MODELING FLOOD REDUCTION SCENARIOS FOR A SMALL
COASTAL COMMUNITY

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By
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ABSTRACT

Modeling Flood Reduction Scenarios for a Small Coastal Community

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The Arroyo Grande Creek Watershed, an approximately 170 mi² watershed located on the central coast of California, drains to the Pacific Ocean via the Arroyo Grande Creek that passes through several coastal cities including the community of Oceano. At the mouth of the Creek is the Arroyo Grande Lagoon, which is connected to another lagoon known as the Oceano Lagoon, by a tidal flap-gate whose hydraulics is a function of water levels in the two lagoons. Historically the Oceano Lagoon has played a part in floods that have occurred in the community of Oceano. The most recent flooding occurred in 2010 when a storm with about a 10-yr frequency caused flooding that led to an estimated property damage of about two million dollars. This study was conducted to understand hydrology of the Arroyo Grande watershed that also feeds Lopez Lake, a reservoir that provides water for drinking, agriculture, and environmental flows; to characterize hydraulics of the Oceano Lagoon; and to explore scenarios for flood mitigation. Objectives of the study are to provide a better understanding of the causes of the historical floodings; map the extent of floodings for various storm events including 10 year, 50 year, and 100 year under current conditions; and examine potential solutions to reduce future floodings. Surface water hydrology of the Arroyo Grande Creek Watershed was studied using HEC-HMS to quantify runoff specifically into the Oceano Lagoon. HEC-HMS was calibrated using known streamflow to improve the accuracy of the model. The HEC-HMS model was developed using spatial data that was organized in ArcMAP. Data such as elevation, land use, soil type, and impervious surface were processed using HEC-GeoHMS and exported to HEC-HMS. Mitigation measures were simulated in HEC-HMS by adjusting parameters such as the outlet configuration and the increased volume in Oceano Lagoon. Each mitigation measure delivered varying effectiveness. Results show that while the peak flow and volume in the lagoon can be reduced, larger design storms will continue to inundate the area unless drastic steps are taken. The findings could assist local flood control agencies by evaluating the risks of continuing to use the existing drainage system, and identifying opportunities available to reduce those risks.

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Chapter 1: Introduction

Flooding is a devastating natural disaster that occurs throughout the United States and the world. Monetary losses from floods are estimated around \$2.9 billion dollars annually here in the United States (FEMA, 2013). With the seemingly increasing frequency of large storms like Hurricane Sandy, it is important for flooding potential to be analyzed in communities around the world. While Federal Emergency Management Agency (FEMA) has worked to create maps of potential flood regions for the 100 year storms and larger, many areas frequently flood under smaller recurrence interval storms. These smaller flooding events, and the responsibility of preventing them, will often fall to the local public municipalities.

While large storms like Hurricane Sandy cause widespread flooding, localized flooding can frequently occur for smaller design storms. This flooding can result from inadequate storm drainage facilities, clogged culverts and inlets, and improperly designed and poorly graded drainage paths. Flooding can also be caused by the decrease in infiltration brought on by urbanization throughout the watershed. Urbanization is defined as the growth of urban areas by migration of people to city areas (Mays, 2005). Urbanization increases runoff volumes and peaks because of increased impervious surface and decrease in infiltration. Figure 1 illustrates the impact of urbanization on runoff.

Figure 1. Relationship Between Runoff Percentages and Percent Impervious Surface (The Federal Interagency Stream Restoration Working Group, 2010)

Coastal communities are especially vulnerable to flooding because of the relatively high groundwater levels, and the combined impacts of storm surge and high tides can increase the elevation of the water in coastal lagoons. This increase in water level combined with increased runoff from large storms increases the flood risk in the low lying coastal areas. Currently, coastal lagoons located on the Carmel River, and Neary Lagoon in Santa Cruz have adopted lagoon management plans to reduce the flooding risk. The mitigation methods used to reduce flooding potential include, among others, mechanically breaching the lagoon, and sediment removal and erosion control (Chartrand, Hastings, & Hecht, 2006; Monterey Peninsula Water Management District, 2005).

The risk of flooding of coastal communities is expected to increase because of climate change and the associated sea level rise. The threat of sea level rise is projected to increase the amount of people affected by flooding on the order of millions (Adger, 2007). Much time and effort by engineers, community members, and policy makers is spent deciding how to reduce the risk of flooding in these coastal areas. Some of the questions that need to be examined are the volume of water that is entering coastal lagoons, the peak flow that is entering coastal lagoons, and the best alternatives to reduce the effects of the flooding. Through monitoring programs, rating tables can be created to estimate the flow rates and volume. Computer models are a useful tool with many advantages including the ability to look at hypothetical storm events, such as a 100 year storm, and the flooding impacts that result. The use of computer models combined with the use of measured stream flow and precipitation data has been a proven way to determine the volume of runoff for various intensity storms (Scharffenberg & Flemming, 2009).

There exist several types of software, both public and proprietary, that are used to model and simulate the rainfall runoff relationship in watersheds. Simulation software can also model the rainfall runoff relationship in a watershed two different ways. A distributed model is a more detailed model where the flows are modeled for both the watershed and the channel elements (Mays, 2005). A lumped model generalizes parameters as an average over the entire watershed, or subwatershed (Redfearn, 2005). A lumped model is often chosen because of data availability and possible computational limitations with a distributed model (Vieux, 2004).

Chapter 2: Background

The Community of Oceano (Oceano) is a small coastal community located in southern San Luis Obispo County, California. It is bordered to the south by the Arroyo Grande Creek, which was channelized into a levee system through the community in the late 1950's. To the north and east lie the City of Grover Beach and the City of Arroyo Grande, respectively. The Arroyo Grande Creek is the outlet for the larger Arroyo Grande Creek Watershed which drains approximately 170 sq. miles. Figure 2 shows the location of Arroyo Grande Watershed and the location of the Oceano Lagoon Sub-basin, also known as the Meadow Creek Watershed. The land use within the watershed mainly consists of undisturbed land and irrigated agriculture. Urbanization has occurred near the outlet of the watershed in the community of Oceano, and in the upper watershed with the growth of Arroyo Grande, Pismo Beach, and Grover Beach, resulting in a decrease in pervious surface. During the early development of Oceano little consideration was given to storm water and flood control infrastructure because of the high infiltration rate of the underlying soils (Raines, Melton & Carella, Inc., 2004). With the increase in urbanization of Oceano, flooding has become an issue throughout the community. The City of Grover Beach and the City of Pismo Beach, also urbanized communities, have drainage and waterways that are tributary to the Oceano Lagoon. See Figure 2 below which summarizes the drainage paths in the subwatershed that drains to the Oceano Lagoon.

Figure 2. Drainage Paths in Subwatershed to Oceano Lagoon

Oceano Lagoon is a shallow vegetated lagoon that drains into the Arroyo Grande Creek near its outlet to the ocean. The flow control structure that connects the lagoon to the Arroyo Grande Creek is known as the Sand Canyon flap gates. Surrounding the lagoon are homes and businesses, and important infrastructure such as the Union Pacific Railroad, California Highway 1, Oceano Airport, and the South San Luis Obispo County Sanitation District. The most recent flood events occurred in December 2010, where a 10

year frequency storm was followed by a 2 year storm (Reinhart, 2011). The estimated maximum water level from this set of storms is approximately 12 feet above mean sea level (Engelskirger, 2013). The approximate bottom elevation of the Oceano Lagoon is 3 feet, which means the water level was 9 feet above the lagoon bottom. The flood waters are made up of storm water runoff from the both the City of Grover Beach and the City of Pismo Beach that is conveyed through storm drains, and sheet flow that is channeled through swales and culverts from Oceano to the lagoon. The flooding events in December 2010 led to flooding on the airport runway, the sanitation district, Highway 1, approximately 39 homes, and 8 apartments. The damage from this flood was estimated to be approximately \$2 million dollars (Lambert, 2011). It was also believed to contribute to a failure of the sanitation district pumping systems that resulted in untreated sewage being spilt in the floodwaters (Lambert, 2012). The flooding issue comes at great cost to the community and permanent mitigation measures have yet to be established.

Permanent mitigation measures have not been established because the Oceano Lagoon is at the downstream end of a large watershed where there are several jurisdictions contributing to the issue, including: City of Pismo Beach, City of Grover Beach, California State Parks, and the County of San Luis Obispo. Developing feasible mitigation measures that can be implemented is typically done by the agency where the flooding problem affects its constituents, and so improvements are selected to address their specific problem and are usually limited to improvements that can be done within that agency's jurisdiction. Sometimes proposed improvements are not effective, since the improvements are selected under a focused approach rather than a regional approach which would better address the problem at the source and address project impacts

upstream and downstream. Ideally a regional approach to flooding issues is the way to go; however, it would require collaboration amongst the agencies within the watershed which can take years to coordinate since each agency has many varying priorities.

Additionally, the problem with analyzing mitigation measures for flooding in Oceano, as well as many other communities around the world with flood issues, is that accurate models and representations of the watersheds do not exist. This paper will explain the process to create a geospatial model using ArcGIS and publicly accessible model and watershed information. With proper calibration, the model mimics the hydrologic characteristics of the Arroyo Grande Creek Watershed. Finally, the study will attempt to identify viable permanent solutions to the flooding issues within Oceano and demonstrate their effectiveness for design storms of 10, 50, and 100 year frequencies, and possibly serve as a regional guide in taking the next steps in flood prevention in the Arroyo Grande Creek Watershed.

The Watershed Simulation Model

The U.S. Army Corps of Engineers' Hydrologic Engineering Center model known as Hydrologic Modeling System (HEC-HMS) was selected for this study. HEC-HMS offers a number of rainfall-runoff modeling techniques including several synthetic unit hydrograph (UH) methods and infiltration estimation approaches. The Natural Resources Conservation System (NRCS) UH method was selected for the runoff model, and the NRCS curve number method was identified as the ideal choice for infiltration estimation in the development of the model of the Arroyo Grande Watershed for several reasons. Most of the runoff and loss modeling methods that are available through HEC-HMS require much more detailed information than can be provided for the entire 170

square mile watershed. Some of these methods allow for parameters such as curve numbers to be applied over the watershed in a grid divided into small squares of equal value. Other methods such as the Green Ampt and the Soil Moisture Accounting method would be better suited for a continuous simulation model rather than the event based model that is created for the purpose of this project. Some of these methods would require the use of additional data such as temperature and climate information which are not crucial for the event model being developed in this study.

The model created was semi-distributed; the watershed was subdivided into subwatersheds and model parameters were averaged over each subwatershed. To increase the detail and possibly accuracy, a fully distributed (e.g., gridded) model can be used. This would, however, require a higher level of detailed information such as radar rainfall throughout the watershed. Such detailed data is not available for the Arroyo Grande Creek watershed.

Although HEC-HMS was chosen for this study for its versatility and user friendly interface, many other commonly used modeling programs also exist. One common modeling program is the U.S. Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) which may have many modeling advantages, including the ability to model Low Impact Development controls throughout the watershed. SWMM was not the software of choice for this study because it was designed to model urban watersheds. The Arroyo Grande Creek Watershed is mostly undeveloped and irrigated agricultural land use. Another modeling program that could have been used for model creation is the EPA's Soil and Water Assessment Tool (SWAT). SWAT is a physically based model and requires information regarding variables such as weather, soil

properties, topography, vegetation, and land management properties (Neitsch, Arnold, Kiniry, & Williams, 2009). Some advantages of SWAT include the ability to change land management practices, and the ability to also analyze parameters such as sediment transport, and water quality. SWAT was not chosen for this work due to the large amount of information needed to develop the model. SWAT is also a continuous model as opposed to the event based model that was needed for the analysis of the Arroyo Grande Creek Watershed.

Relevant Previous Work

The Oceano Lagoon has been studied as far back as 1989 with the goal of reducing flooding to the surrounding homes and infrastructure. Dr. David Chipping of California Polytechnic State University, San Luis Obispo (Cal Poly) performed this study of the Meadow Creek Drainage for the California Department of Parks and Recreation. The purpose of this study was to analyze runoff from the Meadow Creek Watershed, which drains into the Oceano Lagoon and to make recommendations for flood reduction in the area. The report looked at historic maps of the area and derived the area of watershed that contributes runoff to Meadow Creek, a tributary to the Oceano Lagoon. The recommendations from the report were to maintain the Carpenter Creek Channel as a flood control outlet and prevent high flows from traveling downstream into the Oceano Lagoon by the installation of a gate structure in the Meadow Creek. Figure 3 below summarizes the creeks mentioned in the study.

Figure 3. Creek and Watershed Feature Described in (Chipping, 1989)

More recently in January 2013 Cannon released analysis on a proposed project to reduce localized flooding in low lying locations. These include the area of Highway 1 and 13th Street as well as 40.5 acres of neighborhoods in the Community of Oceano. The project chosen is the improvements of storm drains in the affected area and a detention basin with a low and high flow flap gates that will discharge into the Arroyo Grande Creek before the runoff has a chance to enter the Oceano Lagoon.

Waterways Consulting in 2010 performed analysis and modeling in the Arroyo Grande Creek Watershed (Dvorsky, 2010). The goal of Waterways Consulting's work is to develop a Waterway Management Program to increase the capacity within the leveed

portion of the channel and simultaneously increase the quality of habitat for sensitive species. The study focused on vegetation management, sediment management, raising the levees, and raising the Union Pacific Railroad Bridge.

A drainage study has been conducted by Raines, Melton & Carella for the Community of Oceano in 2004. The study was conducted in response to flooding events in the Oceano area during March 2001. This drainage study looks at localized flooding in the areas west of the Oceano Lagoon; it does not analyze the flooding issues in and around the Oceano Lagoon. The study proposed projects to reduce localized flooding.

Study Objectives

The previous studies all focused on flood mitigation in the Arroyo Grande Creek watershed, and none of them addressed the Oceano Lagoon and the adjacent residential areas. The proposed upstream mitigation measures will have some positive effect at reducing the flow in the Oceano Lagoon, but mitigation measures specifically targeting the lagoon need to be analyzed for maximum effectiveness. Chipping (1989) focused on water entering the Oceano Lagoon but suggested little changes to the mitigation measures already in place besides maintaining Carpenter Creek as a flood diversion channel. The current state of the channel is not adequate for drainage to the Ocean.

This study was initiated with two goals in mind:

1. **Determine the relationship between rainfall in the watershed and runoff into the Oceano Lagoon.** The study is an event based model that will focus on the extent of flooding caused by 10, 50, and 100 year frequency design storms. To determine the runoff for the given design storms a model will need to be created that can accurately simulate the watershed characteristics within the Arroyo

Grande Watershed specifically the sub-basin that contains the Oceano Lagoon. This will help determine the volume of water entering the lagoon and the flow rate throughout the storm period.

2. **Identify feasible flood mitigation measures within the Oceano Lagoon and determine their effectiveness.** Three separate mitigation measures were discussed with the San Luis Obispo County Public Works Department. The effectiveness of each of these mitigation measures is evaluated in this study to help identify which of the three mitigation measures will be the most effective and also to provide the amount of reduction that would be achieved compared to the current conditions in the watershed.

Chapter 3: Data

The development of the watershed model required various types of data input to build and validate with accuracy. Geospatial data including soil type, land use, impervious surface, and digital elevation model (DEM) were used to delineate the watershed and to extract basin characteristics needed to build and calibrate HEC-HMS. ArcGIS, Geographic Information System (GIS) software developed by Environmental Sciences Research Institute (ESRI), was used to organize the geospatial data and delineate the watershed. Due to the age of the DEM features like the levee alignment where added with the use of ArcCatalog and tools in ArcGIS that allow DEM manipulation. Precipitation data for the Arroyo Grande Watershed, stream flow for Lopez Creek, and approximate maximum water elevation for flooding events where used for analysis. The location of the stream gage and precipitation gage can be seen in the figure below.

Figure 4. Location of Lopez Creek Stream Gage and AGAG Precipitation Gage

Precipitation Data

The San Luis Obispo County Flood Control and Water Conservation District, under the purview of the County Public Works Department, operates and maintains several rain gages within the Arroyo Grande Watershed. There are multiple types of gages in the watershed including recording gages, Automated Local Evaluation in Real Time (ALERT) radio gages, and observation gages. The gage chosen for the analysis is the station known as AGAG #739, the gage is regularly maintained and has a period of reliable data that was available. AGAG is located about midway through the watershed on the Arroyo Grande Creek and is equipped with a tipping bucket rain gage. The average rainfall in the watershed is approximately 16" in the lower portion of the watershed (Chipping, 1989).

Design storms were created using a SCS type I rainfall distribution for a 24-hr time period. The SCS rainfall distribution is a synthetic storm hyetograph. The United States is divided into four sections each with a different hyetograph. (Mays, 2005) Type I is representative of the rainfall pattern that occurs in the south west of the United States with wet winters and dry summers. To determine the hyetograph for the desired design storm NOAA Atlas 14 Precipitation Frequency Data Server (PFDS) is used. The (PFDS) delivers a precipitation frequency estimates that have been computed using a regional frequency analysis approach (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 2012). For the 24 hour duration, the 100 year recurrence has a total rainfall depth of 5.3 inches, 50 year 4.79 inches, and 10 year 3.6 inches.

Stream flow and Elevation Data

Stream flow data along the Arroyo Grande Channel is limited in its availability, while water surface elevation is measured at several locations using radar and nitrogen bubbler systems; flow is measured at select locations on a monthly basis. The availability of this data is limited and was not used in this study. To help with validation the USGS stream gage that is located upstream of the Lopez Reservoir along the Lopez Creek was used. Lopez Creek is the main tributary of inflow into Lopez Lake. Stream flow releases from Lopez Lake into the Arroyo Grande Creek satisfy environmental and agricultural needs, during the summer months this is the only flow in the creek. The USGS field office in Santa Maria is in charge of maintenance and monitoring of the site. The data after being sent to the field office is verified and published on-line. The period of record for the site dates back to 2007 and includes both runoff and stream flow depth (USGS National Water Information System, 2013). The flooding that occurred in December 2010 is used as the reference for both flow and also the maximum water level that occurred around the Oceano Lagoon. This water level was determined from visual inspection after the floodwaters subsided in the areas surrounding the lagoon. Important reference elevations from around the lagoon were determined from surveys performed by Cannon, a local engineering design firm in San Luis Obispo. These elevations include the elevation of the surrounding roads, bridges, and finished floors in the surrounding neighborhood. Some other important known elevations include the invert of the outlet culverts known as the Sand Canyon Flap gates.

Land Elevation, Use and Soil Types

The digital elevation model, land use, impervious surface, and hydrography data was obtained from the USGS using the National Map Viewer, formerly Seamless Data Warehouse map tool (National Map Viewer, 2012). This data combined with the use of ArcMap extensions was instrumental to create the parameters of Curve Numbers for each sub-basin.

Soil data was obtained from the Natural Resource Conservation Service (NRCS) website known as the Soil Data Mart. The soil database is termed the Soil Survey Geographic (SSURGO) and includes soil information as well as shape files that are ArcMap compatible. The data was extracted from the data files using Microsoft Access databases (Staff, 2012). The soil data is imperative to the determination of the NRCS Curve Numbers.

Modeling Methodology

Model creation was achieved using three different types software. The basic delineation and development of spatial parameters of the watersheds were created using ArcGIS. AutoCAD was used to develop an elevation volume chart that will be used to determine the extent of flooding in the Oceano Lagoon. HEC-HMS is the program where the bulk of analysis takes place, including calibration and validation. Validation is considered the most important step in establishing model credibility (Nix, 1994). Having a model that closely follows natural conditions gives credibility to the goal of the model which is the comparison of possible solutions to reduce flooding in the Oceano Lagoon area.

Chapter 4: Watershed Delineation

HEC-GeoHMS

Development of the Arroyo Grande Watershed began with obtaining digital spatial data and importing that data into ArcMap. Two data sets were required to begin analysis and delineation using ArcMap, the DEM and the Hydrography data. The DEM is digitized elevation raster, which consists of a matrix of cells each representing a value for different types of data (ArcGIS 9.2 Desktop Help, 2008). The raster is from the National Elevation Dataset (NED), and is accurate to approximately 1/3 arc second. This roughly translates to one representative elevation per 10 meters by 10 meters land area. The Arroyo Grande Watershed contains small streams and flat topographic features that may not be captured with the 1/3 arc second accuracy. To remedy the possible lack of accuracy, hydrography shape files must be used to edit the DEM, and ensure that current stream locations are in the proper location. The hydrography shape files are available from USGS and represent stream and creek flow paths, points are also available that represent USGS stream gage sites.

The program extension used in the delineation process is HEC-GeoHMS or Hydrologic Engineering Center Geospatial Hydrologic Modeling System Extension. The Hydraulic Engineering Center is a division of the Army Corp of Engineers. HEC-GeoHMS is free software available for download and works in conjunction with ArcMap. HEC-GeoHMS main function is to create maps and model files that can be transferred to HEC-HMS and help build HEC-HMS model for the watershed. The tools in the ArcMAP extension prepare the basin model for transfer into HEC-HMS.

To begin model creation the DEM is added to the current ArcMap. To increase the accuracy of the DEM the hydrography shape file containing the current location of streams is burned into the DEM. This process is known as DEM reconditioning, and involves the DEM elevation being raised or lowered to ensure that the information about barriers such as small creeks can be seen on the DEM. A feature that was missing on the DEM and the Hydrography shape file is the existing levee system that divides a portion of the lowest subwatershed. To include the levee system on the DEM, ArcCatalog was used to create a shape file representing the levee system. This levee shape file was burned into the DEM similarly to the hydrography shape file. The HEC-GeoHMS program has various features that allow the delineation of watersheds by using a step by step guide found in the HEC-GeoHMS User's Manual. Some of the functions include determining the flow direction, stream definition, sub-watershed definition and linkage of streams and subwatersheds (Flemming & Doan, 2009). HEC-GeoHMS creates a basin file, which describes the physical properties of the watershed and the topology of the stream network (Scharffenberg & Flemming, 2009). This file is created in ArcMAP and is programmed to open in HEC-HMS. The delineated watershed can be seen in the figure below.

Figure 5. Delineated Watershed Map

HEC-HMS Background

Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) is software created by the U.S. Army Corps of Engineers after 30 years of experience with hydrologic simulation software (Scharffenberg & Flemming, 2009). HEC-HMS is used to simulate runoff in the Arroyo Grande Watershed. The model combined with a topographic model of the Oceano Lagoon will help determine the elevation and volume of water in the lagoon after simulated storms. The latest flooding events that occurred in December 2010 were considered for simulation of runoff because the approximate maximum water level in the Oceano Lagoon is known.

As in most watersheds information and recorded data is hard to come by. Because of the lack of data an event based simulation was chosen for this study. There are disadvantages when choosing a single event based model compared to a longer period continuous based model. Parameters that get adjusted for a single storm event may not translate to a continuous based model or even a different single storm event during a different time period (Nix, 1994). For this reason this study is not applicable for dry antecedent conditions, but only applicable to wet conditions where there is a high risk of flooding occurring in the watershed.

The components of each single event based model include loss and transform of each sub-basin for each subwatershed. The loss method helps estimate the amount of rainfall lost to infiltration, initial abstraction, depression storage, and canopy interception and, is therefore not available to produce runoff. Some of the loss methods programmed into HEC-HMS work only for single event simulations (Scharffenberg & Flemming, 2009).

The loss method chosen for this analysis is the SCS, now NRCS, rainfall runoff relation. This method depends on the estimation of initial abstraction and storage potential of a watershed by determining a curve number (CN). The CN is a unit less parameter that describes the land use, antecedent moisture conditions, and land cover of a watershed (Mays, 2005). CN for each subwatershed was determined using spatial data in ArcMAP by assigning a CN to each cell. The CN was then averaged over the entire subwatershed. The following equations are used to determine additional parameters for the CN method.

Initial Abstraction:

$$I_a = 0.2S$$

Where:

I_a is the Initial Abstraction

S is the Potential Maximum Retention

Potential Maximum Retention:

$$S = \frac{1000}{CN} - 10$$

Where:

S is the Potential Maximum Retention

CN is the Curve Number

The transform method refers to the technique used to determine runoff hydrograph produced by the rainfall after accounting for losses such as infiltration and initial abstraction (Scharffenberg & Flemming, 2009). The transform method chosen for this study was the SCS Unit Hydrograph Transform Method. This method uses a generalized unit hydrograph that is created from observed data and scaled by the time to peak (i.e., time lag plus one-half of the duration of the unit hydrograph) to develop an adjusted unit hydrograph for the watershed (Scharffenberg & Flemming, 2009). The lag time for each subwatershed was determined using the time lag equation from NRCS given below.

Lag Time:

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$$

Where:

- t_L is the Lag Time
- L is the Hydraulic Length in feet
- S is the potential maximum retention
- Y is the watershed slope in percent

AutoCAD Civil 3D

AutoCAD Civil 3D (Civil 3D) is a design suite software that is produced by Autodesk Inc., the leader in 3D design, engineering and entertainment software (Staff A. , 2013). For this study, Civil 3D was used to create an elevation storage model for the Oceano Lagoon. The DEM used as stated above is not of high enough accuracy to develop an elevation storage relationship accurately. Topographic information, including a bathymetric survey of Oceano Lagoon, which was taken after the December 2010 flooding, was provided by the County to assist with this study (Cannon, 2012). The topographic information was provided as survey points and contour lines in the area around the Oceano Lagoon. These points were used to create a surface in Civil 3D and layers representing elevation above the lagoon were created and compared to the elevation of the lagoon. Civil 3D has tools to calculate the volume between two known surfaces. These elevations and the volume that exist at each were recorded to create the elevation storage relationship. The elevation storage relationship and the Civil 3D topographic output can be seen below.

Figure 6. Sample Civil 3D Topographic Output

Elevation Storage Chart for Oceano Lagoon		
Elevation	Volume (cu. yd.)	Volume (AF)
0	0	0
2	2034	1.3
4	11852	7.3
6	39756	24.6
8	86375	53.5
10	178372	110.6
12	445550	276.2
14	1025454	635.6
16	1819066	1127.5
18	2754529	1707.4
20	3792194	2350.5

Table 1. Elevation Storage in Cubic Yards and Acre-Feet for the Oceano Lagoon

Model Setup

The HEC-HMS model was developed from the basin model that was created and imported from the HEC-GeoHMS extension in ArcMAP. Information that describes each subwatershed like, area, impervious surface, curve number, stream connectivity, sub-basin connectivity is imported with the basin model file. Several other parameters were not imported but rather added after importing the basin model file.

Observed data was among the additional data that was added into the HEC-HMS model. Observed stream flow at the Lopez Creek Gage located upstream of Lopez Lake. Precipitation data for December 2010 from the AGAG Gage maintained by San Luis Obispo County Public Works Department was applied over the entire Arroyo Grande Watershed. These two types of data were added to HEC-HMS with the distinction of being time series data. Time series data is observed data, and necessary for calibration and validation (Scharffenberg & Flemming, 2009). Time series data needs start and stop date and the time step between each point of known data. For this simulation the cumulative rainfall was chosen as the input data and was added at a 1 minute time step. For December 2010, the time period was set as December 1, 2010 at 00:00 to December 31, 2010 24:00.

HEC-HMS allows the use of paired data for the description of attributes such as reservoirs and junctions. For this study Oceano Lagoon is simulated as a reservoir in the model. HEC-HMS requires reservoirs to define releases in one of three ways: outflow structures, outflow curve, or specified release. Oceano Lagoon has an outlet structure made up of two pipe arch culverts with flap gates at the downstream end. The loss coefficient created by the flap gates is unknown; the outflow of the culverts will be

calibrated to match the approximate maximum water elevation in the lagoon during the December 2010 flooding. To describe the storage of a reservoir in HEC-HMS, paired data must be entered to describe the relationship. There are two types that can be used to describe the relationship, elevation storage or an elevation area curve. The elevation storage information created from the Civil 3D topographic information is input as paired data and used to determine the elevation of the reservoir throughout the model simulation.

HEC-HMS uses meteorological controls to describe the boundary conditions of the sub-basins in terms of the type of rainfall and the method that rainfall is distributed. HEC-HMS has seven different methods to describe precipitation over the watershed (Scharffenberg & Flemming, 2009). This study utilizes observed data in the form of a Specified Hyetograph to describe precipitation for the initial calibration and validation. Several County maintained rain gages exist in the Arroyo Grande Watershed, #739 AGAG, Oceano #795, and two near Lopez Lake, #737 Lopez Dam and #707 Lopez Rec Area. The gages at Lopez Lake appear to have overestimated the total rainfall after internal review of the data (Cranor, 2013). #795 Oceano is near the ocean and was not considered a good estimation of rainfall over the entire watershed. #739 AGAG was chosen because it is a well maintained rain gage located in the City of Arroyo Grande along the Arroyo Grande Creek, which is more central to the watershed. Meteorological controls also allow for methods of evapotranspiration and snowmelt to be accounted for within the model simulations. For this single event based analysis evapotranspiration is assumed zero because of the short time step involved for each event.

Simulation and Calibration

The simulation of the model requires Control specifications to define when each simulation begins and ends, and also the time step that HEC-HMS will use in the analysis. Three Control Specifications were used for the analysis to determine average adjusted parameters for the watershed. Each time period was chosen with the goal of isolating a single storm event in the watershed. The simulation is run with the parameters that were determined during the ArcMAP watershed delineation. These parameters will be an initial parameters used for the simulation of each chosen control specification period. These simulations will be used to perform optimization which will attempt to calibrate the model using processes built in to HEC-HMS.

Optimization is a form of parameter estimation, which adjusts parameters so that simulated results more closely match observed results. To perform optimization a previous simulation trial is selected as well as observed data that it will attempt to match. It is important to know that parameter estimation is not perfect but a valuable tool in model calibration (Scharffenberg & Flemming, 2009). HEC-HMS performs parameter optimization with the use of seven different pre-programed objective functions. Objective functions measure the variation between observed data and simulated hydrographs (Scharffenberg & Flemming, 2009). Optimization begins with initial parameters and adjusts them to match the observed stream flow as closely as possible. In this study, calibration runs were created for three separate storms of varying severity. To calibrate each unique storm three different objective functions were used. They were selected because they created the best fit in terms of the overall shape of the hydrograph, and minimizing the percent error in terms of peak flow and total volume.

Calibration was performed for storm event simulated during the period of December 17, 2010 at 00:00 to December 20, 2010 4:00 with a time period set at 1 minute. The total depth of rainfall for period is 5.98 inches. The calibration will be considered successful upon a visual inspection of the observed runoff and simulated runoff. It is important that the percent difference for both volume and peak flow be minimized for accuracy of flow routing and determining maximum flood levels. The objective function used to calibrate the simulated time period was Percent Error Peak.

Percent Error in Peak:

$$PEP = \frac{q_{ps} - q_{po}}{q_{po}} \times 100$$

Where:

PEP	is the percent error in peak flow as a percentage
q_{ps}	is the peak flow simulated from HEC-HMS for the time period
q_{po}	is the peak flow observed from collected stream flow data

Figure 7. Objective Function Summary for December 2010 with Percent Error in Peak

Figure 8. Calibrated Hydrograph Comparison for December 2010 Storm

As mentioned above three separate storms were simulated to ensure that the optimized parameters in the watershed are accurate and represent a wide range of conditions if possible. The second storm event that was analyzed was January 2010, with

a Control Specification from January 19, 2010 at 00:00 to January 21, 2010 at 4:00. The total rainfall depth for this time period was 2.83 inches. The same process of both visual inspection and reviewing the Objective Function Summary is used to determine a good fit and proper objective function for the simulation period. The objective function used to calibrate the simulated time period was the Sum of the Squared Residuals.

$$TSAR = \sum_{j=1}^n \{ \sum_{i=1}^n [q_o(t) - q_s(t)]_i \}_j$$

Where:

TSAR is the Total Sum of Absolute Residuals

n is the number of computed hydrograph ordinates

q_o is the Observed flow from collected data at time t

q_s is the simulated flow from HEC-HMS simulation at time t

Project: AG_Watershed Optimization Trial: Jan 2010

Start of Trial: 19Jan2010, 00:00 Basin Model: AG_Watershed

End of Trial: 21Jan2010, 04:00 Meteorologic Model: Jan 2010

Compute Time: 22Feb2013, 18:12:38 Control Specifications: Jan Control

Objective Function at Basin Element "UserPoint3"

Start of Function : 19Jan2010, 00:00 Type : Sum of Absolute Residuals

End of Function : 21Jan2010, 04:00 Value : 68073.6

Volume Units: ☐ IN ☒ AC-FT

Measure	Simulated	Observed	Difference	Percent Difference
Volume (AC-FT)	241.1	273.8	-32.7	-11.95
Peak Flow (CFS)	195.6	187.0	8.6	4.6
Time of Peak	20Jan2010, 15:58	20Jan2010, 15:30		
Time of Center of Mass	20Jan2010, 08:52	20Jan2010, 10:22		

Figure 9. Objective Function Summary for January 2010 Storm Using Sum of Absolute Residuals

Figure 10. Calibrated Hydrograph Comparison for January 2010

The third storm event that was used for model calibration occurred during March 2011. The single storm event had a total rainfall depth of 0.98 inches with a base flow of approximately 50 cubic feet per second. This storm was smaller than the flooding event of 2010 but resulted in minor flooding in areas around the Oceano Lagoon. The Control Specification was from March 24, 2011 00:00 to March 26, 2011 00:00. The objective function chosen to best fit the March 2011 storm event was Peak-Weighted Root Mean Square Error.

$$PWRMSE = \sqrt{\frac{\sum_{t=1}^N (Q_{obs}(t) - Q_{sim}(t))^2 \frac{Q_{obs}(t) + Q_A}{2Q_A}}{N}}$$

Where

PEP is the peak-weighted root mean square error

Q_{Obs} is the observed flow at time t

Q_{Sim} is the simulated flow at time t

Q_A is the mean observed discharge

Figure 11. Objective Function Summary for March 2011 Storm with Peak-Weighted RMS Error

Figure 12. Calibrated Hydrograph Comparison for March 2011

The optimized parameters for each calibrated single storm event were taken and averaged together. Each calibration run determines optimized scale factors that will adjust both the Curve Number and Initial Abstraction for each subwatershed. The average parameter scaling factors are applied to all the subwatersheds and will be used for validation.

Calibration Results			
Run	CN Scale Factor	IA Scale Factor	Lag Time (min)
January 2010	0.28171	1.0201	333
December 2010	0.61491	5.0625	204
March 2011	1.15	0.16516	295

Average	0.68	2.08	277
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Table 2. Summary of Calibrated Scale Factors and Lag Time for Three Observed Storms

Validation

Validation is the process of comparing calibrated model data to collected data that is not used in the calibration. According to (Nix, 1994) “Validation is probably the most important process in establishing model credibility.” As stated above the calibration process was performed for three separate single event simulations. The results gave varying adjustment factors for the parameters of initial abstraction and curve number. The three simulated single storm events were of varying intensity and total rainfall depth. The factors that were adjusted during the calibration runs were averaged to determine factors that would be used for validation compared with observed data. The validation of the model averaging the scale factors from multiple events did not have the desired accuracy, and by visual inspection of the December 2010 runoff hydrograph produced with the averaged scale factors. The hydrograph and simulation run summary can be seen below.

Project: AG_Watershed

Simulation Run: Validation Run Junction: Lopez Creek Gage

Start of Run: 18Dec2010, 00:00	Basin Model: Validation Run
End of Run: 24Dec2010, 12:00	Meteorologic Model: December 2010
Compute Time: 22Feb2013, 14:59:44	Control Specifications: Validation

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Outflow : 1290.4 (CFS)	Date/Time of Peak Outflow : 19Dec2010, 13:09
Total Outflow : 3049.7 (AC-FT)	

Observed Hydrograph at Gage Lopez Creek

Peak Discharge : 890.00 (CFS)	Date/Time of Peak Discharge : 19Dec2010, 11:30
Avg Abs Residual : 158.39 (CFS)	
Total Residual : 1507.4 (AC-FT)	Total Obs Q : 1542.29 (AC-FT)

Figure 13. Validation Simulation for December 2010 with Averaged Parameters

Figure 14. Validation Run Hydrograph Comparison for December 2010 with Averaged Parameters

Some of the factors that may have contributed to the discrepancy may have been the different antecedent moisture conditions of the watershed. Antecedent moisture conditions are the three categories of moisture conditions existing in the soil. They are broken into three categories, low moisture, average moisture which is used for flood estimates, and high moisture which represent heavy rainfall for the previous days (Mays, 2005).

After reviewing the model simulations with the averaged subwatershed parameters it was determined that the amount of error was too high to continue using the parameters. The nature of the model is to determine flooding in the Oceano Lagoon. It was determined that the two of the storms used in the calibration process were smaller than a 2 year recurrence interval (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 2012). To better simulate flooding type scenarios it was decided that the largest storm parameters would better simulate flooding in the Oceano Lagoon. December 2010, was the largest storm event simulated at 5.98 inches, which according to NOAA Atlas 14 is a 25 year storm over a 48 hour period. The validation for the same time period with just the December 2010 calibration parameters is shown below demonstrating a much better fit to the larger storm.

Project: AG_Watershed			
Simulation Run: Validation Dec Param Junction: Lopez Creek Gage			
Start of Run: 17Dec2010, 00:00	Basin Model:	Validation Dec Param	
End of Run: 24Dec2010, 12:00	Meteorologic Model:	December 2010	
Compute Time: 08Mar2013, 10:02:22	Control Specifications:	Validation Param	
Volume Units: ☐ IN ☒ AC-FT			
Computed Results			
Peak Outflow : 848.9 (CFS)		Date/Time of Peak Outflow : 19Dec2010, 13:15	
Total Outflow : 1903.6 (AC-FT)			
Observed Hydrograph at Gage Lopez Creek			
Peak Discharge : 890.00 (CFS)		Date/Time of Peak Discharge : 19Dec2010, 11:30	
Avg Abs Residual : 83.24 (CFS)			
Total Residual : 356.0 (AC-FT)	Total Obs Q :	1547.56 (AC-FT)	

Figure 15. Validation Simulation for December 2010 with December 2010 Parameters

Figure 16. Validation Run Hydrograph for December 2010 with December 2010 Parameters

Chapter 5: Results and Discussion

This chapter will discuss the results of the HEC-HMS model with the feasible flood mitigation measures in place.

Flood Mitigation Measures

After the HEC-HMS model has been calibrated and validated the model was edited to include flood mitigation measures. The mitigation measures were chosen with input from engineers at San Luis Obispo County Public Works Department. The mitigation measures include dredging the lagoon, improvements to the outlet structure at Sand Canyon, and the creation of an ocean breach at a location in the lagoon that would reduce the flow into Oceano Lagoon.

Dredging Oceano Lagoon was chosen as a mitigation measure because the possibility of increasing the volume of storage available in the lagoon. Dredging would be a part of a lagoon management plan similar to the Neary Lagoon Management Plan that is in place in Santa Cruz County (Chartrand, Hastings, & Hecht, 2006), and would require collaboration between California State Parks and the County of San Luis Obispo since portions of the lagoon are owned by each agency. It was determined that a feasible amount of material to remove from the lagoon is approximately 10,000 cu yards. It was proposed that a continued maintenance plan may serve to remove additional sediment from the lagoon in later years (Engelskirger, 2013). It should be noted that sediment is not considered a large contributor to a decreased volume in the lagoon (Chipping, 1989). The dredged material was distributed evenly between the invert of the Sand Canyon Culverts, 6.4' MSL, and the lowest finished floor elevation 10.4' MSL. The location of the dredged lagoon option can be seen in the following figure.

Figure 17. Oceano Lagoon Area of Proposed Dredging

Improvement of the Sand Canyon outlets was identified as a mitigation measure because of the ability to increase flow out of the Oceano Lagoon and away from not only homes in the area but also low lying areas such as the Sanitation District and the Oceano Airport. Sand Canyon outlet structure is a structure of the Arroyo Grande Creek Levee System and is operated and maintained by the San Luis Obispo County Public Works Department. The outlet structure is made up of two corrugated metal pipe arch culverts made with tidal flap gates that prevent high tide, and storm surges from inundating the

Oceano Lagoon area. The flap gates open when the water level upstream is several tenths of a foot higher than the water level downstream. During storm events the high downstream water level often prevents the flap gates from opening enough to drain the Oceano Lagoon fast enough to prevent flooding. New overflow spillways with an inlet elevation below the lowest finished floor elevation of 10.4' mean sea level will be simulated to improve the outflow of the lagoon. The proposed spillways were modeled as two concrete box culverts with dimensions of 8 feet wide and 2.8 feet tall. Both the original culverts and the added spillways are approximately 60 feet long, and extend through the entire levee bank.

Figure 18. Location of the Proposed Overflow Spillway Improvements

The third option that was identified was opening an ocean breach located along Carpenter Creek, located just south of Pismo State Beach North Campground on

California State Parks property. This ocean breach is located downstream from Pismo Lake which drains a portion of the watershed that drains into the Oceano Lagoon. The ocean breach would decrease the total volume and reduce the peak flow into the Oceano Lagoon. The area was specifically chosen for the breach because it is a location where historically the creek would form an ocean lagoon and drain to the ocean. The conditions of Carpenter Creek in 1989 were described as a straight drainage ditch with artificial levees with, and a longitudinal bed that slopes away from the beach (Chipping, 1989). To reopen this historical man made breach would require mechanical means to create a gradient to encourage water to move toward the ocean. During high flows the sand bar would be overtopped or mechanically removed and water would drain to the ocean. Since 2010 the Carpenter Creek has water making its way towards the ocean. Carpenter Creek may have been created mechanically during the 1940's by agriculturalists to increase drainage in the coastal area (Chipping, 1989). San Luis Obispo County Public Works Department is currently developing a Sandbar Management Plan to mechanically breach the Arroyo Grande Creek Lagoon. This plan could be expanded to include the Carpenter Creek breaching site and be managed under the obtained or similar permits.

Figure 19. Location of the Proposed Carpenter Creek Ocean Breach in Relation to the Oceano Lagoon

To simulate the ocean breach, ArcMAP was used in a similar process to the creation of the Arroyo Grande model except the subwatershed was divided at the proposed Carpenter Creek breach. This process created a new subwatershed that had no downstream connectivity, this way the Oceano Lagoon could be looked at without the inflow that would drain out of Carpenter Creek. The delineated watershed with the Carpenter Creek Breach can be seen below.

Figure 20. Delineated Watershed with the Carpenter Creek Breach Mitigation Measure

The combination of the improved outlet at Sand Canyon and the ocean breach at Carpenter Creek were also analyzed together for the 10, 50 and 100 year storm to determine the effectiveness of combining the two options. While it is known that the ocean breach will reduce the effect of the improved outlet it is still important to note that under the conditions of the 100 year storm that flooding still occurred on a significant level in the Oceano Lagoon area.

Evaluation of HEC-HMS Results

As stated above the HEC-HMS validation using averaged parameters was not successful at predicting the runoff for a single storm event in the Arroyo Grande Watershed. The analysis continued using the parameters from the December 2010 calibration, the smallest storm analyzed using the HEC-HMS model was a 10 year storm which was equivalent to the storm experienced in December 2010. Using HEC-HMS and considering the Oceano Lagoon as a reservoir, the storage, elevation, inflow and outflow of the lagoon was determined. Each proposed mitigation measure was simulated with HEC-HMS for a 24 hour 10, 50, and 100 year storm frequency. The results are summarized below.

Figure 21. Simulation Summary of Oceano Lagoon for 10 Year Storm with No Mitigation Measures

Project: AG_Watershed_Lagoon

Simulation Run: 50 Year Reservoir: Oceano Lagoon

Start of Run: 10Dec2013, 00:00 Basin Model: AG_Watershed
End of Run: 15Dec2013, 00:00 Meteorologic Model: 50 Year
Compute Time: 24Feb2013, 20:31:24 Control Specifications: 50 Year

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Inflow : 1021.4 (CFS)	Date/Time of Peak Inflow : 10Dec2013, 13:54
Peak Outflow : 278.0 (CFS)	Date/Time of Peak Outflow : 10Dec2013, 22:50
Total Inflow : 853.5 (AC-FT)	Peak Storage : 481.9 (AC-FT)
Total Outflow : 859.5 (AC-FT)	Peak Elevation : 13.1 (FT)

Figure 22. Simulation Summary of Oceano Lagoon for 50 Year Storm with No Mitigation Measures

Project: AG_Watershed_Lagoon

Simulation Run: 100 Yr Reservoir: Oceano Lagoon

Start of Run: 01Dec2013, 00:00 Basin Model: AG_Watershed
End of Run: 05Dec2013, 00:00 Meteorologic Model: 100Year
Compute Time: 24Feb2013, 20:35:32 Control Specifications: 100year

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Inflow : 1129.5 (CFS)	Date/Time of Peak Inflow : 01Dec2013, 13:54
Peak Outflow : 289.1 (CFS)	Date/Time of Peak Outflow : 01Dec2013, 23:37
Total Inflow : 951.6 (AC-FT)	Peak Storage : 548.7 (AC-FT)
Total Outflow : 957.6 (AC-FT)	Peak Elevation : 13.5 (FT)

Figure 23. Simulation Summary of Oceano Lagoon for 100 Year Storm with No Mitigation Measures

Figure 24. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 10 Year Storm with No Mitigation Measures

Figure 25. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 50 Year Storm with No Mitigation Measures

Figure 26. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 100 Year Storm with No Mitigation Measures

The dredged lagoon with increased capacity of 10,000 cubic yards was simulated first with very little improvement over the existing conditions. The overall increase in capacity is only approximately 6.2 acre feet when the peak volume during the December 2010 storms is approximately 280 acre feet. This increase in volume will not prevent flooding especially during larger frequency storm events. The dredged lagoon mitigation measure will not impact the peak flow rate into the Oceano Lagoon. The dredged lagoon simulation resulted in an increase of 1.5% in peak volume for the 10 year, increase of 1% for the 50 year, and increase of 1% for the 100 year frequency storms. The peak elevation did not change for the three simulations. The summary of the results and the hydrographs for the simulations can be found below.

Project: AG_Watershed_Lagoon

Simulation Run: DL 10 year Reservoir: Oceano Lagoon

Start of Run: 20Dec2013, 00:00	Basin Model: Dredged Lagoon
End of Run: 25Dec2013, 00:00	Meteorologic Model: 10 Year
Compute Time: 24Feb2013, 15:23:42	Control Specifications: 10 Year

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Inflow : 767.6 (CFS)	Date/Time of Peak Inflow : 20Dec2013, 13:54
Peak Outflow : 251.9 (CFS)	Date/Time of Peak Outflow : 20Dec2013, 21:04
Total Inflow : 641.5 (AC-FT)	Peak Storage : 339.3 (AC-FT)
Total Outflow : 647.6 (AC-FT)	Peak Elevation : 12.3 (FT)

Figure 27. Simulation Summary of Oceano Lagoon for 10 Year Storm with Dredged Lagoon

Project: AG_Watershed_Lagoon

Simulation Run: DL 50 Year Reservoir: Oceano Lagoon

Start of Run: 10Dec2013, 00:00	Basin Model: Dredged Lagoon
End of Run: 15Dec2013, 00:00	Meteorologic Model: 50 Year
Compute Time: 24Feb2013, 15:25:12	Control Specifications: 50 Year

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Inflow : 1021.4 (CFS)	Date/Time of Peak Inflow : 10Dec2013, 13:54
Peak Outflow : 278.3 (CFS)	Date/Time of Peak Outflow : 10Dec2013, 22:50
Total Inflow : 853.5 (AC-FT)	Peak Storage : 485.6 (AC-FT)
Total Outflow : 859.6 (AC-FT)	Peak Elevation : 13.1 (FT)

Figure 28. Simulation Summary of Oceano Lagoon for 50 Year Storm with Dredged Lagoon

Figure 29. Simulation Summary of Oceano Lagoon for 100 Year Storm with Dredged Lagoon

Figure 30. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 10 Year Storm with Dredged Lagoon

Figure 31. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 50 Year Storm with Dredged Lagoon

Figure 32. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 100 Year Storm with Dredged Lagoon

The improvement of the Sand Canyon outlet structure increased the outflow once the Oceano Lagoon reaches the invert elevation of 9 feet above mean sea level. This option was the most effective at reducing the peak volume in the lagoon. Similar to the dredging option the Sand Canyon Outlet improvement will not reduce the peak inflow into the Oceano Lagoon. The improved outlet resulted in a decrease of 31% in peak volume for the 10 year, decrease of 37% for the 50 year, and decrease of 38% for the 100 year frequency storms. The maximum water elevation decreased by, 0.8 feet, 1.0 feet, and 1.2 feet for the three simulated storms respectively. The summary of the results and the hydrographs can be found below.

Project: AG_Watershed_Lagoon

Simulation Run: OI 10 Year Reservoir: Oceano Lagoon

Start of Run: 20Dec2013, 00:00 Basin Model: Outlet Improvements
End of Run: 25Dec2013, 00:00 Meteorologic Model: 10 Year
Compute Time: 24Feb2013, 12:58:12 Control Specifications: 10 Year

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Inflow : 767.6 (CFS)	Date/Time of Peak Inflow : 20Dec2013, 13:54
Peak Outflow : 454.5 (CFS)	Date/Time of Peak Outflow : 20Dec2013, 17:17
Total Inflow : 641.5 (AC-FT)	Peak Storage : 231.1 (AC-FT)
Total Outflow : 626.1 (AC-FT)	Peak Elevation : 11.5 (FT)

Figure 33. Simulation Summary of Oceano Lagoon for 10 Year Storm with Outlet Improvements

Project: AG_Watershed_Lagoon

Simulation Run: OI 50 Year Reservoir: Oceano Lagoon

Start of Run: 10Dec2013, 00:00 Basin Model: Outlet Improvements
End of Run: 15Dec2013, 00:00 Meteorologic Model: 50 Year
Compute Time: 24Feb2013, 13:01:33 Control Specifications: 50 Year

Volume Units: ☐ IN ☒ AC-FT

Computed Results

Peak Inflow : 1021.4 (CFS)	Date/Time of Peak Inflow : 10Dec2013, 13:54
Peak Outflow : 580.7 (CFS)	Date/Time of Peak Outflow : 10Dec2013, 17:30
Total Inflow : 853.5 (AC-FT)	Peak Storage : 301.8 (AC-FT)
Total Outflow : 828.7 (AC-FT)	Peak Elevation : 12.1 (FT)

Figure 34. Simulation Summary of Oceano Lagoon for 50 Year Storm with Outlet Improvements

Figure 35. Simulation Summary of Oceano Lagoon for 100 Year Storm with Outlet Improvements

Figure 36. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 10 Year Storm with Outlet Improvements

Figure 37. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 50 Year Storm with Outlet Improvements

Figure 38. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 100 Year Storm with Outlet Improvements

The ocean breach at the Carpenter Creek was the third possible solution analyzed. The creek channel is bordered to the south by the Pismo Beach Golf Course and the Pismo State Beach North camp ground and Monarch Butterfly Grove to the north. The current channel has a sluice gate where the Carpenter Creek connects to the Meadow Creek. The water level appears to be the same on both sides of the sluice gate assumed to be because of leakage through the levee and sluice gate (Chipping, 1989). Opening an ocean breach at Carpenter Creek effectively reduced both the peak flow into the Oceano Lagoon. The ocean breach resulted in a decrease of 24% in peak volume for the 10 year, decrease of 26% for the 50 year, and decrease of 26% for the 100 year frequency storms. The decrease in peak inflow is approximately 21% for the 10 year, decrease of 21% for the 50 year, and decrease of 21% for the 100 year frequency storms. The maximum

water elevation decreased by, 0.6 feet, 0.7 feet, and 0.8 feet for the three simulated storms respectively. The summary of the results and hydrographs can be found below.

Figure 39. Simulation Summary of Oceano Lagoon for 10 Year Storm with Ocean Breach

Figure 40. Simulation Summary of Oceano Lagoon for 50 Year Storm with Ocean Breach

Figure 41. Simulation Summary of Oceano Lagoon for 100 Year with Ocean Breach

Figure 42. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 10 Year Storm with Ocean Breach

Figure 43. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 50 Year Storm with Ocean Breach

Figure 44. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 100 Year Storm with Ocean Breach

The final flood mitigation measure analyzed was the combination of both the improved outlet and the ocean breach at Carpenter Creek. The improved outlet was the most effective at reducing the peak volume of water in the lagoon while the ocean breach decreased the total volume and peak inflow into the lagoon. The combined solution is a good approach because of the added benefits of each mitigation measure. The combined solution (i.e., outlet improvement and ocean breach) resulted in a decrease of 40% in peak volume for the 10 year, decrease of 46% for the 50 year, and decrease of 48% for the 100 year frequency storms. The decrease in peak flow is approximately 21% for the 10 year, decrease of 21% for the 50 year, and decrease of 21% for the 100 year frequency storms. The maximum water elevation decreased by, 1.2 feet, 1.3 feet, and 1.4 feet for

the three simulated storms respectively. The summary of the results and hydrographs can be found below.

Figure 45. Simulation Summary of Oceano Lagoon for 10 Year Storm with Combined Solution

Figure 46. Simulation Summary of Oceano Lagoon for 50 Year Storm with Combined Solution

Figure 47. Simulation Summary of Oceano Lagoon for 100 Year Storm with Combined Solution

Figure 48. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 10 Year with Combined Solution

Figure 49. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 50 Year Storm with Combined Solution

Figure 50. Elevation/Storage and Inflow/Outflow of Oceano Lagoon for 100 Year Storm with Combined Solution

The following tables summarize the simulation results sorted by the storm frequency, i.e. 10 year, 50 year, and 100 year. Inundation maps were also developed from the Civil 3D surface and the maximum water elevation contour from each simulation. The mitigation measures are visually compared for each design frequency storm. Note that the existing conditions, or no mitigation measures, is the same elevation for each storm as the dredged lagoon option.

Mitigation Measure	Volume (AF)	Peak Flow (cfs)	Maximum Water Level (ft.)
No Mitigation	335.3	767.6	12.3
Dredged Lagoon	339.3	767.6	12.3
Outlet Improvement	231.1	767.6	11.5

Carpenter Creek Breach	253.6	609.3	11.7
Combined Measures	199.8	609.3	11.1

Table 3. Simulation Results for 10 Year Storm

Mitigation Measure	%Volume Reduction	% Peak Flow Reduction	Decrease in Water Level
No Mitigation	N/A	N/A	N/A
Dredged Lagoon	1%	0%	0
Outlet Improvement	-31%	0%	0.8
Carpenter Creek Breach	-24%	-21%	0.6
Combined Measures	-40%	-21%	1.2

Table 4. Mitigation Measure Simulation Reduction Percentages

Figure 51. Inundation Map for 10 Year Storm with Mitigation Measures

Mitigation Measure	Volume (AF)	Peak Flow (cfs)	Maximum Water Level (ft.)
No Mitigation	481.9	1021.4	13.1
Dredged Lagoon	485.6	1021.4	13.1
Outlet Improvement	301.8	1021.4	12.1
Carpenter Creek Breach	355.7	810.7	12.4
Combined Measures	260.1	810.7	11.8

Table 5. Simulation Results for 50 Year Storms

Mitigation Measure	%Volume Reduction	% Peak Flow Reduction	Decrease in Water Level
No Mitigation	N/A	N/A	N/A
Dredged Lagoon	1%	0%	0
Outlet Improvement	-37%	0%	1
Carpenter Creek Breach	-26%	-21%	0.7
Combined Measures	-46%	-21%	1.3

Table 6. Mitigation Measures Simulation Reduction Percentages

Figure 52. Inundation Map for 50 Year Storm with Mitigation Measures

Mitigation Measure	Volume (AF)	Peak Flow (cfs)	Maximum Water Level (ft.)
No Mitigation	548.7	1129.5	13.5
Dredged Lagoon	552.4	1129.5	13.5
Outlet Improvement	338.9	1129.5	12.3
Carpenter Creek Breach	407.8	897	12.7
Combined Measures	286.4	897	12.1

Table 7. Simulation Results for 100 Year Storm

Mitigation Measure	%Volume Reduction	% Peak Flow Reduction	Decrease in Water Level
No Mitigation	N/A	N/A	N/A
Dredged Lagoon	1%	0%	0
Outlet Improvement	-38%	0%	1.2
Carpenter Creek Breach	-26%	-12%	0.8
Combined Measures	-48%	-12%	1.4

Table 8. Mitigation Measures Simulation Reduction Percentages

Figure 53. Inundation Map for 100 Year Storm with Mitigation Measures

Chapter 6: Conclusions

Though model validation conclusions are not ideal, it proves to provide an accurate depiction of the Arroyo Grande Watershed during large storm and flood type events. The volume and peak flows observed at the Lopez Creek stream gage for the December 2010 storms match the model simulation output. The proposed mitigation measures were simulated in the calibrated watershed and simulations were run for a 10, 50, and 100 year return storm period. These results are compared to the simulated results for the existing watershed with no mitigation measures.

The results from the analysis indicate that the dredging of 10,000 cubic yards of material from the lagoon will not decrease the maximum water elevation. The simulations also indicate that the peak volume of the lagoon will increase, which makes sense because of the minor increase in capacity that results from the removal of sediment.

The proposed improvements to the Sand Canyon outlet structure decreased the maximum water elevation and the peak volume in the lagoon. This alternative ultimately had no effect on the peak inflow into the Oceano Lagoon. The reduction in the peak volume in the lagoon was in the 30% range for each storm frequency simulation. This relates to a maximum water elevation decrease between 0.8 feet and 1.2 feet, depending on the frequency storm. This is a significant decrease but not enough to prevent the lowest finished floor elevation from flooding even during the 24 hour 10 year frequency storm. There would be additional concerns with the construction and placement of the overflow culverts. For example, if the Arroyo Grande Creek is not wide enough at the location where the culverts are installed tail water effects may cause water to flow from the creek to the Oceano Lagoon possible exasperating the issue. For the purpose of the

analysis the initial elevation in the Oceano Lagoon was assumed to be 7 feet mean sea level and the tail water effects are assumed negligible. These values were determined to be reasonable through trial and error to recreate the maximum water elevation during the December 2010 storms. The culverts remain an effective flood mitigation measure.

The ocean breach at Carpenter Creek was effective at reducing the peak volume, maximum water surface elevation, and the peak inflow into the Oceano Lagoon. This option was not as effective compared to the Sand Canyon outlet structure improvements, but could still be an effective option for flood mitigation. The reduction in peak lagoon volume varied approximately from 24% to 26% depending on the frequency storm simulated. The reduction in peak inflow into the Oceano Lagoon was approximately 21% for each simulated storm frequency. The maximum water surface elevation varied between 0.6 feet to 0.8 feet depending on the storm frequency. The Carpenter Creek Breach is an effective solution to reduce the flooding in Oceano Lagoon. Though similar to the other options simulated, the flooding is not completely eliminated even during the 10 year storm.

The most effective mitigation measure that was simulated was the combination of the Sand Canyon outlet structure improvements and the ocean breach at Carpenter Creek. This combination will increase the outflow of the lagoon and reduce the peak inflow into the Oceano Lagoon. The reduction in peak lagoon volume was 40% to 48% for the various frequency storms simulated. The reduction in inflow is approximately 21% the same reduction that was simulated with just the Carpenter Creek ocean breach. The maximum water level decrease in the lagoon ranges from 1.2 feet to 1.4 feet depending on the frequency storm simulated. Unfortunately the decrease in flood elevation was not

enough to eliminate the flooding in the lowest finished floor homes. Any flood mitigation measures are more effective in conjunction with others. Combining these mitigation measures will deliver the best results for flood protection.

Recommendations for Future Work

Given the conclusions of this study, future analysis is still desired to increase the accuracy and expand the usefulness of the model for San Luis Obispo County Public Works Department. While the data was validated using known stream flow data and also the approximate maximum water level, better data collection methods should be used throughout the watershed to increase accuracy of the model.

While HEC-HMS allowed a simple user interface and allowed for the easy creation of an event based model, the creation of a continuous model could also provide a long term planning tool for the County of San Luis Obispo. To create a long term model the NRCS Curve Number Method that was chosen would not be reliable because it does not take into account evaporation and infiltration. HEC-HMS has the tools to analyze continuous models effectively, other programs like SWMM could also be used to great effectiveness.

The model is limited by the accuracy of the DEM provided by the USGS. The topography near the Oceano Lagoon is relatively flat and the DEM which has horizontal resolution of 10 meters by 10 meters is not accurate enough to account for minor changes in elevation. The DEM obtained from the USGS was created using information that predates the installation of several large features in the watershed including Lopez Dam and the Arroyo Grande Levee system. Topographic information that is collected at a higher accuracy should be collected and used to create a higher accuracy DEM for the delineation of the watershed to increase accuracy of the sub-basin boundaries.

The collection of reliable data is the cornerstone of model creation. While the stream flow data that was used in the development of the hydrologic analysis is from the USGS and has been verified by their staff, the location of the stream gage is far away from Oceano Lagoon where the analysis was focused. Stream flows should be measured not only for the Arroyo Grande Creek but also in the Oceano Lagoon knowing these flows would only increase the accuracy of the calibration and validation process. This data would be difficult to collect because of the numerous culverts and drainage outlets into Oceano Lagoon. The rainfall data collected is operated by the County of San Luis Obispo and is well maintained throughout the entire watershed.

To create a continuous simulation model which is desirable for planning, additional data needs to be collected. Climate data such as temperature, wind speed and solar radiation will help increase the accuracy of the long term model. This information can be obtained from the California Irrigation Management Information System (CIMIS) station. There is a CIMIS station located in Nipomo California located approximately 10 miles south of the Arroyo Grande Watershed.

The model accuracy can be increased with the use of a distributed type instead of the semi-distributed method that was chosen. Similar information would be collected and organized using ArcGIS but would also be able to account for changes in slope and the drainage network (Vieux, 2004). The distributed model would break down each sub-watershed into smaller grids and determine the parameters for each.

Several assumptions were used in the creation of this model including that the high levels in the Arroyo Grande Creek forced all the water in the adjacent subwatershed to drain into the Oceano Lagoon. While for the 100 year design storm this assumption is

reasonable, using the watershed model in conjunction with a model of the Arroyo Grande Creek could influence the flow out of the Oceano Lagoon and also provide further information such as the possible risk of the levees overtopping increasing the flooding in the lower elevations around the Oceano Lagoon.

Bibliography

- Adger, N. (2007). Climate change 2007: Impacts, adaptation and vulnerability summary for policy makers. *Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report* (pp. 1-22). Brussels: Intergovernmental Panel on Climate Change.
- ArcGIS 9.2 Desktop Help. (2008, September 22). Retrieved from ESRI :
<http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=welcome>
- Cannon. (2012). *Preliminary design report for Highway 1 at 13th Street drainage improvement project in Oceano*. San Luis Obispo.
- Chartrand, S., Hastings, B., & Hecht, B. (2006). *Neary lagoon: Lagoon-specific sedimentation management plan*. Santa Cruz: Balance Hydrologies, Inc.
- Chipping, D. D. (1989). *Hydrology of the meadow creek drainage, San Luis Obispo County, California*. San Luis Obispo: California Polytechnic State University San Luis Obispo.
- Cranor, S. (2013, January 15). (E. Perez, Interviewer)
- Dvorsky, J. (2010). *Arroyo Grande creek channel waterway management program*. San Luis Obispo: Waterways Consulting, Inc.
- Engelskirger, N. (2013, January 25). P.E. (E. Perez, Interviewer)
- FEMA. (2013, February 15). *Flood facts*. Retrieved from The Official Site of the NFIP:
http://www.floodsmart.gov/floodsmart/pages/flood_facts.jsp
- Flemming, M. J., & Doan, J. H. (2009). *HEC-GeoHMS geospatial hydrologic modeling extension*. Davis: U.S. Army Corp of Engineers Hydrologic Engineering Center.
- Lambert, C. (2011, January 22). How the flooding in Oceano went from bad to worse. *The Tribune*.
- Lambert, C. (2012, October 3). Treatment plant to be fined \$1.1 million for Oceano sewage spill. *The Tribune*.
- Mays, L. W. (2005). *Water resources engineering*. Tempe: John Wiley & Sons, Inc.
- Monterey Peninsula Water Management District. (2005). *Study plan for long term adaptive management of the Carmel river state beach and lagoon*. Carmel: Monterey Peninsula Water Management District.
- National Map Viewer. (2012, August). Retrieved from USGS National Map Viewer:
<http://viewer.nationalmap.gov/viewer/>

- Neitsch, S., Arnold, J., Kiniry, J., & Williams, J. (2009, August). *Documentation: Soil & water assessment tool*. Retrieved from Soil & Water Assessment Tool:
<http://twri.tamu.edu/reports/2011/tr406.pdf>
- Nix, S. J. (1994). *Urban stormwater modeling and simulation*. Boca Raton: Lewis Publishers.
- Raines, Melton & Carella, Inc. (2004). *Oceano drainage flood control study*. San Luis Obispo: RMC Inc.
- Redfearn, H. D. (2005). *Rainfall-runoff changes due to urbanization: A comparison of different spatial resolutions for lumped surface water hydrology models using HEC-HMS*. Denton: University of North Texas.
- Reinhart, M. (2011). *Arroyo Grande creek channel winter 2010 precipitation*. San Luis Obispo: San Luis Obispo County Public Works Department.
- Scharffenberg, W., & Flemming, M. (2009). *Hydraulic modeling system HEC-HMS user's manual version 3.4*. Davis: U.S. Army Corp of Engineers.
- Staff. (2012, September). *Natural Resources Conservation Service*. Retrieved from United States Department of Agriculture, Soil Survey Geographic (SSURGO):
<http://soildatamart.nrcs.usda.gov/>
- Staff, A. (2013, January). *About Autodesk Company*. Retrieved from Autodesk :
<http://usa.autodesk.com/company/>
- The Federal Interagency Stream Restoration Working Group. (2010, 10 01). *Stream Corridor Restoration*. Retrieved from USDA Natural Resources Conservation Service:
<http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/quality/?cid=stelprdb1043448>
- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. (2012). *NOAA atlas 14 precipitation-frequency atlas of the United States volume 6 version 2.1: California*. Silver Spring: U.S. DOC, NOAA, NWS.
- USGS National Water Information System. (2013, January 21). *USGS 11141280 Lopez C NR Arroyo Grande CA*. Retrieved from USGS Web Site:
http://waterdata.usgs.gov/ca/nwis/uv?site_no=11141280
- Vieux, B. E. (2004). *Distributed hydrologic modeling using GIS*. New York: Springer Science & Business Media, Inc.