0.4 feet as compared to the gauge. This suggests that a system loss that is not represented in the model. Losses not accounted for in the model include evaporation and lateral seepage from the AG lagoon through the beach which may explain the difference in modeled versus measured water levels. Additionally, the topographic survey of the breach is likely to underestimate the actual opening size which would scour during higher flow events releasing water from AG Lagoon and allowing

Meadow Creek Lagoon to drain. As a further check on the accuracy of the model and estimated inflows, modeled water levels were compared to measured data on the upstream side of the Meadow Creek Lagoon culverts. As shown in Figure 5, simulated water levels match the gauge until the water levels in AG lagoon begin to recede after which Meadow Creek Lagoon modeled water level remains approximately 0.3 feet higher than measured water levels at this point. The elevated water levels in Meadow Creek Lagoon are a function of the higher than expected levels in AG Lagoon which is a function of other sources of loss not represented in this model run. A refinement to the model calibration could include estimating these losses and including them in the simulation; this refinement is discussed in further detail below under "Proposed Modeling Refinements."

Further upstream, near Pier Avenue, modeled water levels do not match very well with the measured gauge data. One reason for this may be that the upper part of Meadow Creek Lagoon and the lower part are not fully hydraulically connected, so water levels rise in upstream Meadow Creek Lagoon more than they do near the connection with AG Creek. A beaver dam between the two gauges was removed in early December 2011; it's possible that this dam was reconstructed before the measured/modeled January 2012 event. Another reason for this difference may be that the AG Creek levels back up into Meadow Creek Lagoon due to poorly sealed flap gates. The gauge measurements indicated that this is probable (i.e. water level fluctuations on the upstream side of the gates closely match the downstream side). While these results are relevant to calibration, they are less relevant to flood modeling, as most of the problems associated with flooding occur around the downstream end of Meadow Creek Lagoon. However, future model refinements should at the very least identify the source of this error, and assess its relevance to overall lagoon hydraulics (see "Proposed Modeling Refinements" below).

Breach Scenarios Modeling

In order to characterize how various configurations of the AG Lagoon breach influence water levels in Meadow Creek Lagoon, model runs were constructed for two flooding events: one on March 20-21, 2011 and another for the Christmas 2010 event that flooded low-lying homes around Meadow Creek Lagoon. For both events, boundary inflows were estimated using the same methods as for the calibration event.

The March 2011 event modeled unsteady hydrographs with peak flows of 247 cfs in Meadow Creek, and 942 cfs in Arroyo Grande Creek. Iterating the breach height provides a range of possible outlet scenarios and corresponding upstream water levels in Meadow Creek Lagoon. The shape of the breach will evolve through time as flood levels and scour potential fluctuate. However, for the purposes of this analysis, the breach was idealized as a 500-foot wide spillway with a constant elevation for each model iteration. The relationship between breach elevation and Meadow Creek Lagoon elevation for the March 2011 event is shown in Figure 6. As described above, the hydraulic model does not account for seepage through the beach from AG Lagoon which will be larger for higher water levels in the lagoon. Thus this relationship represents a slightly more conservative approximation of water levels in Meadow Creek than may be expected for this type of event. The results indicate that for the modeled AG lagoon configuration and flows, a beach berm elevation of +9.6 ft NAVD88 is enough to induce water surface elevations in Meadow Creek Lagoon of +10.4 ft NAVD88, which is the approximate threshold for flooding of the lowest homes around the lagoon.

The Christmas 2010 event modeled unsteady hydrographs with peak flows of 106 cfs in Meadow Creek, and 1381 cfs in Arroyo Grande Creek. During this event, the stage recorders in Meadow Creek Lagoon contained several periods of discontinuous data and apparent inconsistencies and thus were not used to construct the hydrograph for flows into the lagoon. Instead we constructed an inflow hydrograph for Meadow Creek by scaling the estimated flows in Arroyo Grande Creek by the ratio of the drainage areas of the two creeks (138.6 sq-mi for Arroyo Grande Creek, and 10.64 sq-mi for Meadow Creek). Our attempts to model this event were complicated by the response of the model to setting a beach berm height any lower than +7 ft NAVD88. Below this height, the model went "unstable" and returned unreliable results. Above this elevation, the modeled flood response was enough to induce flooding around Meadow Creek Lagoon above the +10.4 ft NAVD88 threshold. Our suggestions to improve model stability at these flows are described below under "Proposed Modeling Refinements."

Implications for Lagoon Flooding

The analyses indicate that the invert (sill) elevation of the lagoon outlet does affect the flooding potential for the low-lying areas that surround Meadow Creek Lagoon. However, the mechanisms of flooding in the system and the complications of modeling these mechanisms are such that it is inadvisable to define a single "target" outlet invert elevation for flood management purposes. Different rainfall events will induce different flows, which will have different flood threshold elevations. In addition, the invert elevation of the outlet varies with both wave action, which typically tends to raise the elevation (i.e. building of the beach berm), and outflow, which tends to lower the elevation (i.e. scour). Since coastal storms typically influence both wave action and outflow, the invert elevation of the mouth can vary on an hourly basis during the flood event. Consequently, the quasi-dynamic hydraulic modeling described here is an approximation of the system's actual dynamics; it has multiple uncertainties and areas for improvement. Nonetheless, the key questions we are trying to address with this model are: (1) what can we learn about the system's hydrodynamics, and (2) what changes to outlet management could be worth pursuing?

The preliminary modeling effort indicates the following:

- Management of the mouth as a means of reducing flood risk is supported by the model results, but it is unclear whether mouth management alone is sufficient or practical.
    - A mouth elevation below about +9.5' NAVD will reduce flood potential for conditions similar to the March 2011 event.
    - A lower, undetermined mouth elevation is necessary to reduce flood potential for conditions similar to the Christmas 2010 event.
- Increasing the storage volume in the Meadow Creek Lagoon will likely reduce flood risk.
- Additional modeling can provide useful information for flood risk reduction as well as multi-objective lagoon management.

The results also indicate that incremental improvements to the model can improve its utility. We recommend the improvements listed below in the approximate order of their priority, based on a consideration of benefit and cost:

- Improvement of inflow hydrographs via a more detailed consideration of watershed conditions and/or measurements;
- Implementation of a more rigorous analysis of the elevations of the gage data provided by the County;

- Improved modeling of the AG Lagoon, including dynamic modeling of the ocean water level boundary condition and breach geometry, preferably informed with additional survey data;
- Expansion of the model upstream in surface water and drainage system areas.
- Development of model refinements with new data collection, including:
    - Outlet and AG Lagoon surveys during open conditions, coincident with other data, for model calibration and validation;
    - Flow measurements in the lagoon at controlled cross sections (e.g. bridges)
    - Additional survey data of the upstream portion of the lagoon; and
    - Storm system flow data.

We can provide additional detail about proposed model refinements upon request.

Our analyses thus far have indicated that potentially feasible interim outlet management measures should encourage the outlet to breach sooner and scour deeper than it otherwise would during a given flooding event. One potential way to do this would be the installation of coarser, more permeable material at a location in the beach berm that is closer to where Arroyo Grande Creek exits its leveed, riparian corridor (creek mouth). The installation of this material would encourage the lagoon outlet to form at this location, shorten the distance between the creek mouth and the creek outlet, and facilitate the more rapid scour of the outlet so that flows have less opportunity to accumulate within Arroyo Grande Lagoon (and therefore Meadow Creek Lagoon) during a storm event. A more rigorous analysis of opportunities and constraints, including coordination with local regulatory agencies, will allow us to refine this potential management measure and develop an interim sandbar management plan.

Conclusions

The work accomplished to-date has resulted in a tool that approximates hydrologic and hydraulic conditions in the Meadow Creek Lagoon – Arroyo Grande Lagoon system. The H+H models are useful now and can be incrementally improved over time with supplemental model data and calibrations. The model demonstrates the significant influence of the beach – mouth conditions on flood risk in Meadow Creek Lagoon. Model improvements can enhance the precision and accuracy of the model, which can in turn facilitate the development and analysis of appropriate mouth management actions. The model indicates that potential management measures at the creek outlet should facilitate the outlet to breach sooner and scour deeper than it otherwise would during a given flooding event.

References

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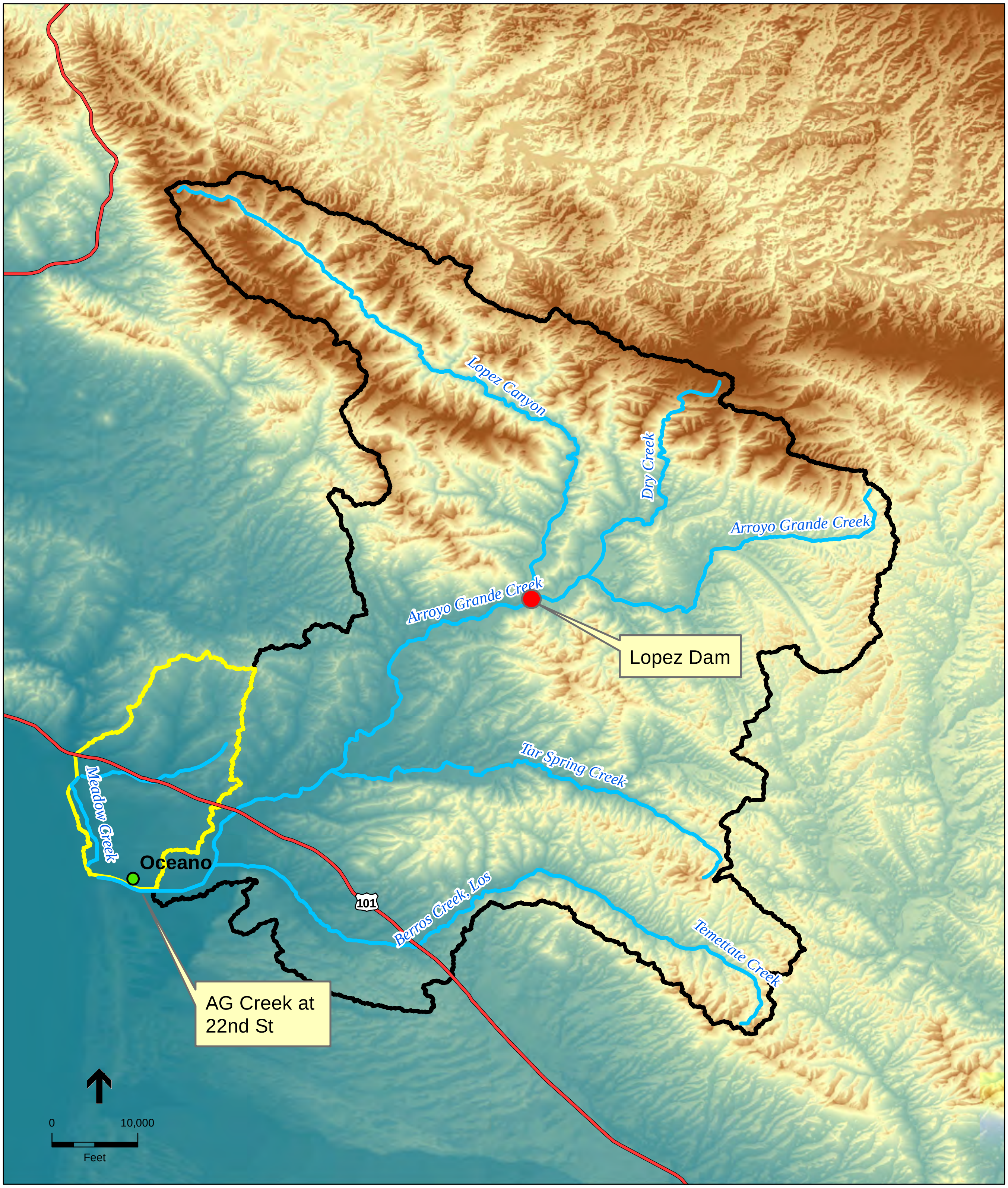
LIST OF FIGURES



SOURCE: USGS DEM (2009)

Arroyo Grande Interim Sandbar Management. D211720

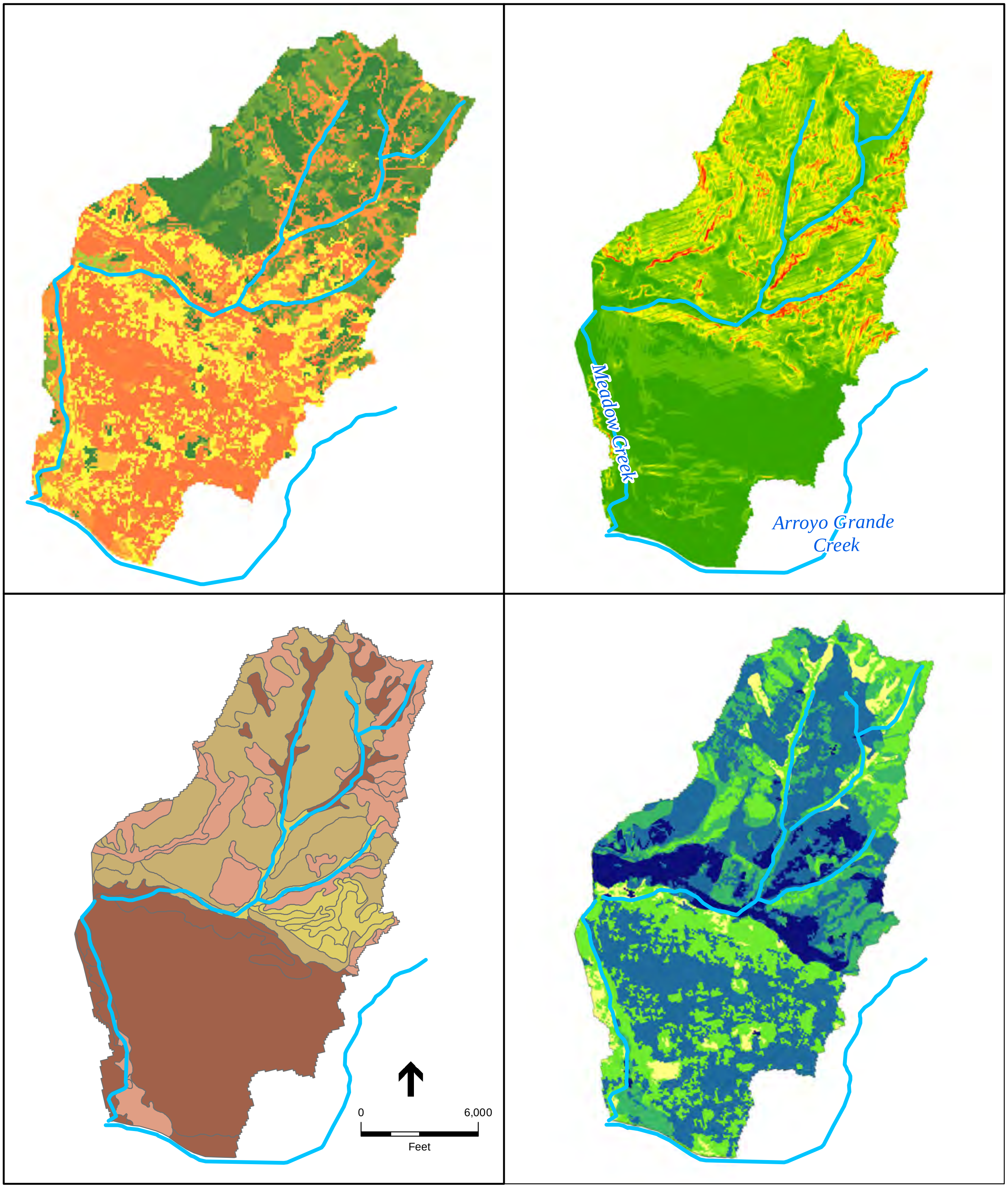
Figure 1

Arroyo Grande Creek and Meadow Creek Watershed Overview

Channels
Meadow Creek Watershed
Arroyo Grande Watershed

Elevation

376.9
188.4
-0.1



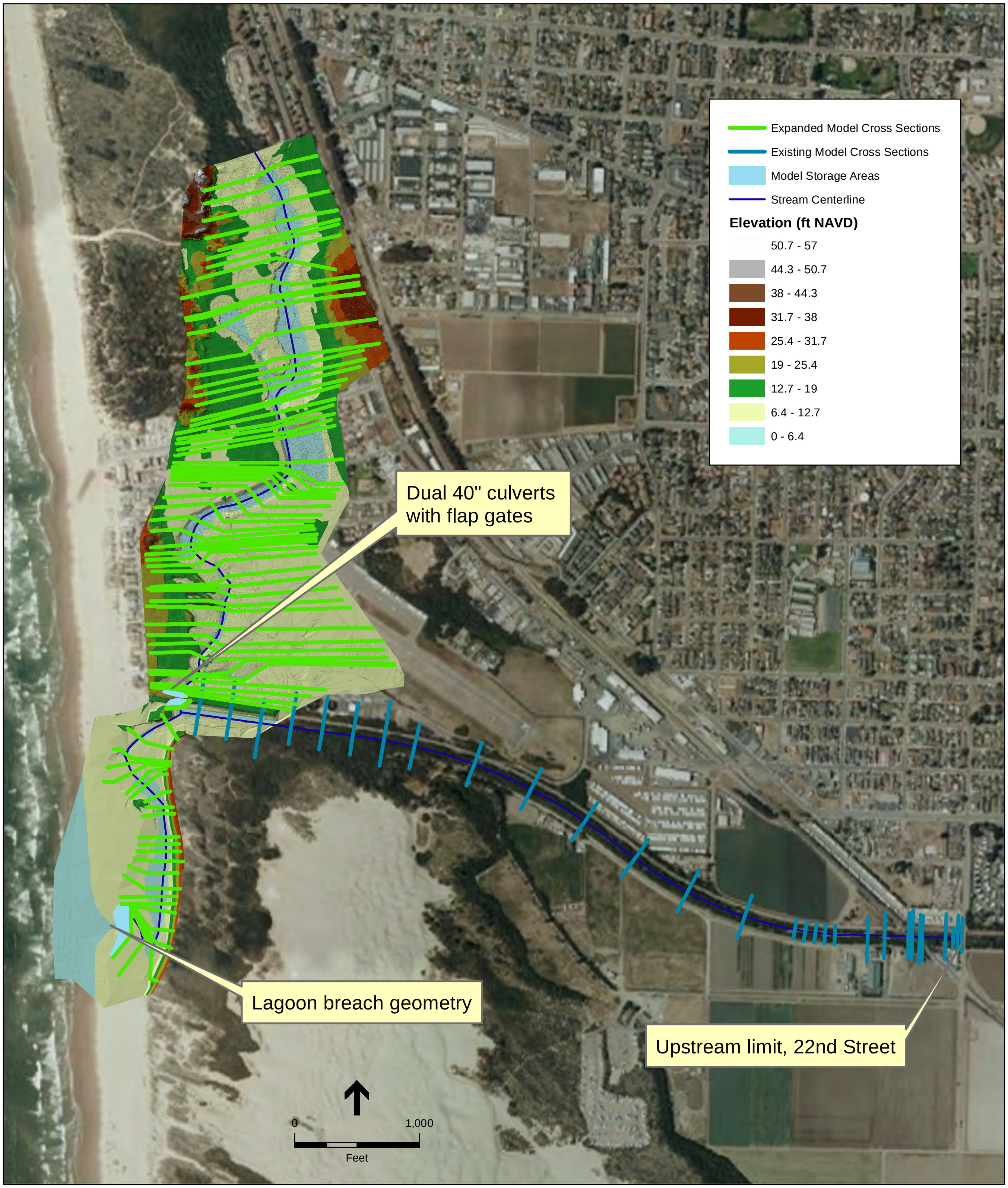
SOURCE:National Land Cover Database(2006), NRCS Soil Survey Geographic, USGS DEM(2009)

NLCD Landuse Class	Slope %)	Hydrologic Soil Group	Curve Number
Barren Land (Rock/Sand/Clay)	0 - 1.13	A	30 - 36
Cultivated Crops	1.13 - 2.75	B	37 - 61
Developed, High Intensity	2.75 - 4.25	C	62 - 76
Developed, Low Intensity	4.25 - 5.75	D	77 - 85
Developed, Medium Intensity	5.75 - 7.50		86 - 100
Developed, Open Space	7.05 - 9.65		
Emergent Herbaceous Wetlands	9.65 - 12.51		
Evergreen Forest	12.51 - 16.88		
Grassland/Herbaceous	16.88 - 31.89		
Mixed Forest			
Open Water			
Pasture/Hay			
Shrub/Scrub			
Woody Wetlands			

Arroyo Grande Interim Sandbar Management. D211720

Figure 2

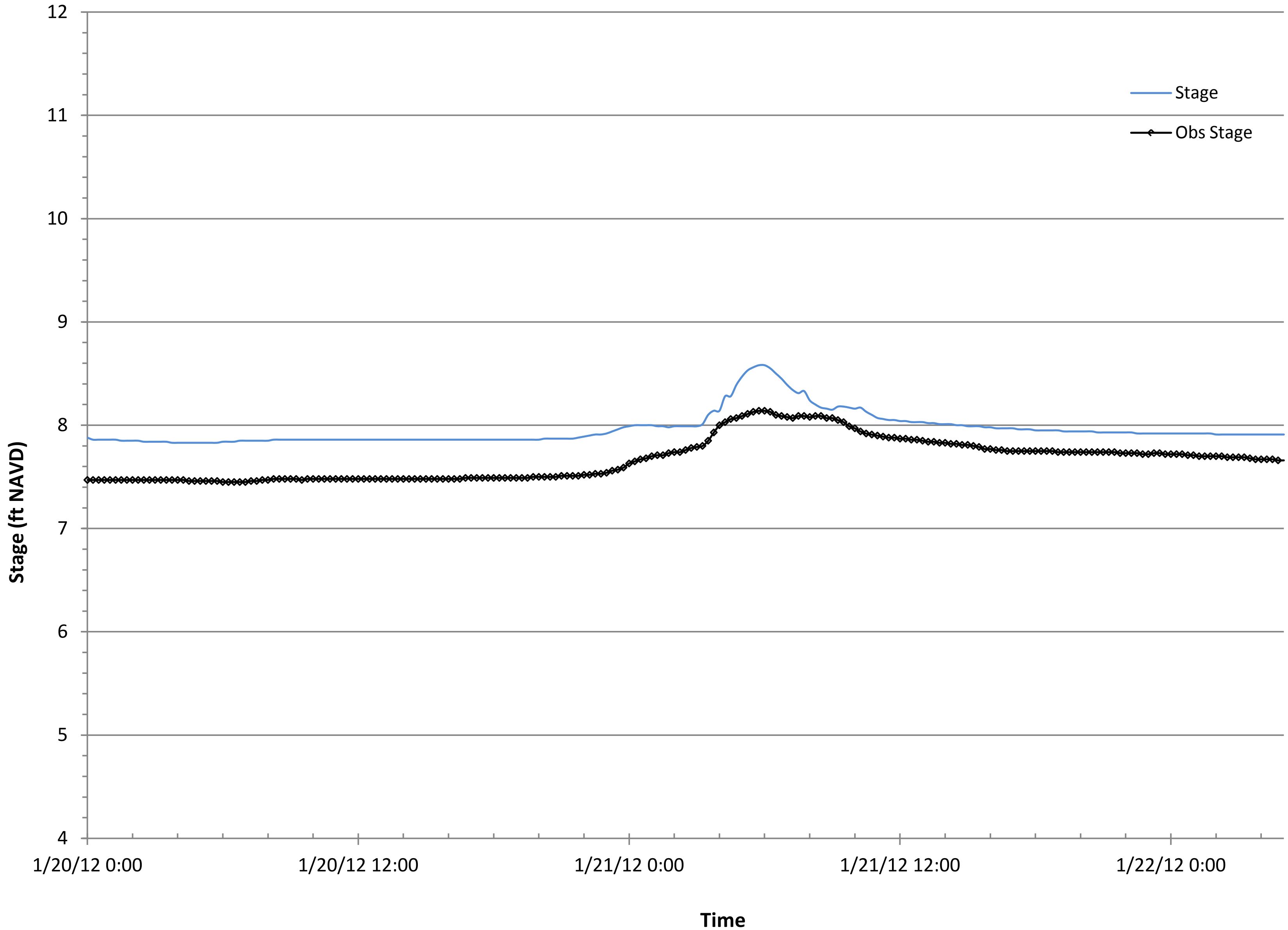
Meadow Creek Curve Number GIS Inputs



SOURCE: NAIP (2010)

Arroyo Grande Interim Sandbar Management. D211720

Figure 3
Arroyo Grande Creek and Meadow Creek Hydraulic Model Layout

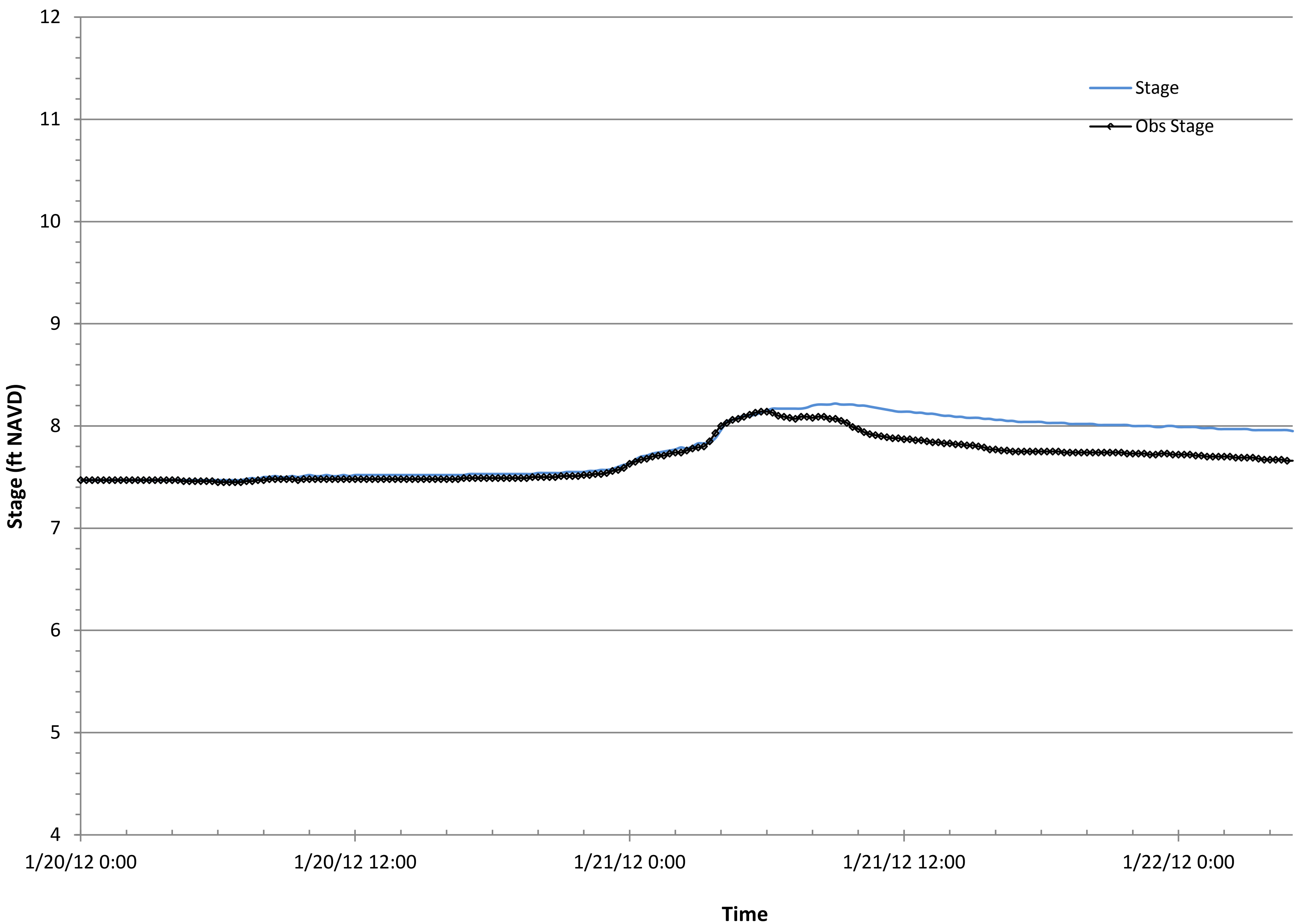


Arroyo Grande Interim Sanbar Management. D211720.00

Note: Provisional results

Figure 4

Hydraulic Model Calibraion on Downstream Side of Oceano Lagoon Flap Gates for January 2012 Storm

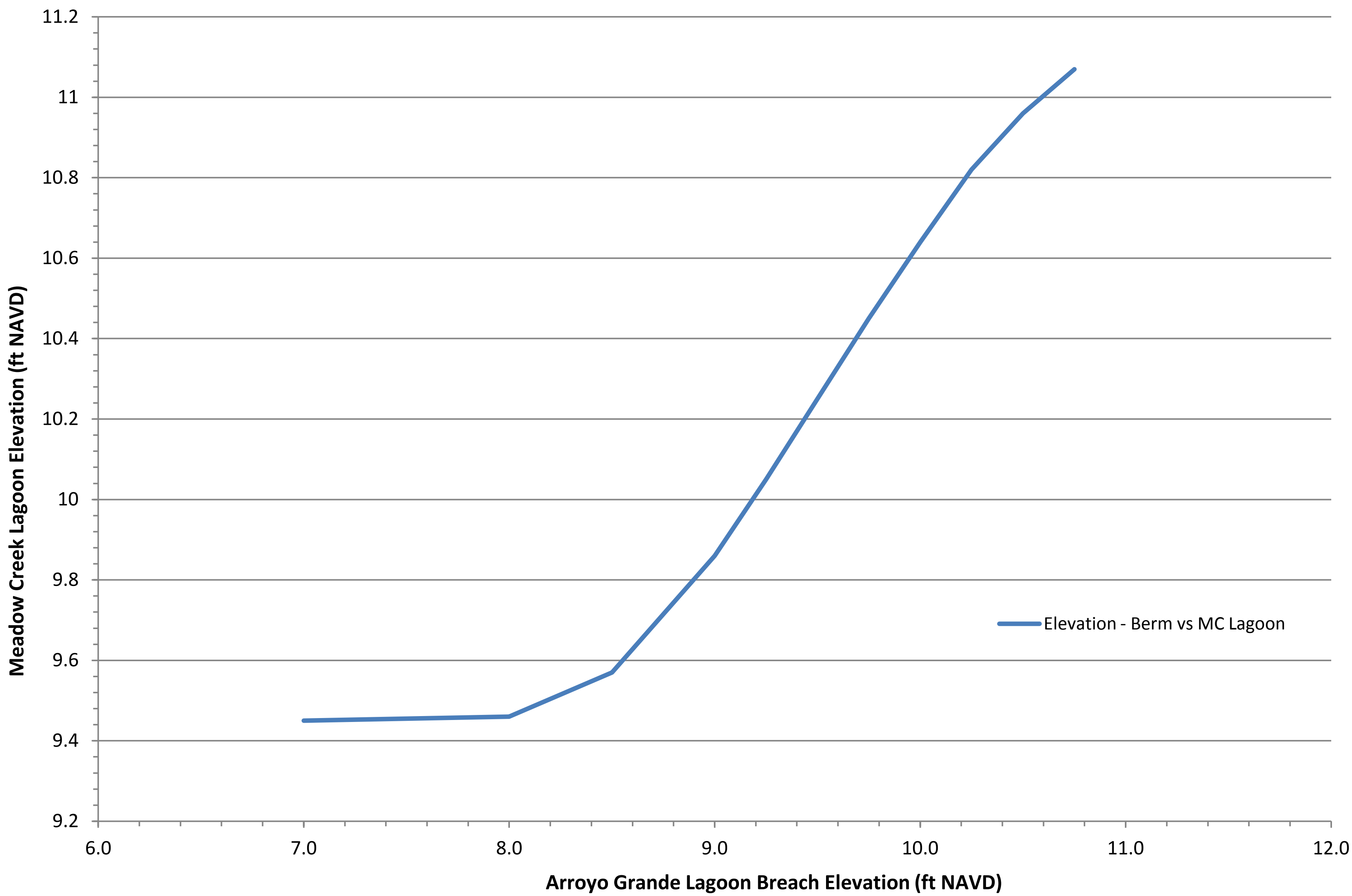


Note: Provisional results

Arroyo Grande Interim Sandbar Management. D211720.00

Figure 5

Hydraulic Model Calibration on Upstream Side of Oceano Lagoon Flap Gates for January 2012 Storm



Note: Provisional results

Arroyo Grande Interim Sandbar Management. D211720.00

Figure 6

Modeled Meadow Creek Lagoon Water Surface Elevation as a Function of Arroyo Grande Lagoon Breach Elevation for an Event on March 20, 2011

Appendix B

Quantitative Conceptual Model Setup

Appendix B – Quantitative Conceptual Model Setup

The QCM predicts the evolution of the berm crest elevation by tracking the cumulative effect of the accretive forces acting on the beach berm over time. The model tracks these effects using a simple time-advancement scheme based on the following formulation:

Z_berm_new = Z_initial + timestep * (Steady Accretion Rate + Rapid Accretion Rate)

Past studies of similar lagoons (e.g. Crissy Field) have shown that wave driven beach accretion acts in two modes, the first mode is the continuous, "steady accretion" caused by small to medium sized waves during normal conditions, and second is the "rapid accretion" caused by large waves during infrequent storm events. In both modes of accretion the beach berm elevation has been observed to grow towards the limit of wave run-up at a rate scaled by the incident wave power. For our model we use the Stockton Total Water Level (TWL) as an estimate for the limit of run-up. The QCM accounts for the two modes of accretion through the following parameterization:

Steady Accretion Rate=	c1 * WavePower * (TWL – Z_berm)	
Rapid Accretion Rate =	c2 * (WavePower - c3) * (TWL – Z_berm)	for Wave Power>= c3
	0	for WavePower< c3

where c1, c2, and c3 are fitting parameters which have been selected in order to match the estimated lagoon berm crest elevations inferred from the water level record. The model starts with the initial berm height set to match the measured water level in Arroyo Grande Lagoon, and the berm height is reset to equal the TWL on days when major lagoon breaching events were record to represent rapid scour which occurs as water flushes out the lagoon channel.