ESA PWA

550 Kearny Street
Suite 900
San Francisco, CA 94108
415.262.2300 phone
415.262.2303 fax

www.pwa-ltd.com

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

National Oceanic and Atmospheric Administration (NOAA), 2011. 2009 - 2011 California Coastal Conservancy Coastal LiDAR Project, NOAA's Ocean Service, Coastal Services Center, Charleston, SC.

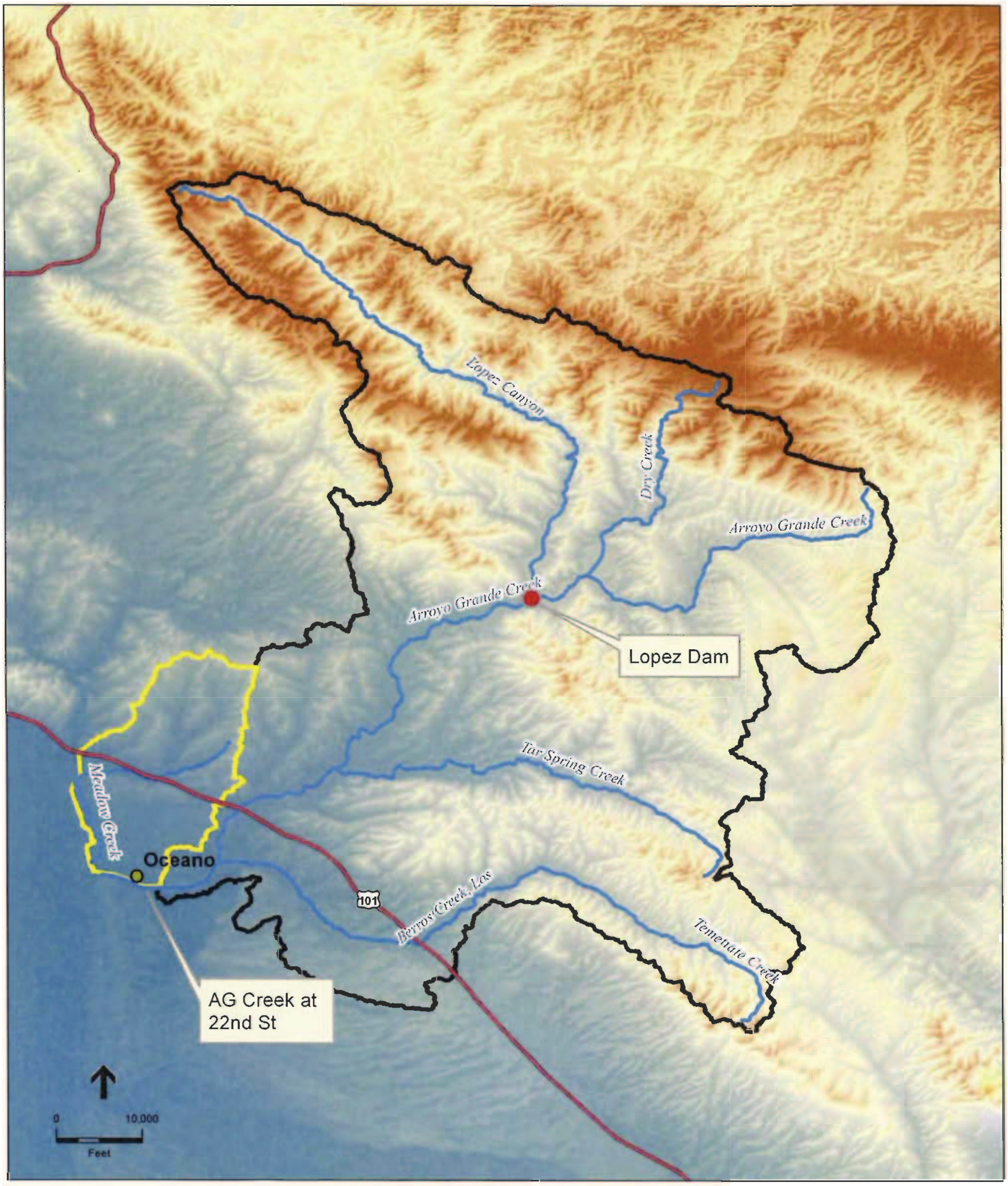
National Resource Conservation Service (NRCS), 1986. Urban Hydrology for Small Watersheds, TR-55.

San Luis Obispo County Department of Public Works, 2011. Hydrograph Input Data for the SCS Hydrograph Model. Location: Arroyo Grande Creek.

Waterways Consulting, Inc., 2011. Arroyo Grande Creek Flooding Analysis Project. HEC-RAS hydraulic model.

United States Department of Agriculture (USDA), 2010. National Agriculture Inventory Program. Aerial photograph flown August 23.

LIST OF FIGURES



Arroyo Grande Interim Sandbar Management. D211720

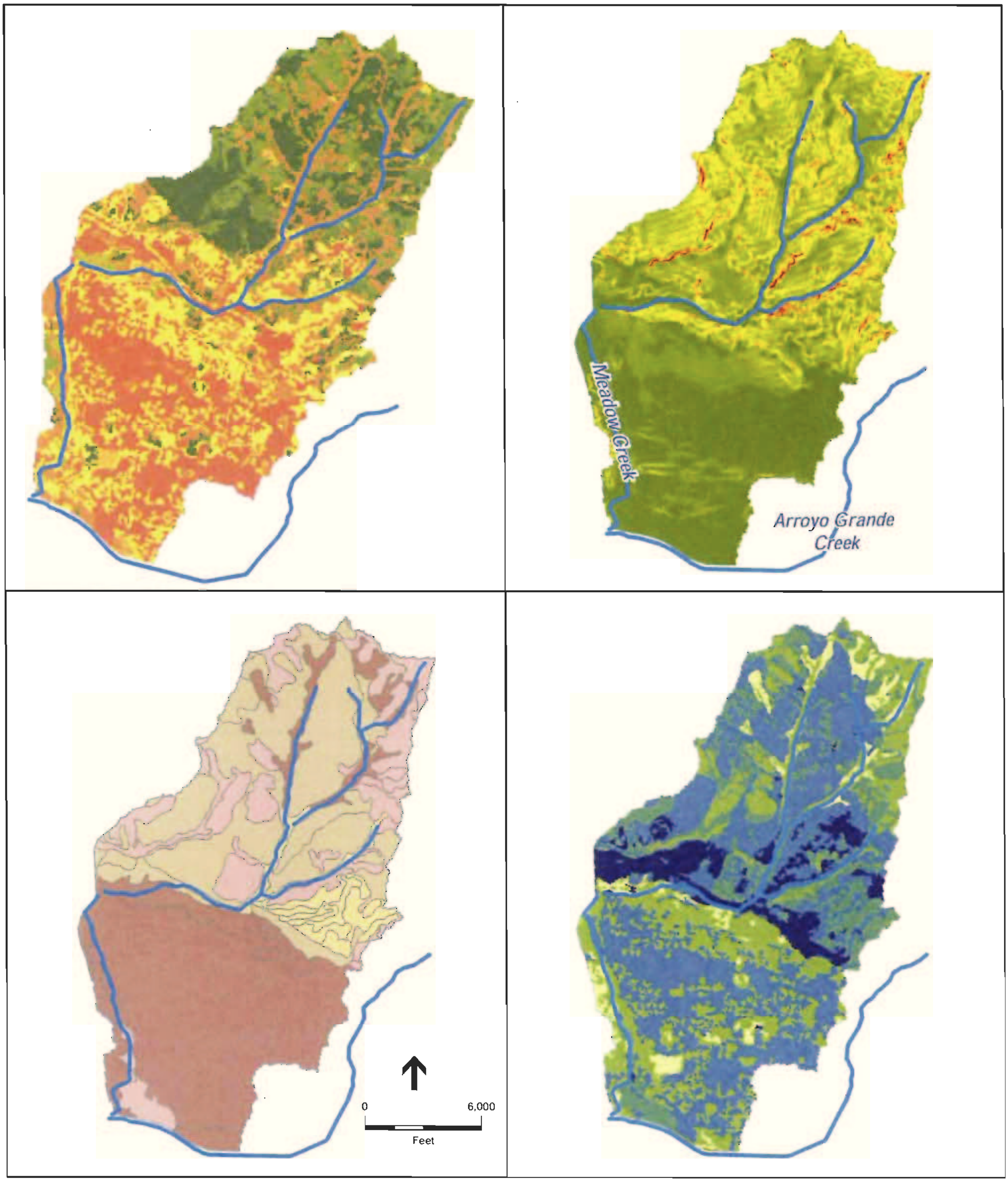
SOURCE: USGS DEM (2009)

Figure 1

Arroyo Grande Creek and Meadow Creek Watershed Overview

Channels
Meadow Creek Watershed
Arroyo Grande Watershed

Elevation
376.9
188.4
-0.1



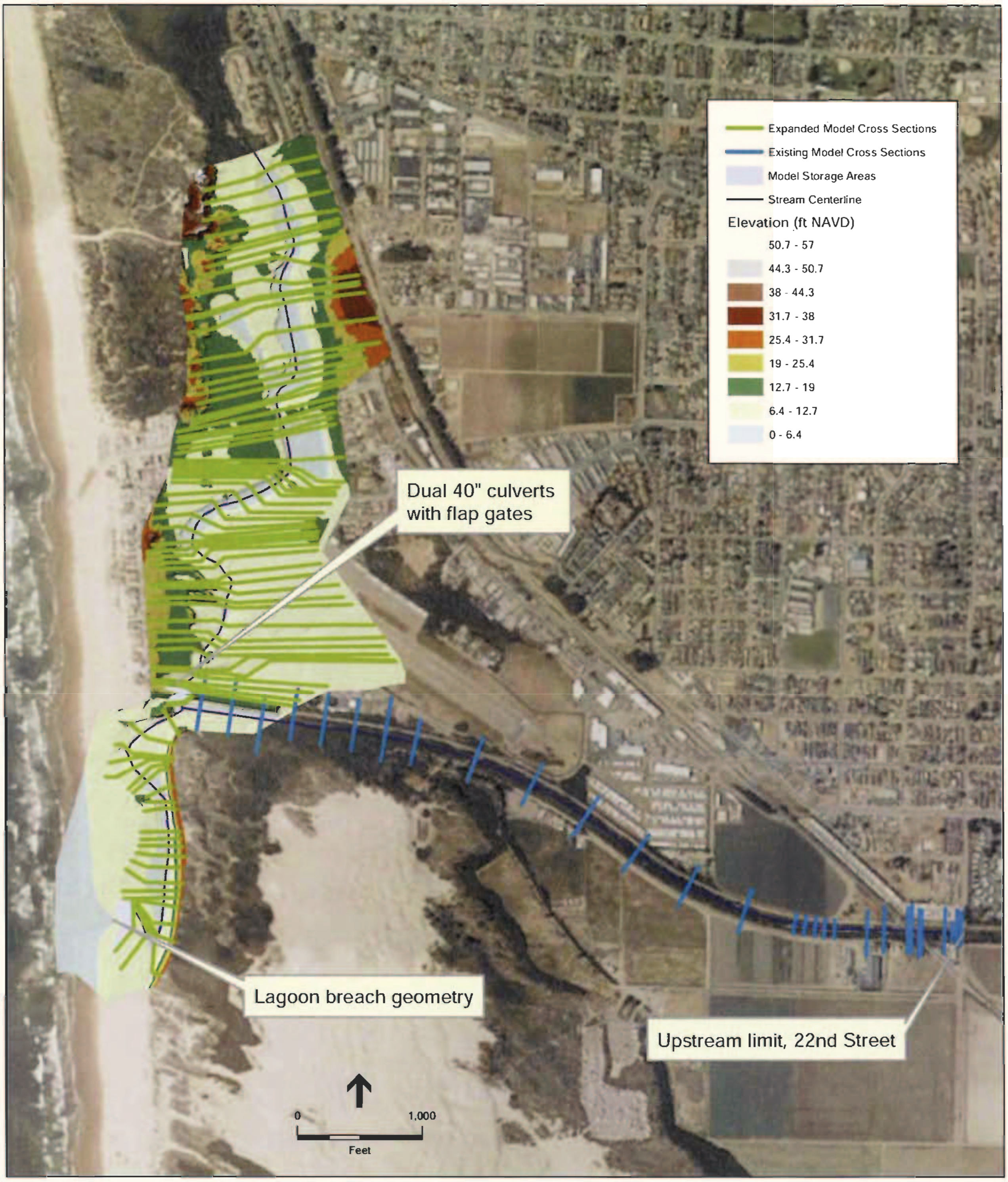
SOURCE:National Land Cover Database(2006), NRCS Soil Survey Geographic, USGS DEM(2009)

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

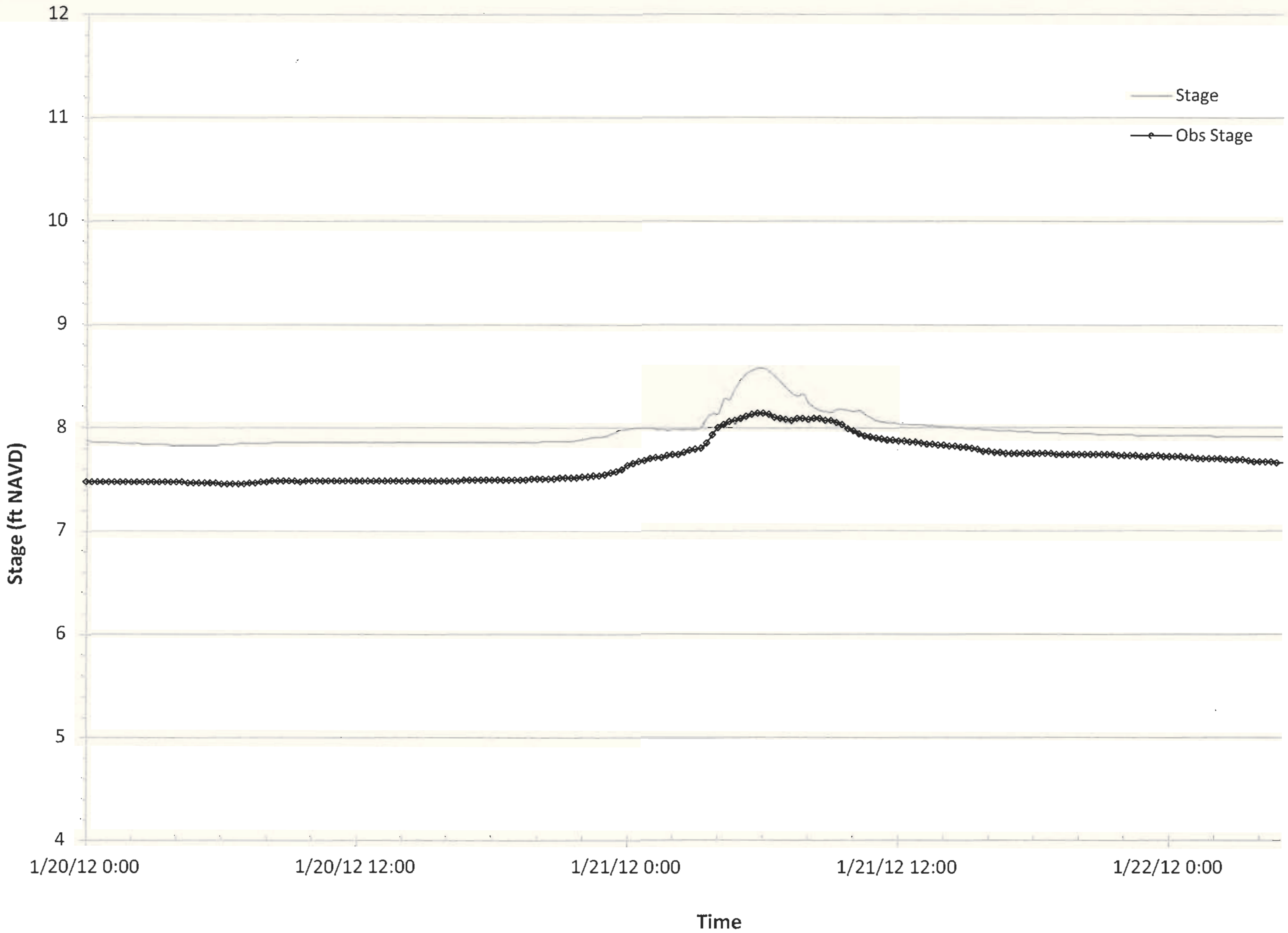
Meadow Creek Curve Number GIS Inputs



SOURCE: NAIP (2010)

Arroyo Grande Interim Sandbar Management. D211720

Figure 3
Arroyo Grande Creek and Meadow Creek Hydraulic Model Layout

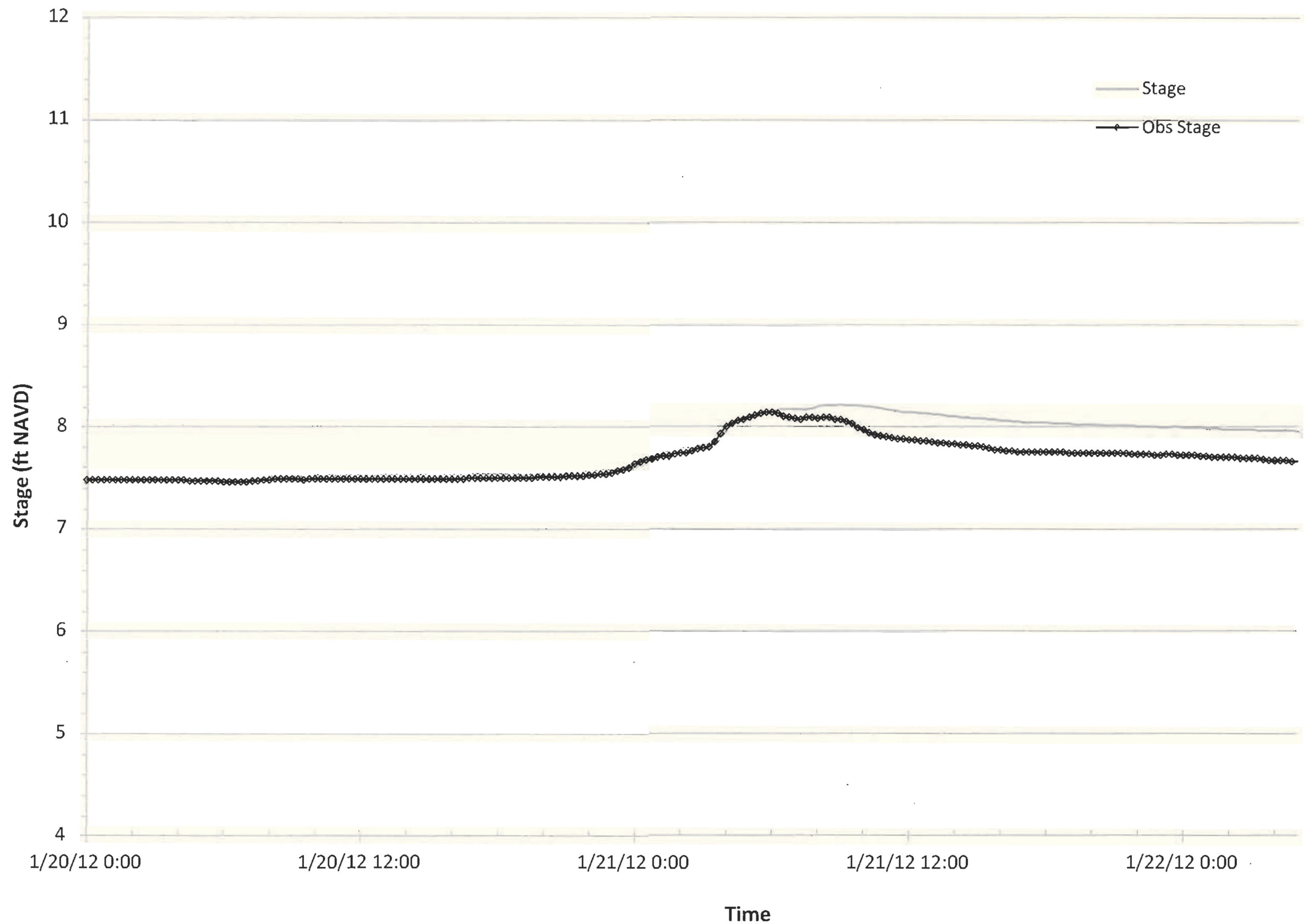


Note: Provisional results

Arroyo Grande Interim Sanbar Management. D211720.00

Figure 4

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

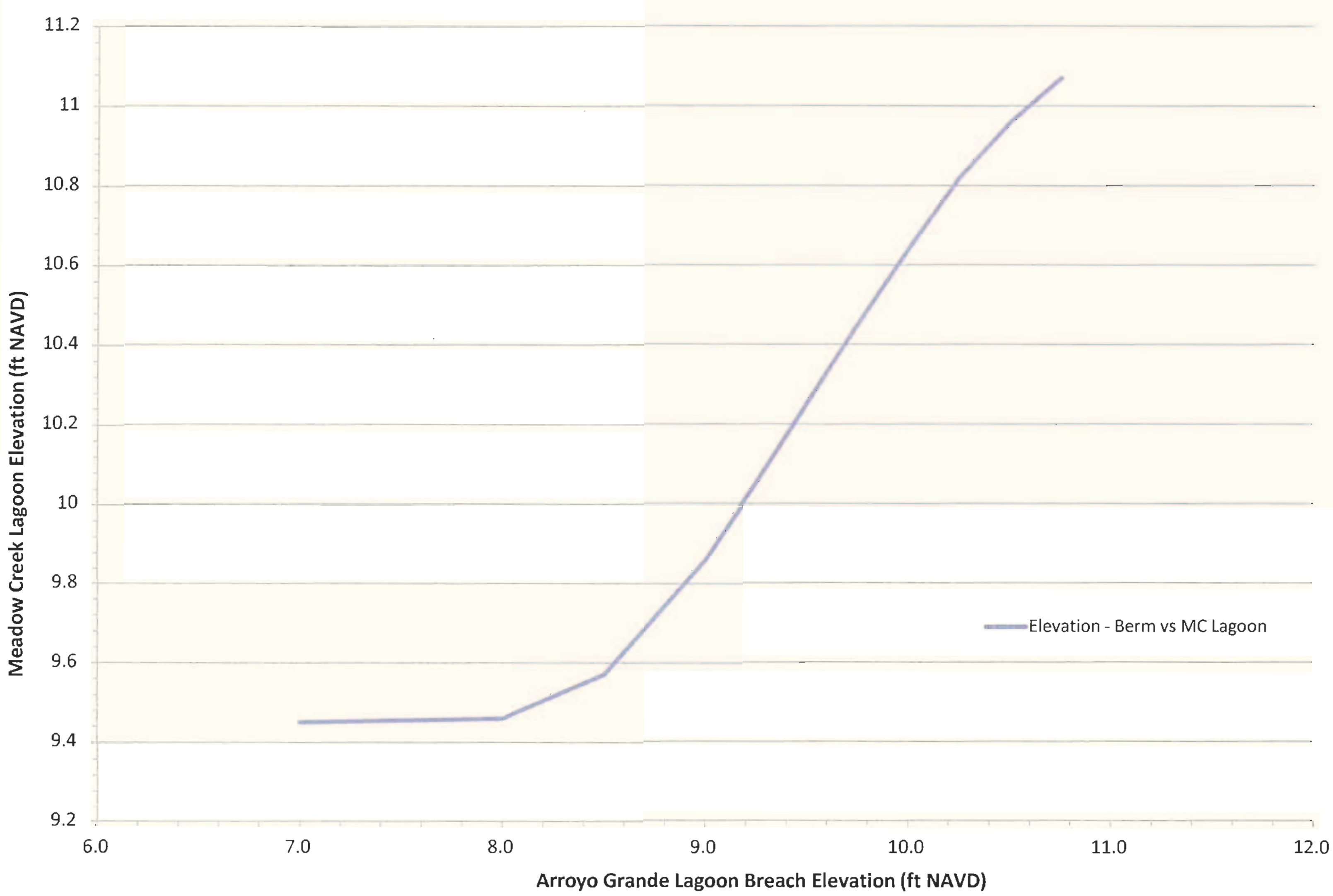


Note: Provisional results

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