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Climate Change Implications for Ballona Wetlands Restoration

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1.0 Executive Summary

The Ballona Wetlands are the last remaining major coastal wetlands in the Santa Monica Bay and Los Angeles County. At one time over 2000 acres, less than 100 acres of the wetland habitats still receive estuarine waters due to the development of roads and railways, a marina, housing and businesses, and the channelization of Ballona Creek. The Ballona Creek Watershed is one of the most developed watersheds in the United States with urbanized areas accounting for approximately 80 percent of the 130 square mile watershed. The Department of Fish and Game, the State Lands Commission, and the California State Coastal Conservancy are working with stakeholders and other agencies to develop a plan to restore wetlands and other habitats on the approximately 600-acre state-owned Ballona Wetlands Ecological Reserve (BWER).

The purpose of the Ballona Wetlands Climate Change study was to investigate the implications of potential changes in precipitation and sea level to the BWER. The study includes the application and integration of multiple models under various climate change scenarios to two proposed wetland restoration alternatives.

The lead agencies, stakeholders, and a scientific advisory committee developed five restoration plan alternatives (Alternatives 1-5) for the BWER, as well as subsequent revisions to Alternatives 4 and 5. This study examines the original Alternative 5 (Alt5) from 2008 and the revised Alternative 5 (RevAlt5) from 2009. Note that these are not the alternatives from the Environmental Impact Reporting process; those alternatives have not been finalized, and these are only two of the graphic options that have been in development. Alt5 would reconnect Ballona Creek with the BWER and restore a large contiguous salt marsh plain. RevAlt5 was modified to account for cost and infrastructure constraints, and to include a continuous slope from subtidal through upland habitats to allow the migration of habitats in the event of sea level rise (SLR). The change from a flat plain in Alternative 5 to a continuous slope in the Revised Alternative provides a unique opportunity to study the potential impacts of SLR and precipitation changes on the two different restoration designs.

The primary models applied in this study are EFDC and HEC-HMS. HEC-HMS simulates the primary hydrologic processes of the watershed (excluding the wetlands), while the EFDC simulates the hydrologic processes of the wetlands. The results of the models, along with observations of existing conditions, are used to develop an understanding of the potential climate change impacts to habitats and species in the wetlands. Given the uncertainty of previous studies of precipitation changes under future conditions in southern California, this study investigated a suite of extreme precipitation scenarios ranging from a 25% decrease to a 25% increase in precipitation.

Low-lying coastal regions, such as the Ballona Wetlands, are particularly vulnerable to changes in sea level. A recent study by Kerr (2008) provides estimates of SLR ranging from 0.8 to 2.0 meters by 2100, roughly three to four times the IPCC (2007) projections. The state of California is currently using projections of 0.4 m by 2050 and 1.4 m by 2100 for all projects along the coast (CO-CAT 2010). To model the impacts of sea-level rise in 2100, this study applies the models with 1.0 m and 1.4 m added to the present-day tidal levels.

In total, a suite of 36 model simulations are performed to investigate the inundation impacts of SLR and changes in extreme precipitation scenarios. Simulations are performed for the two restoration alternatives: Alt5 and RevAlt5 under a combination of three SLR scenarios (0, 100, and 140 cm) and five flood events (T=100-yr, T=100-yr ± 10%, and T=100-yr ± 25%).

The model results show that SLR will have a significant impact on the area of inundation at the BWER. Model outputs for the proposed restoration alternatives suggest in the event of SLR, higher tides and subsequent higher water levels will occur in the BWER. The model outputs depict the new, sinuous creek with smaller intertidal channels across the BWER. Alt5 includes a large flat salt marsh plain (approximately 0.9 km^2) that is inundated approximately 10% of the time under existing climate conditions. With 1.0 m SLR the subtidal area increases, upland areas are reduced, and the plain is inundated approximately 70% of the time. With 1.4 m SLR the plain inundation time increases to 85% of the time.

On the other hand, under the RevAlt5, which has been modified to account for SLR, the high tides have a reduced impact on the flood when compared to Alt5, despite the fact that the percent of area inundated at the peak flood is approximately constant for Alt5 and the RevAlt5. The results for RevAlt5 with 1.0 m SLR show increases in subtidal area and decreases in upland area, with a consistent inland or upland transgression of habitats, and maintaining a greater diversity of intertidal conditions.

When examining the impact of extreme precipitation scenarios, the model results show precipitation and resulting floods cause a steep increase in the amount of wet area within the wetlands under present-day sea levels. However, potential changes to the 100-year precipitation event result in considerably greater impacts on the inundated area for Alt5 than for the RevAlt5, suggesting the Revised Alternative is more resilient to changes in extreme precipitation events.

When considering the combination of SLR with changes in extreme precipitation scenarios, the modeling results show, for both Alternatives, the precipitation change does not cause a considerable change in the amount of wet area for either of the SLR scenarios (1.0 m or 1.4 m). This is because the high sea levels have a greater influence on the flooded area than the extreme precipitation events. This is especially evident for Alt5, for which the modeling result show the wetland inundation levels remain similar regardless of the change in precipitation event magnitude.

Based on the modeling results of inundation frequency and elevation, the study further investigated the implications of climate change on habitat acreage and distribution for the proposed restoration alternatives. With current sea level (SL) conditions, Alt5 supports a large mid salt marsh habitat (1.1 km^2) commonly found in southern California coastal wetlands (Zedler et al., 1999). With SLR, this middle salt marsh habitat (0.07 km^2 with 1.0 m SLR, and 0.03 km^2 with 1.4 m SLR) transitions to mudflat habitat (1.31 km^2 with 1.0 m SLR, and 1.38 km^2 with 1.4 m SLR) assuming other variables such as scour remain consistent with the current conditions. The transition from a vegetated middle marsh wetland system to a mudflat-dominated system would likely cause a shift in the species supported. This is an important consideration for restoration planners who may wish to provide habitat for certain rare or important wetland species.

Habitat distributions were also investigated for the Revised Alternative using similar methods. With current SL conditions, RevAlt5 supports a range (low, mid and high) of vegetated marsh habitats and their adjacent upland habitats (0.86 km^2) typical of southern California coastal wetlands (Sutula et al., 2002; Zedler et al., 1999). With SLR, this alternative also shifts toward a mudflat dominated system (0.11 km^2 with No SLR, 0.86 km^2 with 1.0 m SLR, and 0.91 km^2 with 1.4 m SLR). However, RevAlt5 continues to support a significant area of diverse marsh habitats (0.41 km^2 with 1.0 m SLR, and 0.31 km^2 with 1.4 m SLR).

The results of this investigation may help in planning coastal wetlands restoration projects in the future. For example, in some locations it may be possible to create a series of flat to gently-sloping marshes on a stepped, rather than a continuously sloped, gradient. By creating steps of marsh at increasing elevations, large, flat or gently-sloped marsh habitats that closely mimic natural marshes could be maintained as sea levels rise. Developing a model to assess this type of design may provide insights for future wetland restoration projects that are adaptive to climate change.

2.0 Introduction

Santa Monica Bay is a large urban water body that supports diverse and valuable natural resources as well as the economic and recreational needs of millions of southern California residents and visitors. The interaction of a large urban population with the sensitive resources of the Bay and its watershed provides a good opportunity to study the impacts of urbanization on natural systems.

The Ballona Wetlands are the last remaining major coastal wetlands in the Santa Monica Bay and Los Angeles County. The upstream watershed is one of the most developed watersheds in the United States with urbanized areas accounting for approximately 80 percent of the 130 square mile watershed (Figure 2.1). In 2004, the State of California took title to approximately 600-acres of the remaining Ballona Wetlands in Los Angeles (Figure 2.2) and created the Ballona Wetlands Ecological Reserve (BWER). The State is working with stakeholders to plan the restoration of the BWER, with the goal of ”restoring, enhancing, and creating estuarine habitat and processes in the Ballona Ecosystem to support a natural range of habitats and functions, especially as related to estuarine dependent plants and animals,” among others (PWA, 2006).

In order to return the BWER to a diverse, resilient, and dynamic ecosystem, the Ballona Wetlands Restoration Project initiated by the State stressed in its plan the importance of “restoring inherent ecological processes, improving sustainability and resiliency to adapt to climate change and other environmental changes” (BWRP, 2012). A better understanding of the potential impacts of climate change (i.e. sea level rise and possible changes to extreme precipitation events) on the Ballona Creek Watershed and Wetlands will help accomplish this objective. In this study, we simulate the hydrologic conditions in the watershed using the United States Army Corps of Engineers’ (ACOE’s) Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) and the hydraulic conditions of the wetlands using Environmental Protection Agency’s (EPA’s) Environmental Fluid Dynamics Code (EFDC). These models are applied under various climate change scenarios to existing wetland conditions and proposed wetland restoration alternatives. The results of the models, along with supporting references, are used to improve understanding of the potential climate change impacts to habitats in the BWER under different restoration scenarios and may help planners select a restoration design that best addresses the predicted climate change impacts.

Through the restoration planning process, planners considered various design alternatives for the BWER, encompassing a broad range of potential hydrologic and habitat conditions. For this study, we modeled impacts to a design known as Alternative 5, and a revised version of Alternative 5, known as the Revised Alternative. Alternative 5 (Alt5) includes removing levees to reconnect the Ballona Creek estuary to the BWER and restoring a large contiguous salt marsh plain. This alternative was subsequently revised to account for cost and infrastructure constraints, and to include a continuous slope from subtidal through upland habitats to allow the migration of habitats in the event of sea level rise (SLR). The change from a flat plain in Alternative 5 to a continuous slope in the Revised Alternative (RevAlt5) provides an opportunity to apply site-specific climate change modeling and assist the incorporation of changes in sea level and precipitation in coastal restoration planning. This study examines the original Alt5 from 2008 and RevAlt5 from 2009. Note that these are not the alternatives from the Environmental Impact Reporting process; those alternatives have not been finalized, and these are only two of the graphic options that have been in development.

2.1 Climate change projections and impacts

While it is recognized that there are numerous potential impacts of climate change globally, this study focuses on the implications of potential changes in sea level and precipitation. These are two of the major impacts of climate change to which low-lying coastal regions such as wetlands are particularly vulnerable. The latest report by the Intergovernmental Panel on Climate Change (IPCC) states global average surface air and ocean temperatures are increasing at rates unequivocal to any other period on record including paleologic records (IPCC, 2007). As the climate warms, sea level rises due to melting of land-based ice and thermal expansion of oceans and seas. As with global temperature, it is widely accepted that sea levels have been increasing for the past 1.5 centuries (IPCC, 2007), globally and in California (Cayan et al., 2008). Global average sea level has risen at a rate of 1.8 mm/yr since 1961 and has accelerated to a rate of 3.1 mm/yr since 1993 (IPCC, 2007). It is very likely that anthropogenic greenhouse gas increases contributed to sea level rise during the latter half of the 20th century (IPCC, 2007).

Projections of climate change over the remainder of the century indicate that temperature is virtually certain to increase continuously and substantially in response to anthropogenic inputs of greenhouse gases (IPCC, 2007). As a result, sea level will also continue to rise. IPCC (2007) projections of mean global sea level rise, depending on the greenhouse gas emissions scenario, range from 20 to 60 cm by the year 2100, and are now considered to be grossly underestimated. Recent studies by Kerr (2009) and Vermeer and Rahmstorf (2009) provide more realistic estimates of global sea level rise ranging from 80 to 200 cm, roughly three to four times the IPCC (2007) projections (Figure 2.3). The major reason for the discrepancy is recent evidence for rapid changes resulting from ice sheet breaks; this process is not included in the IPCC (2007) models. The state of California is currently using projections from 101 to 140 cm by 2100 (CO-CAT, 2010), based on Vermeer and Rahmstorf (2009). Scenarios applying California's projections (100 and 140 cm) are investigated in this study.

Changes in extreme high sea level closely follow changes in average sea level and are influenced by extremes of climate and weather on time scales of days and hours, associated with tropical cyclones and mid-latitude storms (IPCC, 2007). Low atmospheric pressure coupled with high winds and high tides produce these severe storm surges, and increase the risk of coastal damage. Changes in the frequency of occurrence of these extreme sea levels are affected by changes in mean sea level and in the meteorological phenomena that cause the extremes.

Cayan et al. (2008), via an analysis of a tide gage record in San Diego, California, show that with the rise in mean sea level, the occurrence of sea level extremes has increased by 30-fold since 1933. As sea level continues to rise from anthropogenic warming, it is likely these extremes will become even more common (IPCC, 2007) and lead to inundation of low-lying areas, as well as damage to coastal structures and severe flooding and erosion.

While it is likely that a warmer climate will result in an increase in global average precipitation, due to increased evaporation and resulting atmospheric water vapor, the direction of change in average precipitation (increase or decrease) will depend on the region (IPCC, 2007). Changes due to climate patterns such as El Nino-Southern Oscillation (ENSO) and northern and southern hemisphere annual modes control the direction of precipitation changes. Since 1976, southern California has seen a 5% increase in the frequency of measurable (>1 mm) daily precipitation events (Higgins et al. 2007). Annual precipitation at the Pasadena United States Historical Climatology Network (USHCN) gage (closest gage to the Ballona Wetlands) has been increasing by 0.7 cm per decade since 1895 and 2.3 cm per decade since 1950 (Figure 2.4).

Unlike sea level, increases in mean precipitation are not necessarily correlated to increases in extreme precipitation. In addition, precipitation extremes do not increase proportionally with increase in atmospheric vapor pressure (O'Gorman and Schneider, 2009). It is likely, however, that the frequency of heavy precipitation events (fraction of total precipitation that falls as heavy, 90th percentile, precipitation) and incidence of drought since the 1970s has increased in many areas (IPCC, 2007). It is more likely than not that anthropogenic climate change has contributed to these global increases (IPCC, 2007). In the western United States, modest increases have occurred in the number of heavy precipitation events (e.g., Karl and Knight, 1998, Madsen and Figdor, 2007, Pryor et al., 2009, Mass et al., 2010). In California, 1-day precipitation events with a recurrence interval of 1 year or longer have increased by 26% since 1948, while in the metropolitan area of Los Angeles-Riverside-Orange Counties, there has been an increase of 58% (Madsen and Figdor, 2007). Mass et al. (2010) find an increasing trend in the top 20, 40, and 60 two-day events at three of the four southern California USHCN precipitations gages they analyzed; although data from the Pasadena gage were not included in the analysis. Higgins et al. (2007) find as much as a 20% increase since 1950 in the total accumulated precipitation resulting from heavy (90th percentile) precipitation days. At the same time, Karl et al. (2009) find that droughts have also become more common in some regions including southern California. Madsen and Figdor (2007) suggest that with increases in the frequency of heavy precipitation (defined above), longer intervals of relatively dry weather would typically occur if there was no change in mean precipitation.

While most agree that there is the potential for changes in the occurrence of extreme precipitation events – both flood and drought based on analysis of climate change over the last 50 years – modeling studies of extreme precipitation changes under future conditions in southern California demonstrate conflicting results (e.g., Bell et al., 2004, Diffenbaugh et al., 2005, Kim, 2005). Bell et al (2004) find that changes in precipitation exceeding the 95th percentile followed changes in mean precipitation, with decreases in heavy precipitation events in the southern California coast. Diffenbaugh et al. (2005) show no statistically significant changes in mean and extreme precipitation along the California coast (Figure 2.5). Kim et al. (2005) display a small, but statistically significant, increase in extreme precipitation event magnitude in southern California. However, they emphasize the high level of uncertainty in these projections in the southern California region. Given the uncertainty in predicting changes to extreme precipitation events in southern California, a suite of precipitation scenarios ranging from a 25% decrease to a 25% increase in extreme precipitation are investigated in this study.

Long-term sustainability of restored coastal wetlands is highly sensitive to climate change, especially to sea level rise and changing precipitation characteristics for several reasons. Tidal wetlands exist within a narrow range of elevations, set primarily by tidal frame (Zedler and Cox 1985; Silvestri et al., 2005). A small change in the tidal frame due to sea level rise would result in movement of the vertical distribution of tidal habitats, depending on the physical condition gradients (Kirwan et al., 2010). Furthermore, it may be very difficult for coastal wetlands in southern California such as BWER to adapt to sea level rise through transgression of habitats to higher elevation higher elevations under existing conditions due to urbanization of the surrounding land and hydrological modifications to the system.

The response of tidal wetlands to sea level rise also depends on sediment supply to the wetland and the associated rate of wetland accretion or loss due to scouring. If sediment is readily available, vertical accretion may keep pace with sea level rise and the spatial distribution of tidal habitats may not change significantly. Because sediment supply may be low, as in urbanized Ballona Creek, accretion rates may be slower than sea level rise and habitats could transgress landward as a result if there is room for them to do so (Figure 2.6).

Restoration planning for the BWER is at the concept design and feasibility analysis stage. Analysis of climate change is appropriate at this stage, as sustainable restoration alternatives can be refined before proceeding to formal review. The restoration alternatives for the BWER include a broad range of concepts ranging from minor changes to the existing conditions, to major earth moving and creation of a sinuous creek channel and unrestricted tidal flows to the wetland.

Figure 2.1. Map of the Ballona Creek Watershed. Figure courtesy PWA (2006).

Figure 2.2. Existing habitat within the Ballona Wetlands. Figure courtesy PWA (2006).

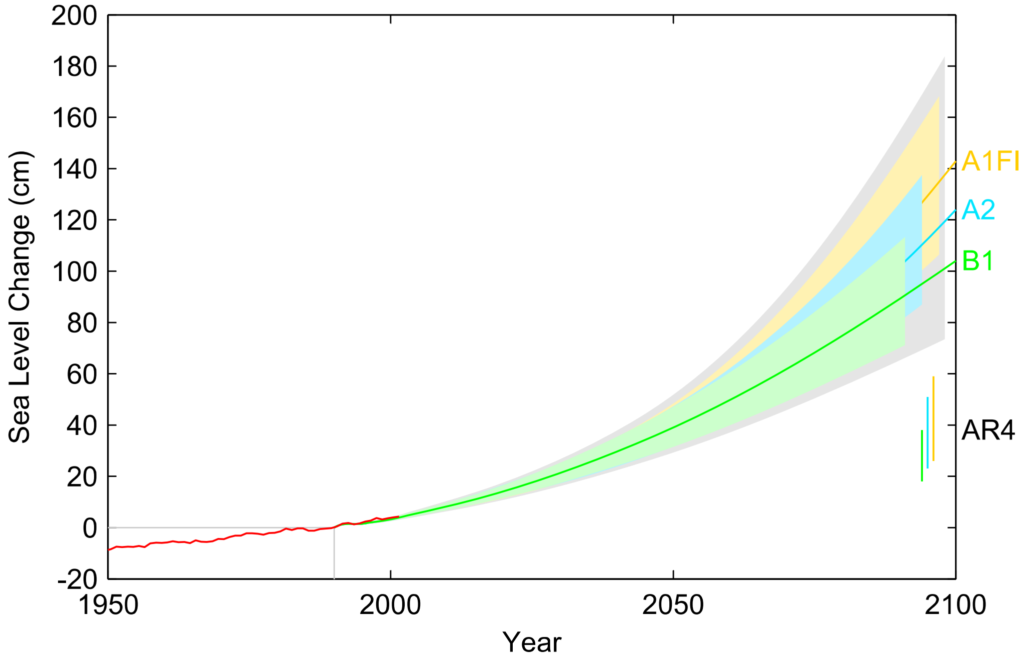


Figure 2.3. Sea level rise observations and projections for the A1F1, A2, and B1 SRES IPCC scenarios. Figure from Vermeer and Rahmstorf (2009).

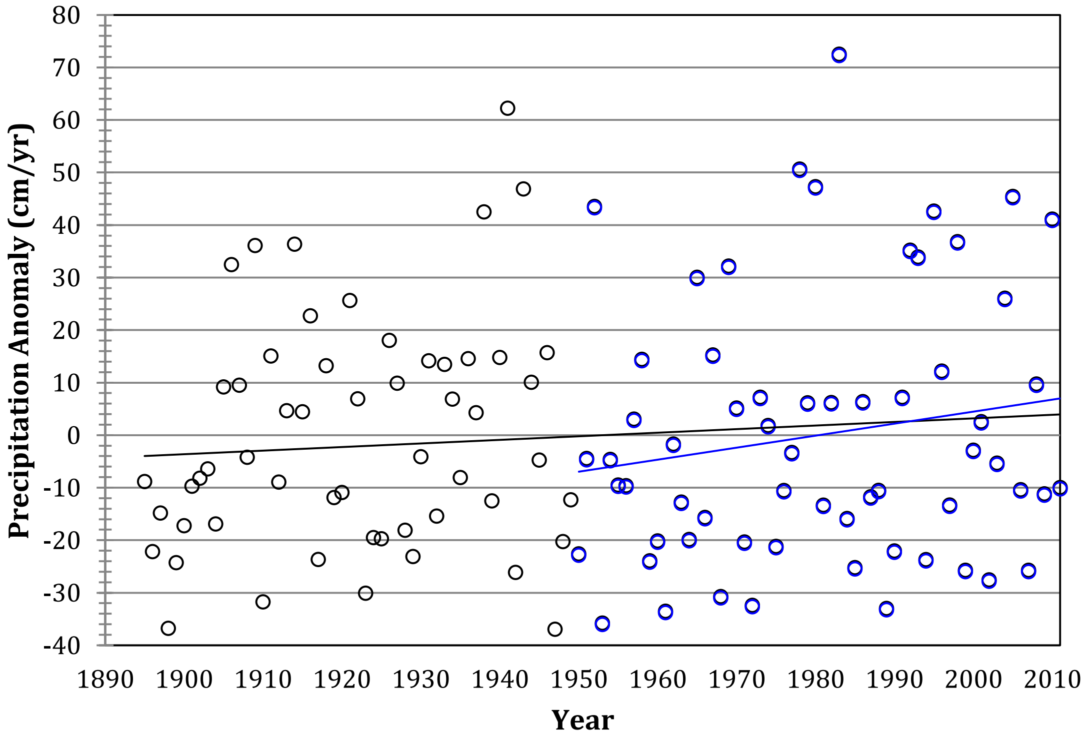


Figure 2.4. Precipitation anomalies (cm/yr) for the United Stated Historical Climate Network gage in Pasadena, California (046719). The black line represents the trend from 1895 to 2011 (0.07 cm/yr); the blue line represents the trend from 1950 to 2011 (0.23 cm/yr).

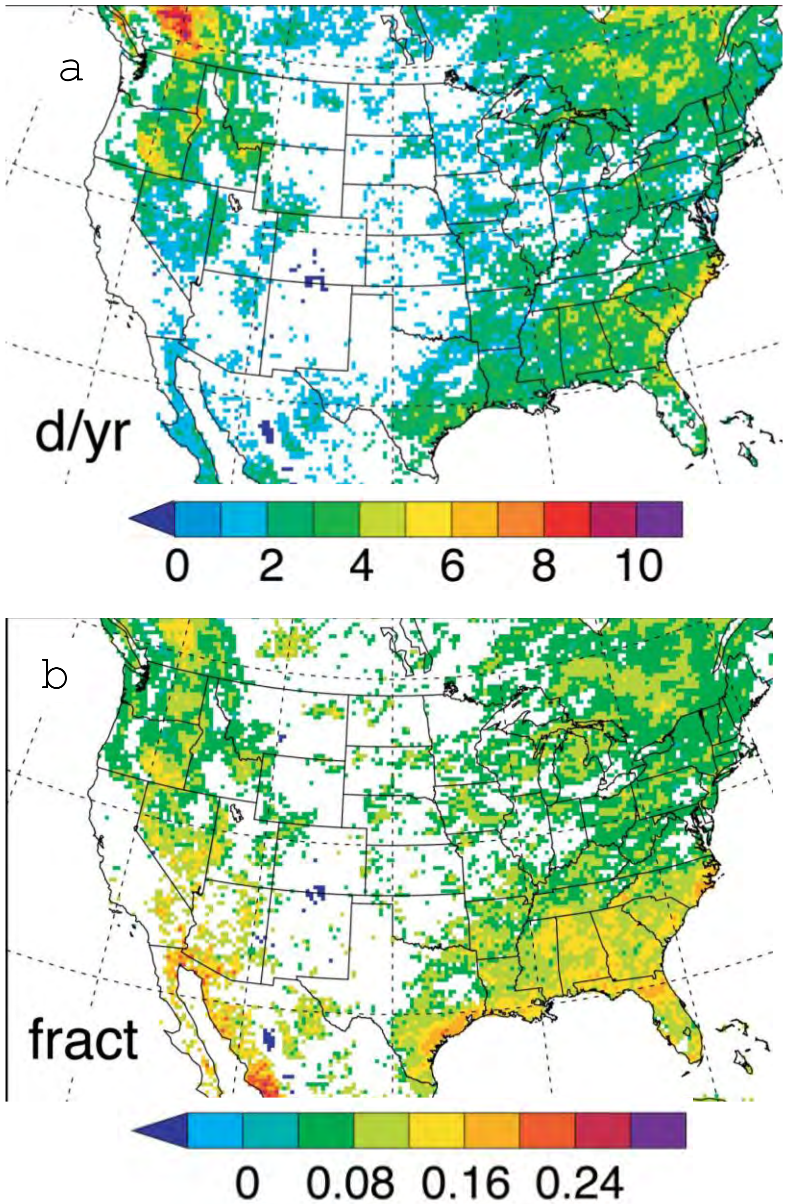


Figure 2.5. Anomalies (A2 minus present day) in (a) P95 precipitation event frequency (days/year) and (b) extreme precipitation fraction. Figure from Diffenbaugh et al. (2005).

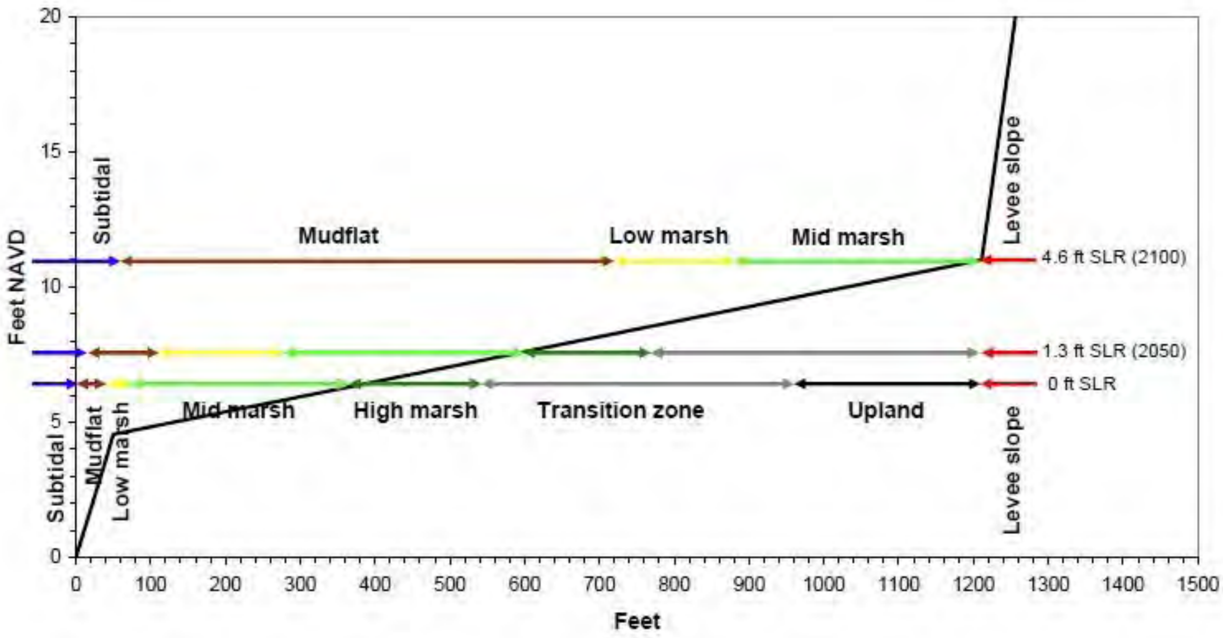


Figure 2.6. Transition of habitats with sea level rise. Figure courtesy PWA (2009).

3.0 Background

The Ballona Creek Watershed covers approximately 130 square miles located in the western portion of the Los Angeles Basin. The headwaters of the watershed are located in the Santa Monica Mountains to the north and the Baldwin Hills to the south. The watershed encompasses most of Los Angeles west of downtown, including Beverly Hills, Culver City, West Hollywood and Inglewood, including 1.6 million residents. Urbanized areas account for 80% of the watershed area, and the partially developed foothills and mountains (Hollywood Hills Baldwin Hills and Santa Monica Mountains) make up the remaining 20%. Over the past 150 years the Ballona Creek Watershed and Wetlands have changed dramatically. To help control surface runoff, the Los Angeles County Flood Control District and the federal government began in the 1930s to channelize, straighten, and deepen Ballona Creek and replace tributary streams with flood control facilities including storm drains, underground culverts, and open concrete channels. The resulting increase in impermeable surfaces changed the natural hydrology of the area, such that runoff now enters the creek and tributaries more quickly and in greater volume than before the area was developed, and less precipitation infiltrates into the ground. Because most of the channels are lined with concrete, native vegetation and riparian habitat in these areas are mostly gone. Marshes and surface springs have disappeared or been capped, including the former La Cienagas and Centinela Springs in Inglewood, for example.

Development of the historical Ballona Wetlands has impacted hydrology and hydraulics in several ways, including: 1) the deposits of fill from the construction of Marina Del Rey, highways and railroads changed the land surface elevation and permeability of the soils; 2) the channelization of Ballona Creek keeps it permanently open to the ocean, and the construction of levees and culverts affects the tidal exchange patterns within the wetland; 3) conversion of marsh to agricultural fields filled the wetland areas and likely reduced tidal exchange; and 4) railroad and highway construction bisecting the wetlands altered the natural routing of freshwater and tidal flows. These changes in hydrology altered the size and function of the native coastal wetland habitats that once existed in and surrounded the current BWER location.

4.0 Hydrology

This study on climate change in the Ballona Creek Watershed and Wetlands investigates the implication of potential extreme precipitation and sea level changes to the BWER. The study applies and integrates multiple models under various climate change scenarios to two potential wetland restoration plans in the BWER. The potential plan referred to as Alternative 5 (Alt5) involves removing the Ballona Creek flood control levees and excavating fill alongside the Creek to allow the Creek to meander through its floodplain. New, earthen levees would be created at the perimeter of the BWER to protect surrounding development from flooding (Figure 4.2). The second potential restoration plan is a revised version of Alt5, referred to as Revised Alternative 5 (or RevAlt5). Revised Alternative 5 accommodates some existing infrastructure constraints at the site, and includes a continuous slope from subtidal through upland habitats to allow the migration of habitats in the event of sea level rise. In RevAlt5 the channel meanders less than in Alt5 and the existing flood control levees remain in place in the far eastern (upstream) portion of the site (Figure 4.3).

4.1 Description of Numerical Models

The primary models applied in this study are the Environmental Fluid Dynamics Code (EFDC) and the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). HEC-HMS simulates the primary hydrologic processes of the watershed (excluding the wetlands), while the EFDC simulates the hydrologic processes in the wetlands. These models are applied under various climate change scenarios to two proposed wetland restoration alternatives: Alternative 5 and Revised Alternative 5. The results of the models, along with existing observations, are used to evaluate the potential climate change impacts to habitats and species in the wetlands.

Environmental Fluid Dynamics Code (EFDC)

EFDC is a state-of-the-science hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions (Hamrick, 1992; Tetra Tech., 2002). It solves three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable-density fluid on a staggered, finite-difference grid. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. EFDC allows for drying and wetting in shallow areas by a mass conservation scheme. The model includes the primary physical processes important to the Ballona Wetland system, including unsteady tidal flow, boundary wetting and drying, and hydraulic control structures, and has been extensively applied and calibrated over the BWER (PWA, 2008).

The model has been configured to predict two-dimensional depth-averaged flow. A curvilinear flexible mesh, enabling the grid to follow dominant terrain features, defines the model domain (Figures 4.1-4.3). A variable grid cell mesh is applied over the domain to balance between resolving physical features and run time. The smallest resolved feature on the domain is the width of the principal wetlands tidal channels, which is approximately 10 m. This resolution was applied to the tidal channels directly adjacent to Ballona Creek and within the BWER. In the other portions of the domain, the cell size is as large as 20 m across. Channels with widths smaller than 10 m, such as Centinela Ditch, are not explicitly resolved. Overall, depending on the scenario [Alt0 (existing condition), Alt5, and RevAlt5], the domain has approximately 43,000 grid cells (Figures 4.1-4.3). For the current model setup, EFDC requires time-varying boundary conditions as input from the ocean in the form of tidal heights and the lowest reach of the watershed in the form of a discharge hydrograph. Verification experiments using the Alt0 configuration accurately predicted water levels typically within 5 cm of observations over a two-week period (PWA, 2008).

Hydrologic Engineering Center Hydrologic Modeling System (HEC_HMS) and Domain

HEC-HMS is a modeling system used to represent watershed rainfall-runoff process. This study implements a HEC-HMS beta configuration of the Ballona Creek Watershed developed and calibrated by the Los Angeles district of the Army Corps of Engineers (USACE 2012). The major elements in their model development include watershed characteristics, basin roughness ("n") values, baseflow, rainfall data, soil loss rate, S-graph, channel routing, and model calibration. The model parameters are estimated through field investigation of the watershed according to the guidelines described in the ACOE Ballona Creek Ecosystem Restoration Feasibility Study (USACE, 2012).

The HEC-HMS domain is the Ballona Creek Watershed (Figure 4.4), decomposed into 42 subbasins (Figure 4.3). The physical characteristics of each subbasin were provided by the ACOE (2008), and included area, length of the longest watercourse, slope, and lag time. The subbasins varied in size from 9.28 mi^2 to less than a square mile. Procedures from the NOAA Atlas 2 Volume XI were used to obtain precipitation depth versus duration values for various recurrence intervals for the Culver City station (Miller et al., 1973). The model was calibrated to the peak discharge values at the Sawtelle Boulevard steam gage (Figures 4.1 and 4.4). Although extensive work has gone into calibrating the model for the Ballona Watershed and simulated hydrographs resulting from the 100-year precipitation event (and other return periods) match observations remarkably well, the configuration is still in beta phase.

In this study, various flood scenarios based on the 100-year precipitation event are simulated and used as input to the upstream boundary of the EFDC model (see Figures 4.1 and 4.4 for precise locations).

4.2 Description of Numerical Experiments

To simulate the hydrologic conditions of the wetlands, EFDC requires time-varying boundary conditions from the ocean and the lowest reach of the watershed. The boundary conditions from the ocean are in the form of tidal heights. The boundary conditions from the watershed are in the form of discharge and are generated by HEC-HMS. In this study, there are two sets of simulations. The first, referred to as *tidal*, requires only time-varying tidal boundary conditions from the ocean. The second set, referred to as *flood*, requires time-varying boundary conditions from both the ocean and watershed. Each set of the above experiments was applied under various sea level rise (SLR) and/or extreme precipitation conditions to the two wetland restoration alternatives.

Tidal Simulations

In this set of numerical experiments, the role of tidal cycles alone on the wetland hydrology is investigated for the two restoration alternatives. Runoff generated from precipitation is assumed negligible, as discussed above. The tidal heights are specified for a representative spring-neap cycle from July 11 to July 30, 2006 (Figure 4.5a). For model spinup purposes, the first four days of the simulation are discarded and the model results are analyzed from July 15 to July 30. To account for end of century SLR projections, additional experiments are performed with 100 and 140 cm added to the present-day tidal levels. One-hundred and 140 cm of SLR represent the lower and upper bounds of end of century projections (Vermeer and Rahmstorf, 2009), which are also used by the state of California for all projects along the coast (CO-CAT 2010) (See Section 2.1). Water surface elevations and inundation levels at current sea level conditions are compared to those at 100 and 140 cm of SLR. The results of these experiments provide an indication of the day-to-day wetland hydrology and associated habitat zones under present-day and future sea level conditions.

In total there are six simulations: one for each of three SLR scenarios for each of the two restoration alternatives. The model timestep for these simulations is 1 second. Each simulation takes approximately one week of wall time on the Loyola Marymount University's (LMU) Hydrology High Performance Computing (HPC) Linux cluster.

Flood Simulations

In this set of experiments, the role of extreme flooding on wetland inundation levels is considered. The output stormflow hydrographs simulated by HEC-HMS, based on the precipitation input, provide the Ballona Creek discharge into the BWER. The baseline simulation considers the 100-yr precipitation event and associated discharge. Previous studies of extreme precipitation changes under future atmospheric greenhouse gas concentration projections in southern California were inconclusive (See Section 2.1). Given this uncertainty, five scenarios based on the 100-yr precipitation event are simulated using the HEC-HMS modeling system: The 100-year precipitation and the 100-year with decreases and increases of 10% and 25%. The 100-yr precipitation event and associated flood is considered the baseline event. The resulting hydrographs are applied as input to EFDC at Sawtelle, Sepulveda Channel, and Centinela Channel for each of the two restoration alternatives (Figure 4.6). In EFDC, the ocean boundary condition is forced by a typical 1.5 day tidal cycle with zero, 100, and 140 cm SLR (July 5.86 to 7.36, 2006 in Figure 4.5b). The peak of the hydrograph is timed such that it coincides with the higher high tide peak so that maximum wetland inundation occurs. In these simulations, inundation area is the primary output considered.

In summary, a suite of 36 flood simulations are performed for two restoration alternatives: Alt5 and RevAlt5. To investigate the impact of SLR and changes in extreme precipitation event magnitude, simulations are performed under a combination of three SLR scenarios (0, 100, and 140 cm) and five flood events (T=100-yr, T=100-yr ± 10%, and T=100-yr ± 25%). These scenarios are summarized in Table 4.1 and the EFDC time-varying boundary conditions are displayed in Figures 4.5 and 4.6.

The model timestep for these simulations is 0.125 seconds. Each simulation takes about four days of wall time on LMU's Hydrology High Performance Computing (HPC) Linux cluster. Despite the shorter simulation period (1.5 days), these simulations are only slightly shorter in terms of wall time compared to the tidal simulations since the timestep is four times smaller. The reasons for the shorter timestep are addressed in the discussion section below.

4.3 Results of Numerical Experiments

In this section, water surface elevations and inundation levels from the numerical modeling experiments described above are compared. For the analysis of inundation levels, an EFDC model gridcell is considered wet, i.e., inundated, when the water depths exceed 0.1 meters.

Impacts of Sea Level Rise – Tidal Simulations

In this subsection, the impacts of SLR on the two proposed restoration alternatives are investigated for the tidal simulations only. Input tidal levels vary from approximately, -0.2 to 2.1 m, 0.8 to 3.1 m, and 1.2 to 3.5 m in the simulations with no SLR, SLR of 100 cm, and SLR of 140 cm, respectively, for both alternatives (Figure 4.5).

With no SLR for Alt5, the resulting inundation areas range from 0.45 km^2 (19% of the wetland area) to 1.71 km^2 (74%), with a mean inundation area of 0.81 km^2 (35%) (Figures 4.7a,b, 4.8a,b, and Table 4.2). In this scenario, approximately 1.26 km^2 or 55% of the BWER experiences both wet and dry conditions (wet-dry active range) throughout a typical spring-neap tide cycle, while the remaining 45% is either completely dry or completely wet for the duration of the simulation analysis period. Note this number is likely to be higher since lower and higher tides as well as storm surges occurring throughout the year were not considered in the simulations.

The EFDC model output suggests that in the event of SLR, higher tides and subsequent higher water levels in the BWER will occur (Figures 4.7 and 4.8). With 100 cm of SLR, the wet-dry active range remains similar to the no SLR scenario (1.30 km^2 or 56%), while the mean inundation area substantially increases to 1.55 km^2 (67%) – an increase of 0.74 km^2 (32%). Sea level rise of 140 cm also results in a similar wet-dry active range of 1.31 km^2 (57%), and an additional increase in mean inundation area to 1.76 km^2 (76%). The large shift in mean inundation levels with SLR is largely determined by the bottom elevation of the wetlands. In Alt5, 0.91 km^2 (29%) of the wetland area lies in the 1.6 to 1.7 m elevation zone (Figure 4.9). Both the low and high end of century SLR projections (100 and 140 cm, respectively) result in a shift in mean inundation levels to above the 1.6 to 1.7 m elevation range (comparing Figures 4.7 and 4.9).

In contrast, the wet-dry active range with RevAlt5 no SLR scenario is comparatively smaller with inundation areas ranging from 0.32 km^2 (14%) to 0.65 km^2 (29%) and a mean area of 0.41 km^2 (18%) (Figures 4.7c,d, 4.8c,d and Table 4.2). With 100 cm of SLR, however, wet-dry active range increases considerably to 0.92 km^2 (41%). At the same time, the mean inundation area substantially increases to 1.35 km^2 (59%). These numbers further increase with 140 cm of SLR to a wet-dry active range of 0.99 km^2 (43%) and mean inundation area of 1.63 km^2 (71%). In short, the more gradual shift in RevAlt5 elevation zones (Figure 4.9) tends to result in less change in inundation area and an increased resilience to SLR.

Impacts of Changes in the 100-year Flood Event Magnitude – Flood Simulations

The impacts of 10% and 25% decreases and increases to the 100-year precipitation event and resulting flood hydrographs as predicted by HEC-HMS on the BWER are investigated for both restoration alternatives (Alt5 and RevAlt5). For these experiments, the tidal cycle from July 5.88 to 7.36, representing an average tide, is timed such that its peak occurs at the flood hydrograph peak (Figures 4.5b and 4.6). The simulations are 36 hours in length, and no SLR is considered.

Ten percent and 25% reductions in the 100-yr precipitation event result in 14 and 36% reductions, respectively, in watershed flood discharge entering the wetlands (Figure 4.6). These values can be compared to the ACOE observation-based discharges from the Sawtelle Blvd gage (lowest gage in the watershed; Figure 4.6b). According to these HEC-HMS modeling results, 10 and 25% reductions in precipitation reduce the flood return periods to approximately 50 and 10 years, respectively. Similarly, 10 and 25% increases in the 100-yr precipitation result in 14 and 35% increases in watershed discharge, respectively. The 14% increase is comparable to approximately the 200-year event and the 35% increase is considerably greater than the 500-year event. These results suggest that non-linearities inherent in the system such as those related to infiltration processes in the watershed amplify the response of stormflow to changes in precipitation. In addition, they imply that small changes in future precipitation may result in large changes in watershed response.

For Alt5 with the baseline flood event (T=100 years), the maximum BWER inundation area modeled by EFDC is 1.64 km^2 (71%) (Figures 4.10 and 4.11 and Table 4.3). Locations near developed areas are inundated during this event, such as at Jefferson Blvd and at Lincoln Blvd (Figures 4.11a). For such a large storm, however, some amount of flooding is generally expected. The peak in wetland inundation area approximately coincides with the inflow hydrograph peak (~6.8 days), showing little time lag due to the small size of the wetlands and the proximity of the discharge gages to the wetlands. The maximum wetland inundation area varies from 1.16 km^2 (50%) to 1.44 km^2 (62%) for the 100-year precipitation/flood event minus 25% and 10%, respectively. Of concern, even the 100-year event minus 25%, which is similar to

10-year event results in flooding near Playa Vista at Jefferson Blvd (Figures 4.11b). As mentioned above, most developments in Los Angeles design for the 10-year flood event. For the 100-year precipitation/flood event plus 10 and 25%, maximum inundations levels are 1.83 km^2 (79%) and 1.92 km^2 (83%), respectively (Figures 4.10 and 4.11 and Table 4.3). In these scenarios, much of the area near the bluffs along the southern boundary of the BWER is also flooded (Figure 4.11d, e).

For RevAlt5, maximum inundation area is 1.93 km^2 (85%) for the baseline flood simulation (T=100yr; Figure 4.10 and 4.12 and Table 4.3). Although the far eastern portion of the BWER and the area south of the creek levees appear to be inundated as a result of the flood, they are actually inundated due to the initial water elevations being set to the tidal levels (Figure 12). These do not change in depth throughout the simulation since they do not interact with the tidal and flood flows and since infiltration, evaporation, and direct precipitation are not considered in the EFDC configuration (described in detail below).

Changes in the 100-year precipitation and associated flood event for RevAlt5 result in a range of maximum inundation areas considerably smaller than the Alt5 simulations (1.74 to 2.04 km^2 for T=100yr-25% or 76 to 90% for T=100yr+25%), similar to the tidal simulations (Figures 10 and 12 and Table 4.3). The RevAlt5 simulations also appear to be less responsive to variations in tidal height, as the inundation amplitudes are somewhat smaller (Figure 4.10). These differences are partly due to the fact that the RevAlt5 initial water depths were considerably higher than those of Alt5 to start the simulations (described in detail below). However, as presented in the tidal simulations, the wet-dry active range is smaller in RevAlt5, suggesting a smaller inundation range and greater resilience to flooding.

In RevAlt5, the change in wetland inundation area tends to decrease as the change in precipitation event magnitude increases, and vice versa. A 25% precipitation decrease results in 29% decrease in wetland inundation area, while a 25% increase results in only a 17% increase in inundation. This is likely a consequence of the wetlands approaching capacity and the floodwater reaching the wetland boundaries with the larger events. This result may not be robust since the EFDC wetland boundaries are considered no flux (similar to a vertical wall) meaning that excess water does not exit the domain (except at the ocean and Ballona Creek boundaries). This implies that the inundated area, and consequently surrounding flooded areas, would potentially increase if the domain boundaries were extended (described in detail below).

Overall, under current sea level conditions, i.e., with no SLR, both restoration alternatives are sensitive to changes in 100-year precipitation event magnitude, with Alt5 being somewhat more responsive, and therefore less resilient, than RevAlt5.

Combined Impacts of Sea Level Rise and Changes in the 100-year Flood Event – Flood Simulations

Here the simulations including the combined impacts of sea level rise and changes in the 100-year flood event magnitude for both restoration alternatives are analyzed. Sea level rise conditions are applied to the tidal cycle with the various changes in flood frequency as is done in the tidal simulations (Figure 4.5b). As with the cases with no SLR, the hydrograph peaks are timed such that they occur at the tidal peaks (Figures 4.5b and 4.6).

For both restoration alternatives when SLR is considered with no change in the 100-yr precipitation event magnitude, significant wetland inundation occurs at approximately day 6.2 – well before any significant flood enters the wetlands from the watershed (Figures 4.13, 4.14, and 4.15). More specifically, a smaller second peak occurs at about day 6.3 coinciding with the peak of the lower high tide (Figure 4.5b). The wetland inundation persists at nearly the level of this smaller peak until the flood and higher high tide occur. With SLR, even at the lower end of century estimate of 100 cm, the peak of the lower high tide level is higher than the peak of the higher high tide level with no SLR (Figure 4.5b). Furthermore, a third peak occurs at approximately day 7.3 after the watershed flood discharge has completely subsided (Figures 4.6 and 4.13). This peak coincides with the lower high tide of day 7, i.e., the following day (Figure 4.5b). In short, SLR dominates the response of wetland inundation to flooding particularly with the Alt5 scenario. RevAlt5 displays a similar but weaker response despite starting at a higher water level (see previous subsection).

When considering the combination of SLR with changes in extreme precipitation event magnitude for Alt5, the wetland inundation levels remain similar regardless of the change in precipitation event magnitude (Figure 4.16). Even with a 25% reduction in the 100-year precipitation event magnitude and resulting 36% decrease in discharge (Figure 4.6c), the wetland inundations levels remain at 80% until the higher high tide drops at day 7.0. This result is similar for RevAlt5 (Figure 4.17).

Summary of Results

HEC-HMS and EFDC are used to model the changes to the hydrology and hydraulics of the Ballona Watershed and Wetlands as a result of potential SLR and changes extreme precipitation event magnitudes. The steep, then flat, then steep system of Alt5 is well designed to accommodate current sea level conditions as well as potential changes in extreme precipitation event magnitude. However, it is not resilient to SLR impacts in that the wetlands remain largely inundated even at lower tides under SLR scenarios. In contrast, RevAlt5 is more resilient to SLR and changes in precipitation event magnitude in that more of the BWER experiences both dry and wet conditions under the SLR scenarios; although under present day SLR conditions the wet-dry range is considerably smaller. When SLR is included in the scenario, changes in precipitation event magnitudes have little effect on the hydrology of the system for both Alt5 and RevAlt5.

Sea level rise is likely to significantly affect the wetland hydrology, impacting the habitat acreages and distributions, within the BWER. The climate change implications for the existing conditions and the proposed restoration alternatives show vast differences in the resulting habitat. These model outputs are discussed in the next section, taking into consideration the predicted changes in habitat acreage based on inundation frequency, elevation and ponding.

Table 4.1. List of scenarios and ocean and upstream boundary conditions. Note that each boundary condition is run under each scenario.

Scenario		**Tidal Boundary Conditions**		**Sea Level Rise (cm)**		**Precipitation Event Boundary Conditions**
Alternative 5		July 11 – 30 (No Flood): 6 simulations (3 for each alternative)		0		No Flood
Revised Alternative 5		July 6, Peak at Flood: 30 simulations (15 for each		100		100 yr - 25%
				140		100 yr - 10%
						100 yr
						100 yr + 10%
						100 yr + 25%

Table 4.2. Mean, minimum, and maximum inundation area (km^2) according to the alternative and SLR scenario.

	Alternative 5 – Tidal						Revised Alternative 5 – Tidal					
	No SLR		SLR = 100 cm		SLR = 140 cm		No SLR		SLR = 100 cm		SLR = 140 cm	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Mean	0.81	35%	1.55	67%	1.76	76%	0.41	18%	1.35	59%	1.63	71%
Minimum	0.45	19%	0.68	29%	0.70	30%	0.32	14%	0.88	39%	1.04	45%
Maximum	1.71	74%	1.99	86%	2.01	87%	0.65	29%	1.80	79%	2.02	89%
Range	1.26	55%	1.30	56%	1.31	57%	0.34	15%	0.92	41%	0.99	43%

Table 4.3. Flood Simulation – Maximum inundation area in km^2 and % for each of the flood with and without SLR simulations. Upper table is for Alt5 and lower is for RevAlt5.

	Maximum Inundated Area Alternative 5 – Flood Simulations									
	T=100yr-25%		T=100yr-10%		T=100yr		T=100yr+10%		T=100yr+25%	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
No SLR	1.16	50%	1.44	62%	1.64	71%	1.83	79%	1.92	83%
SLR=100cm	1.90	82%	1.93	83%	1.95	84%	1.97	85%	1.99	86%
SLR=140cm	1.97	85%	1.98	85%	1.99	86%	2.00	86%	2.03	87%

	Maximum Inundated Area Revised Alternative 5 – Flood Simulations									
	T=100yr-25%		T=100yr-10%		T=100yr		T=100yr+10%		T=100yr+25%	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
No SLR	1.74	76%	1.86	81%	1.93	85%	2.00	88%	2.04	90%
SLR=100cm	1.98	87%	2.03	89%	2.05	90%	2.06	90%	2.07	91%
SLR=140cm	2.04	90%	2.06	90%	2.06	91%	2.07	91%	2.08	91%

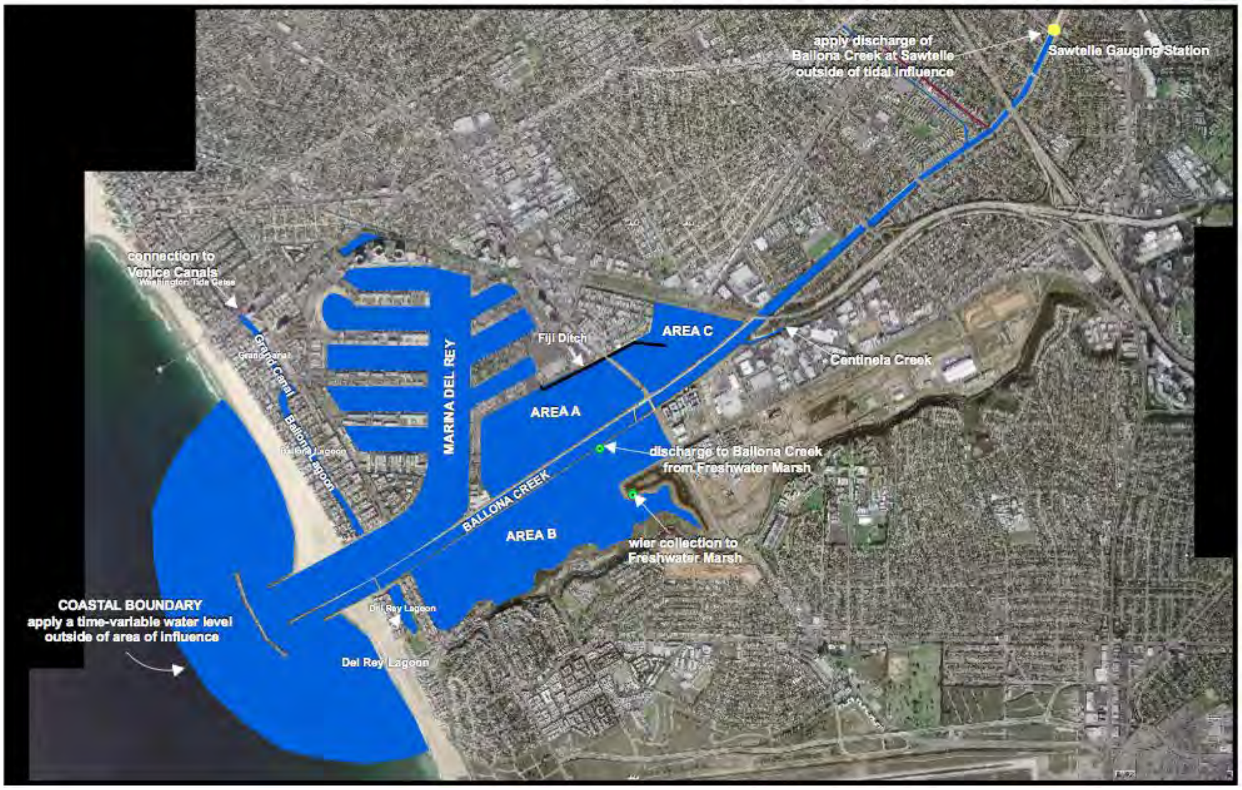


Figure 4.1. EFDC Model Extent for Alternative 0. Figure Courtesy PWA (2008).

Figure 4.2. Map of wetlands (upper panel) and EFDC bottom elevation for the 2008 Restoration Alternative 5 (Alt5).

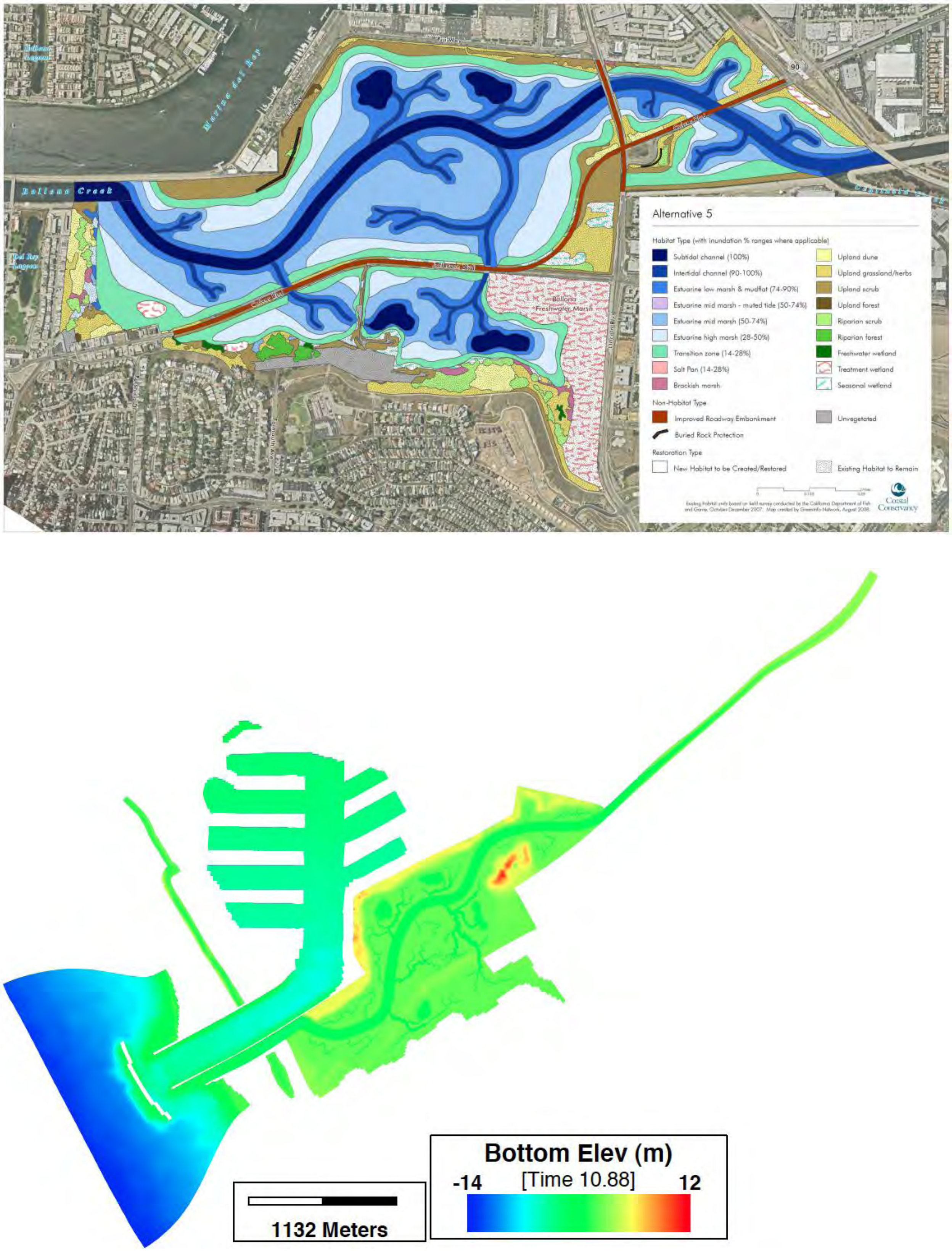


Figure 4.3. Map of wetlands (upper panel) and EFDC bottom elevation for the Revised Restoration Alternative 5 (RevAlt5).

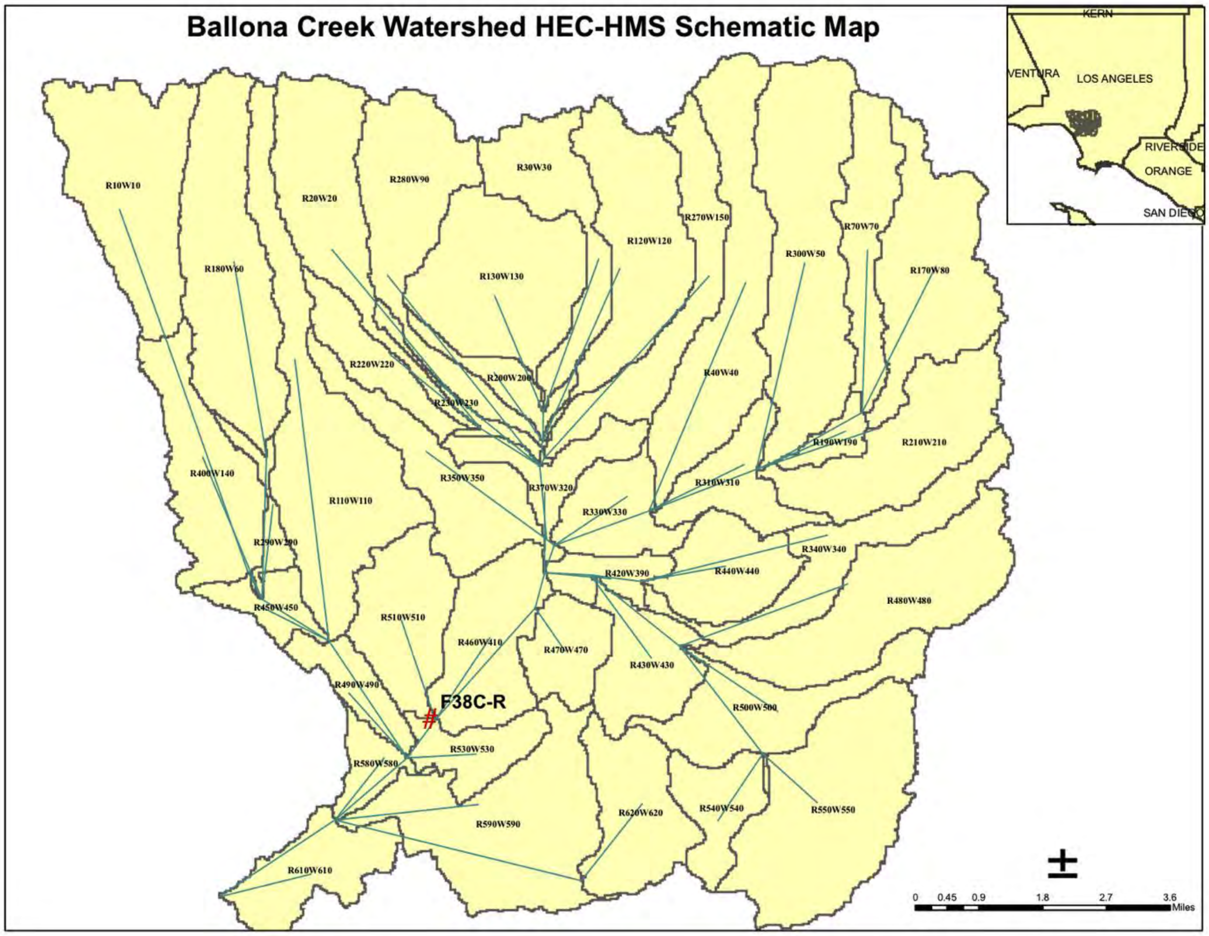


Figure 4.4. Map of Ballona Creek Watershed with ACOE subbasins. Figure from ACOE (2008).

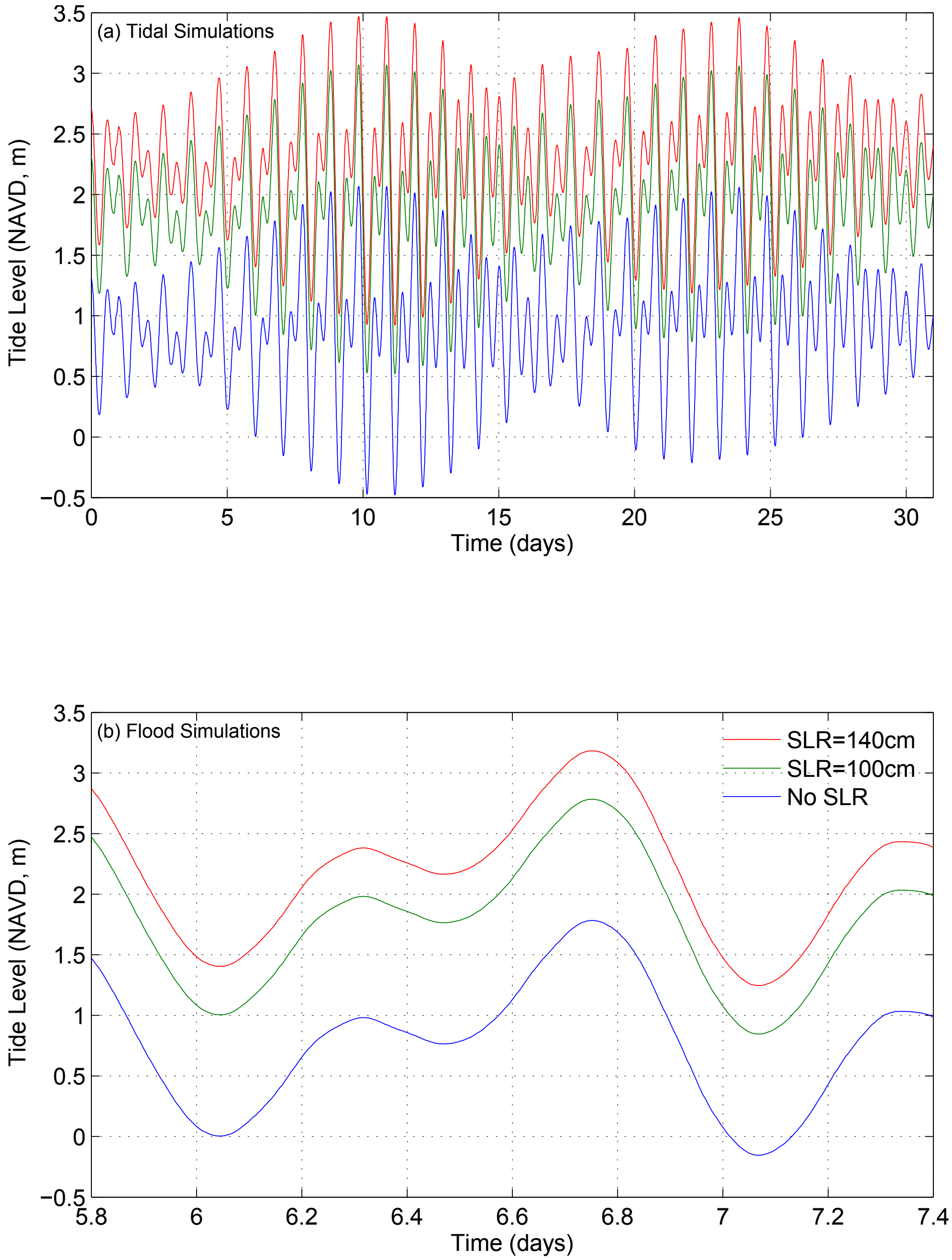
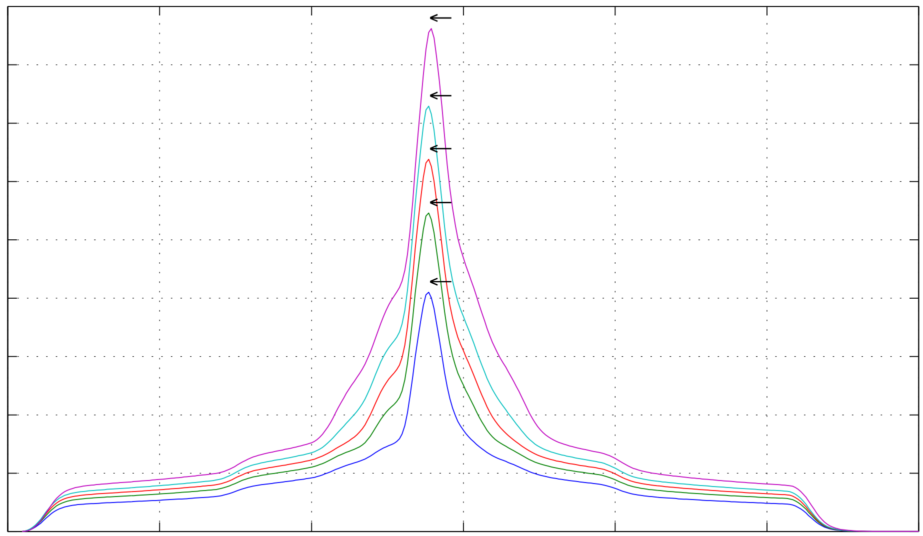


Figure 4.5. July 2006 tidal cycle applied at the EFDC ocean boundary. (a) The tidal simulations use data from day 15 to 30 while (b) the flood simulations use data from day 5.8 to 7.4.



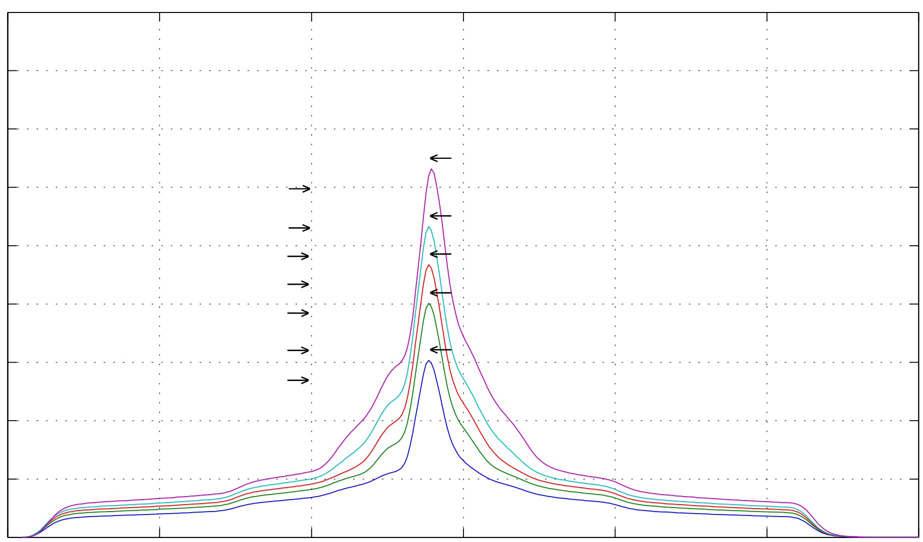


Figure 4.6. HEC-HMS outflow hydrographs for (a) all of the channels (upper panel) and the main Ballona Creek Channel near Sawtelle Blvd (F38C−R; upper panel) for each of the precipitation event magnitudes used as input to the EFDC simulations. The peak flows for each hydrograph are indicated along with the ACOE peak discharge values for return periods varying from T = 5 yr to T = 500 yr. The ACOE peak discharge values are based on observations. All values are in m^3/s.

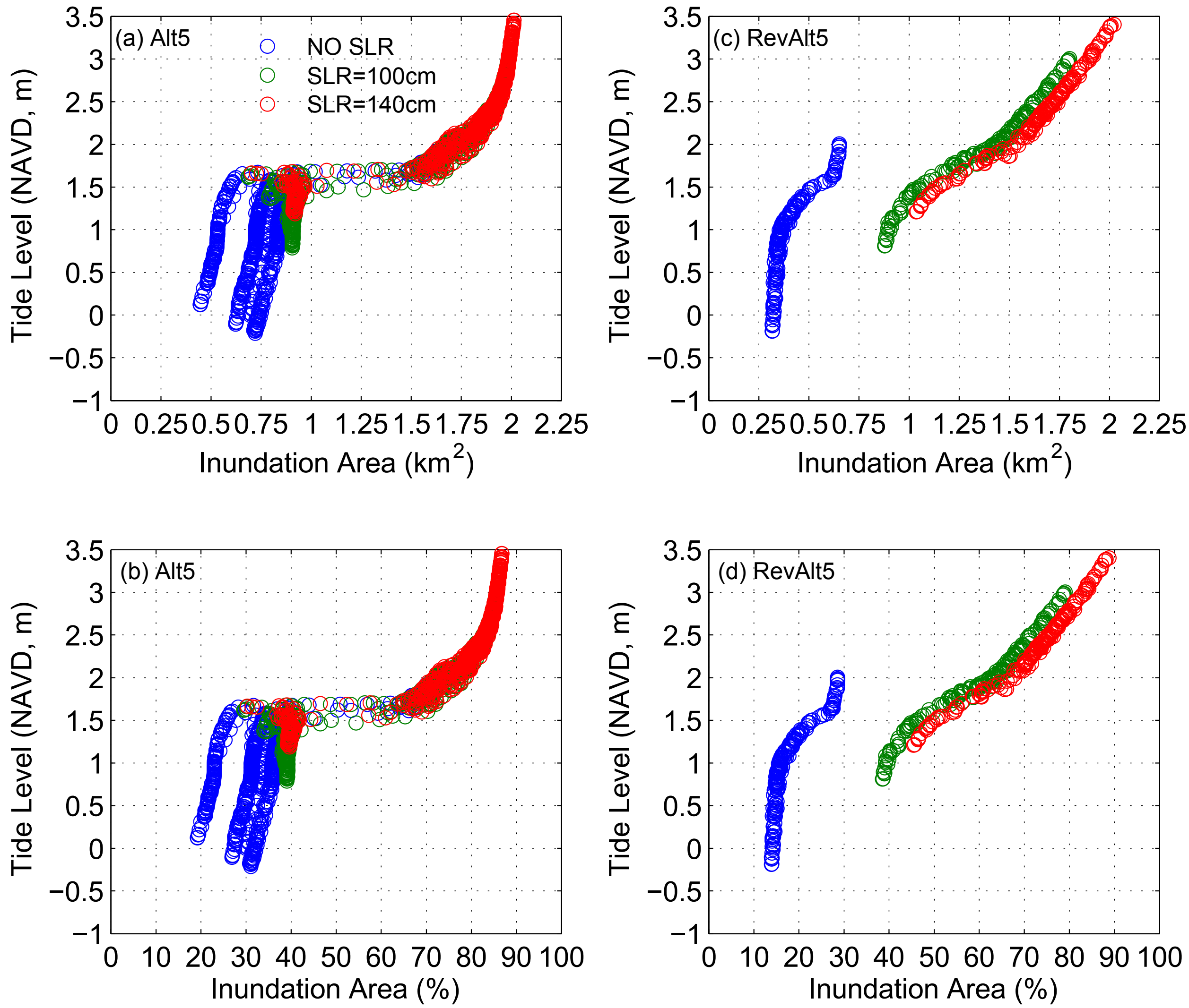


Figure 4.7. Tidal Simulations – Wet area versus tide level for no sea level rise (blue), 100 cm sea level rise (green), and 140 cm sea level rise (red) for both restoration alternatives: (a) Alt5 inundation area in km2; (b) Alt5 Inundation area in percent; (c) RevAlt5 inundation area km2; and (d) RevAlt5 inundation area in percent.

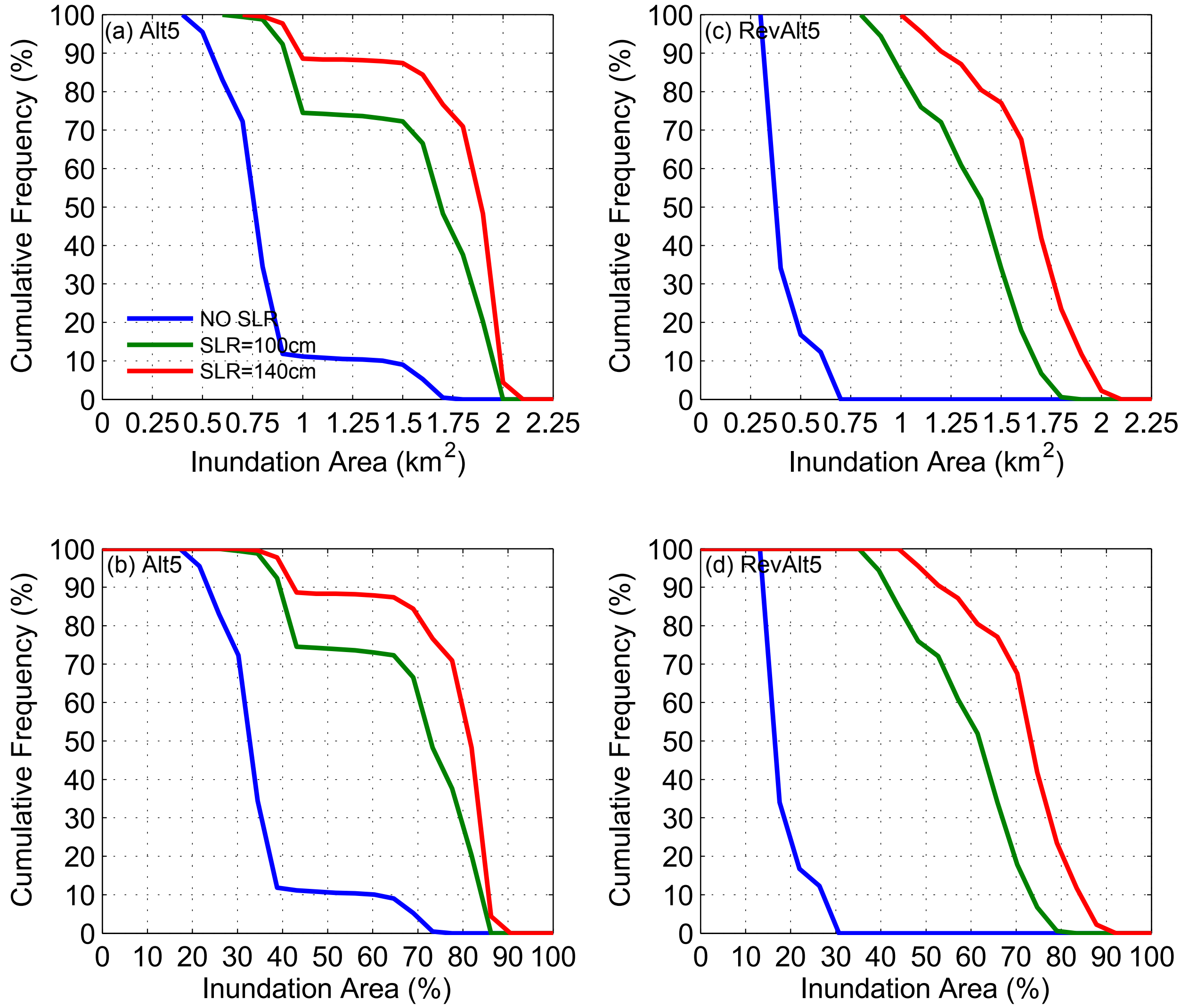


Figure 4.8. Tidal Simulations – Inundation area cumulative frequency for no SLR (blue), 1.0 m SLR (green), and 1.4 m SLR (red): (a) Alt5 inundation area in km^2; (b) Alt5 Inundation area in percent; (c) RevAlt5 inundation area km^2; and (d) RevAlt5 inundation area in percent.

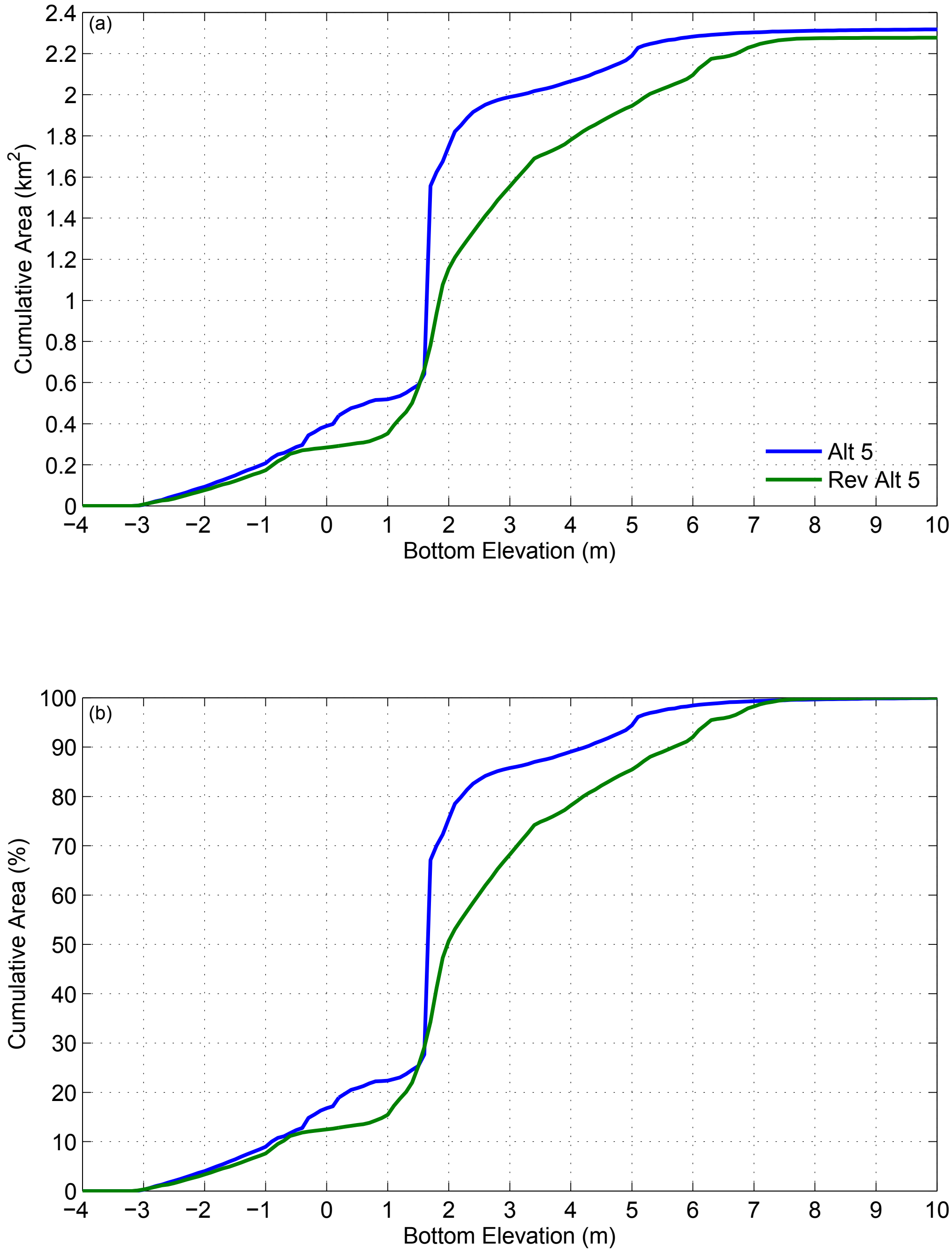


Figure 4.9. Cumulative wetland area as a function of bottom elevation.

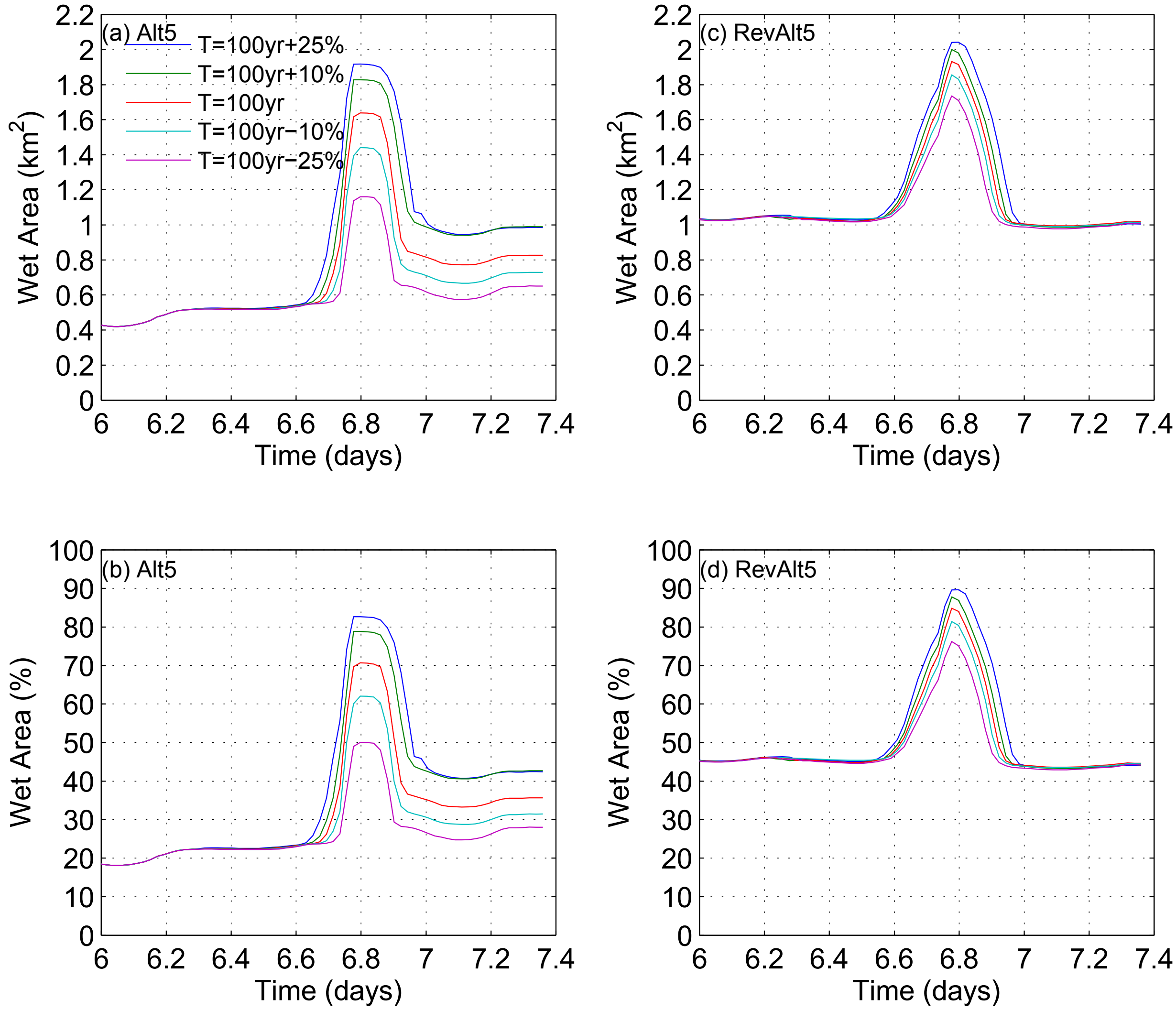


Figure 4.10. Flood Simulations – Wet area versus time for the five flood scenarios with no sea level rise for Restoration Alternative 5 and Revised Alternative 5.

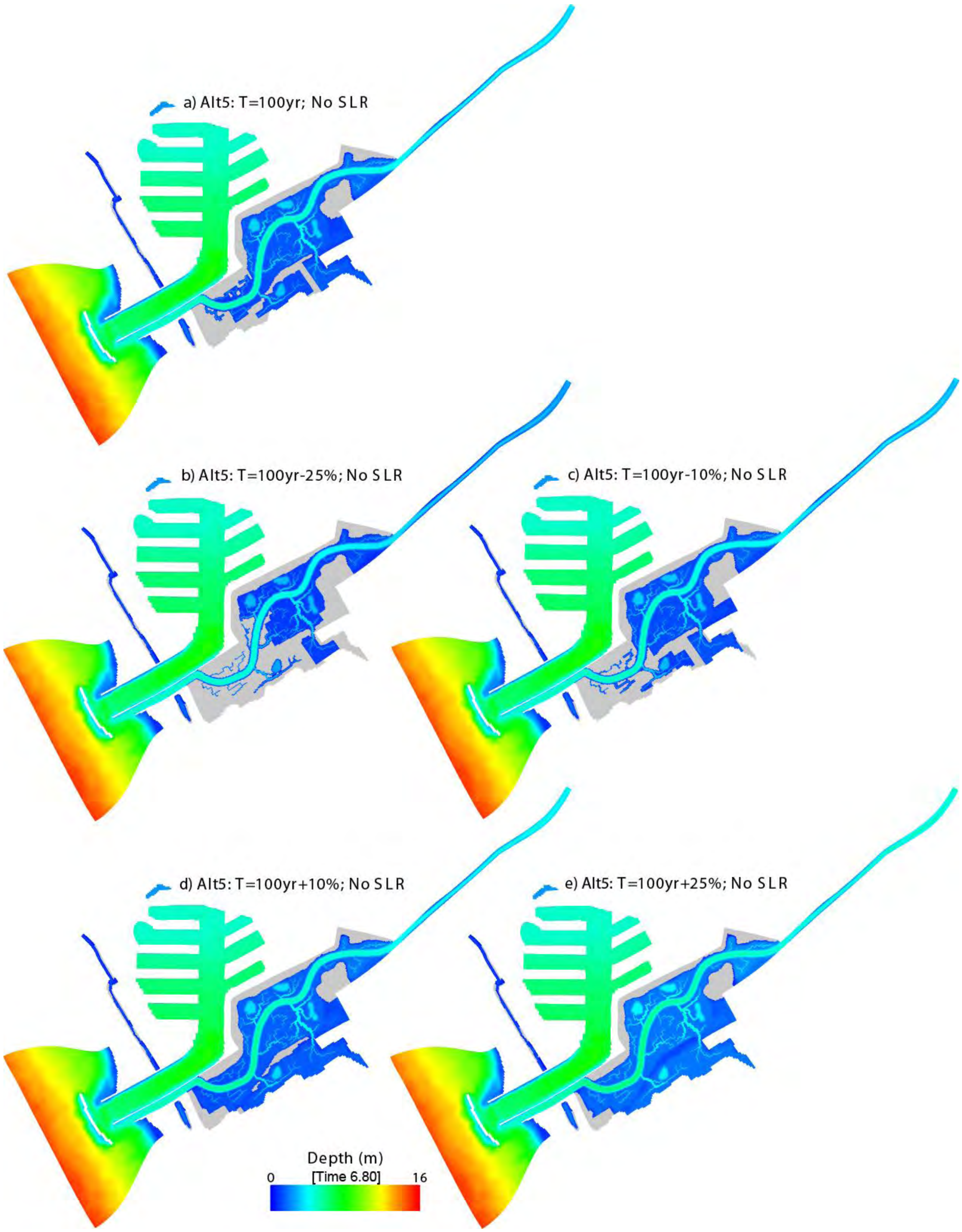


Figure 4.11. Flood Simulations – Alt5: Water depths (m) at maximum inundation (time = 6.80) for the 100-year precipitation event: a) T=100 yr; b) T=100 yr – 25%; c) T=100 yr – 10%; d) T=100 yr +10%; and e) T=100 yr +25%.

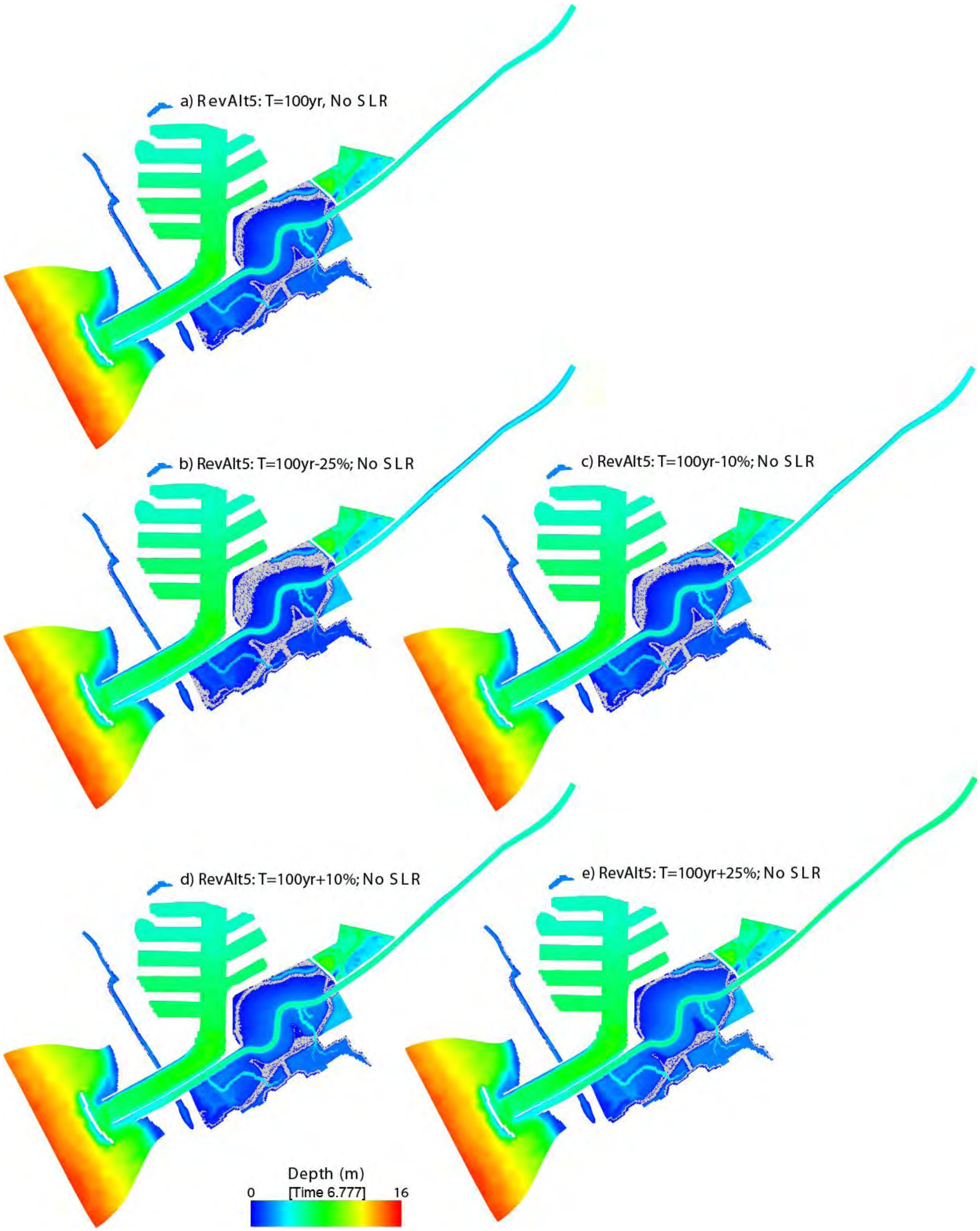


Figure 4.12. Flood Simulations – RevAlt5: Water depths (m) at maximum inundation (time = 6.777) for the 100-year precipitation event: a) T=100 yr; b) T=100 yr – 25%; c) T=100 yr – 10%; d) T=100 yr +10%; and e) T=100 yr +25%.

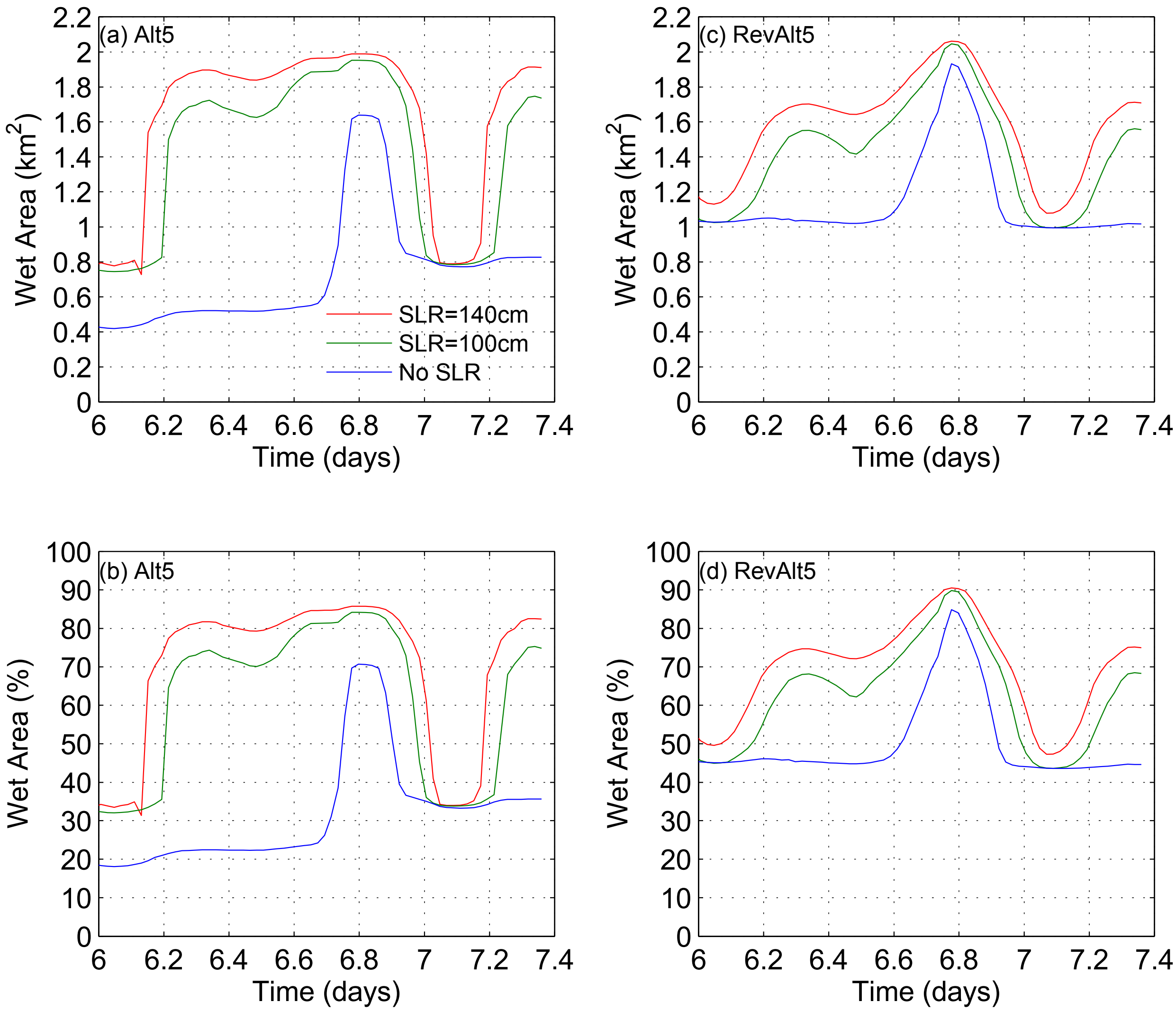


Figure 4.13. Flood Simulations with SLR – Wet area versus time resulting from the 100-yr precipitation event for the three sea level rise scenarios for Restoration Alternative 5 and Revised Alternative 5.

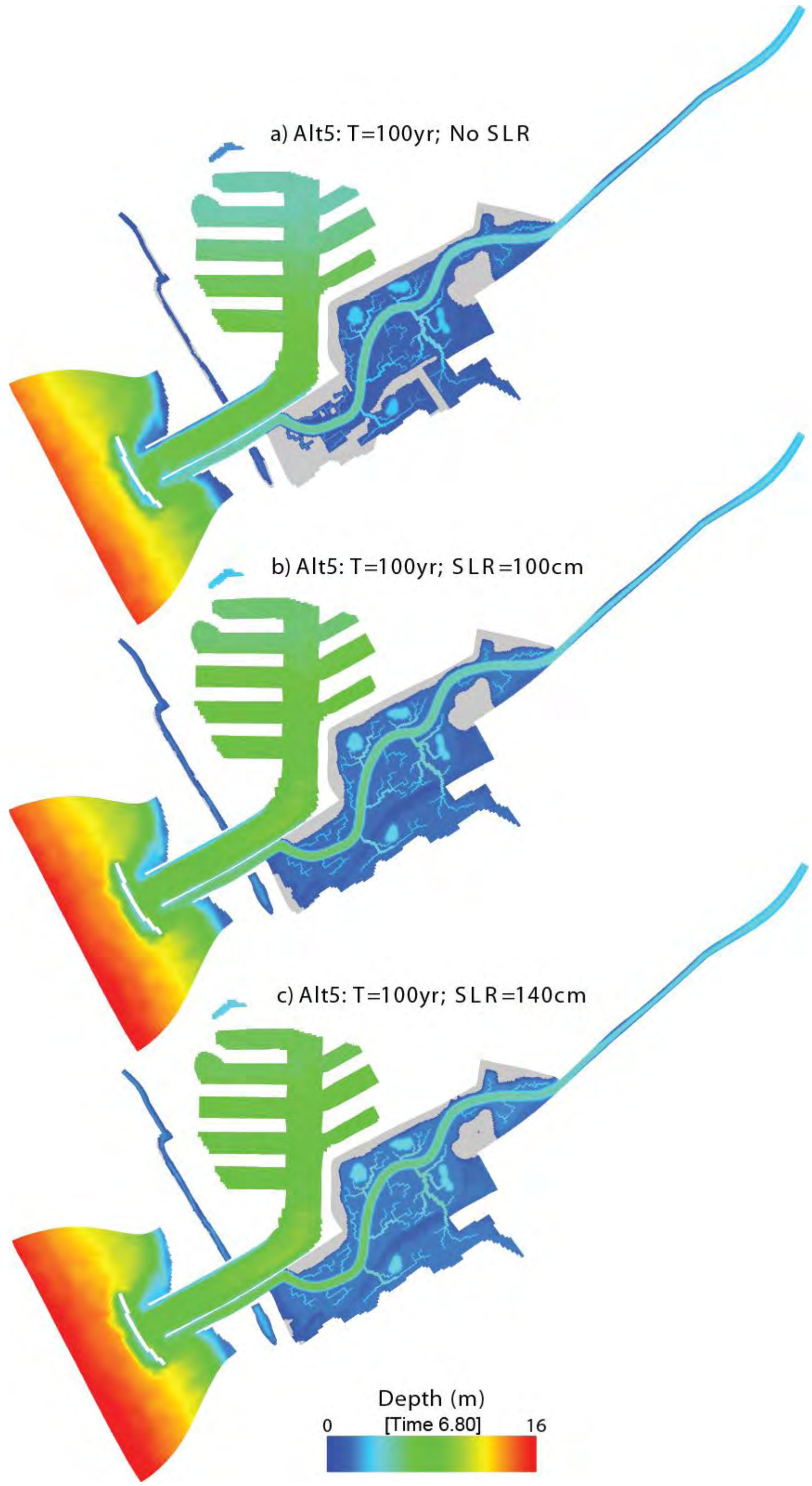


Figure 4.14. Flood Simulations with SLR – Alt5: Water depths (m) at maximum inundation (time = 6.80) for the 100-year precipitation event: a) No SLR; b) SLR = 100 cm; and c) SLR = 140 cm.

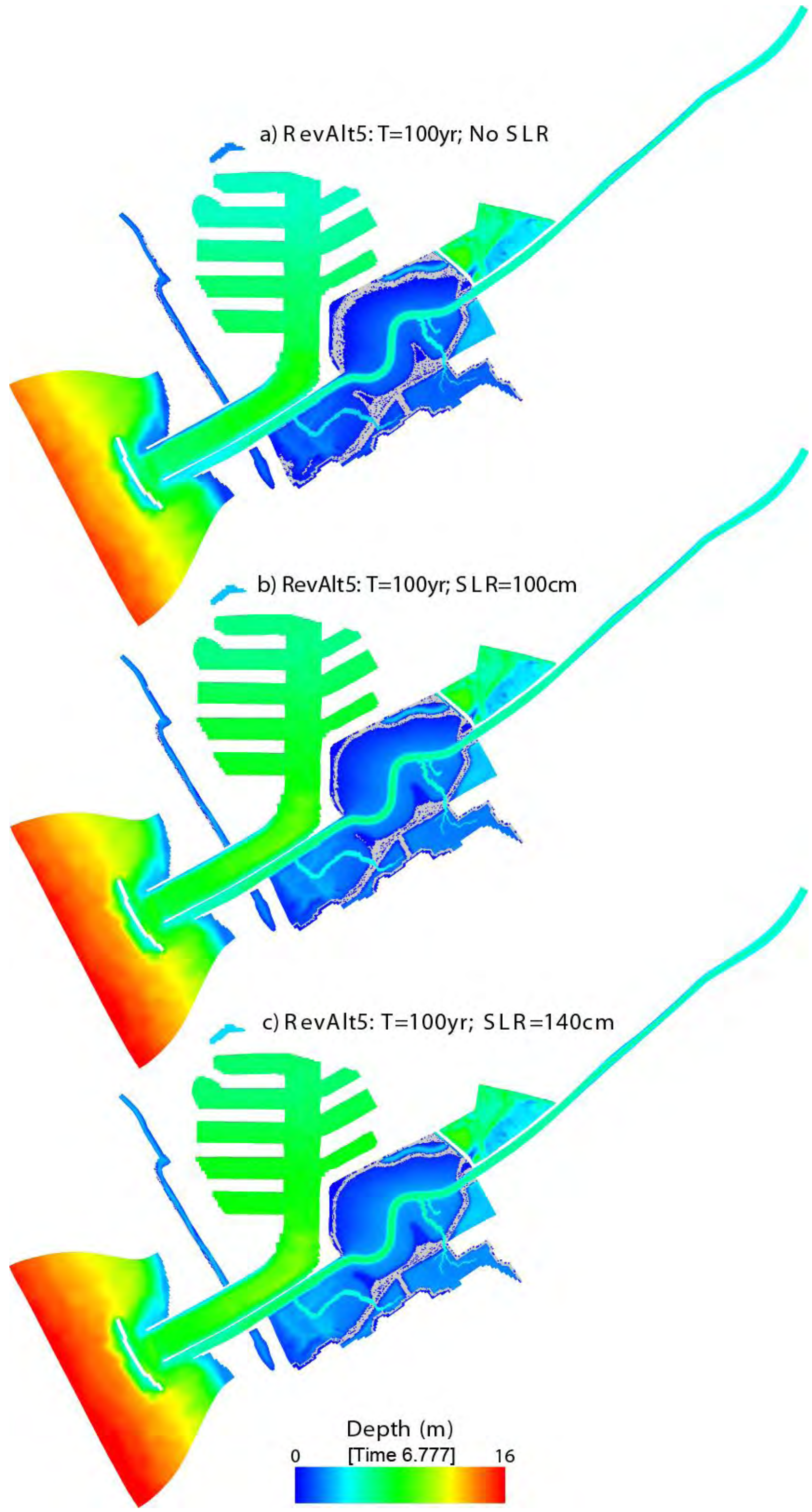


Figure 4.15. Flood Simulations with SLR – RevAlt5: Water depths (m) at maximum inundation (time = 6.777) for the 100-year precipitation event: a) No SLR; b) SLR = 100 cm; and c) SLR = 140 cm.

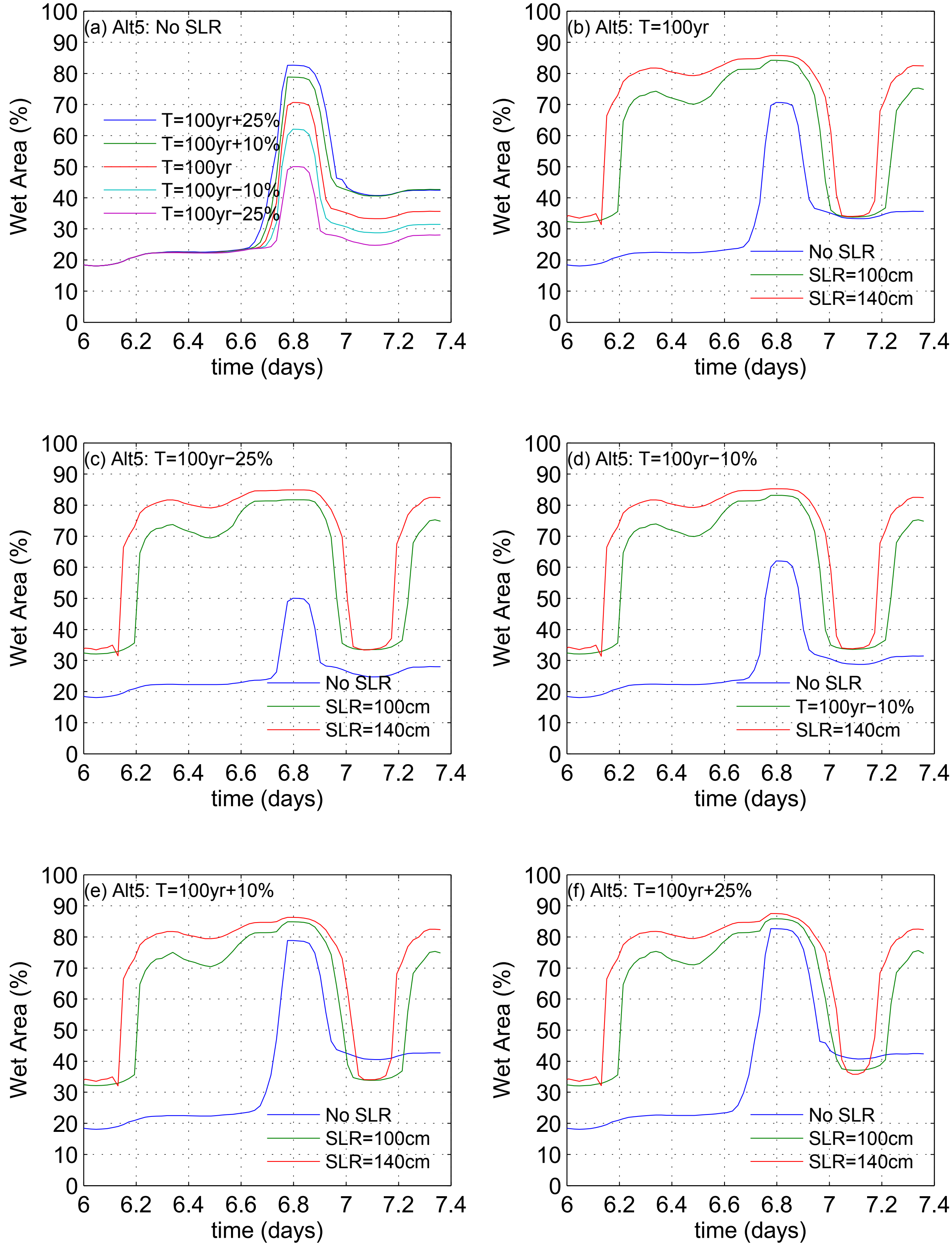


Figure 4.16. Flood Simulations with SLR – Wet area versus time for the five flood scenarios for Restoration Alternative 5.

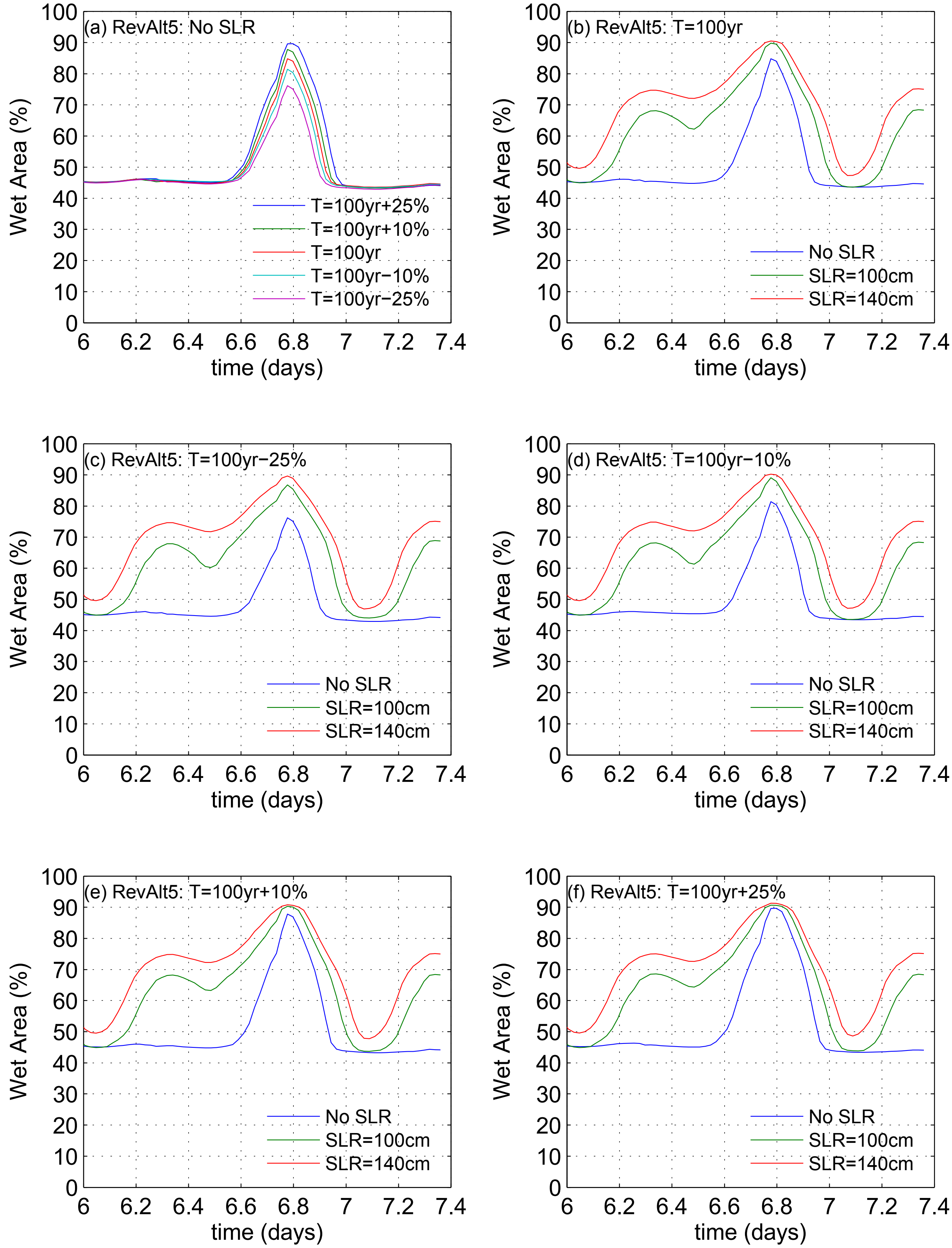


Figure 4.17. Flood Simulations with SLR – Wet area versus time for the five flood scenarios for Revised Restoration Alternative 5.

5.0 Habitat

Climate change has many implications for habitat structure and function in coastal wetlands. The period, depth and frequency of tidal inundation is a major factor influencing the distribution and acreage of habitats in coastal wetlands, which is dependent on tidal range, density of the soil, degree of the slope, and ground elevation. Such changes may modify the plant community composition and the spatial distribution of vegetation (Warren and Nierling 1993, Donnelly and Bertness 2001, Greer and Stow 2003, Watson and Byrne 2009).

Tidal wetlands exist within a very narrow vertical range, set primarily by tidal frame; a small change in the tidal frame would result in movement of the vertical distribution of tidal habitats and their associated plant communities. As sea level rises, habitats that are higher in the tidal frame will be converted to habitats lower in the tidal frame if the space is available (Garrity et al. 2009). As sea level rises, habitats that are higher in the tidal frame will be converted to habitats lower in the tidal frame. For example, high marsh will be converted to low marsh, low marsh to mudflat, and mudflat to open water. If the transitional zone has a shallow slope, higher tide levels due to sea level rise would inundate transitional and upland habitats and convert them to high marsh. The space provided by shallow upland slopes allows tidal habitat to transgress up the slope with sea level rise, thereby maintaining similar acreages of habitat. If the transitional slope is steep, higher elevation habitat acreages would decrease as open water and lower elevation habitats transgress landward. This vertical change in tidal habitats can also be applied to changes in standing water created by depressions in the land. Ponding may become more frequent and persistent, and ponds may become larger and deeper as sea levels rise. The extent to which ponds are created and persist can affect the vegetation in and around the pond. Table 5.1 provides the estimated elevation ranges for habitats within the BWER. The vertical distributions of habitats are analyzed in this study and are based on research in southern California by Ferren et al. (2007), PWA (in progress), and others.

Research in the San Francisco Estuary wetlands and in New England salt marshes suggest wide-scale vegetation change is already occurring due to sea level rise (Donnelly and Bertness 2001, Watson and Byrne 2009). Rare, threatened and endangered species are at risk of population decline or local extirpation through habitat loss, alteration or reduced habitat conditions; twelve such plant species are believed to be locally extirpated from the BWER and environs (USEPA, 2012). Habitat degradation also occurs due to the proliferation of exotic, invasive plant species which have dominated much of the landscape on fill soils at the BWER. Invasive plants alter the vegetation community composition and structure which can result in decreased species richness and limited habitat function (USEPA, 2012).

The spatial distribution of vegetation in a wetland is also a function of soil salinity (Greer and Stow, 2003, Watson and Byrne, 2009). Small changes in the water balance of sensitive habitats, such as seasonal wetlands and brackish marshes, may result in temporary or permanent changes in the salinity regimes of these areas. Although most marsh plants have a broad range of tolerance for elevation or distance to the nearest channel, they often have a narrow soil salinity tolerance (Watson and Byrne, 2009). Soil salinity can vary with degree of tidal inundation, residence time of standing water, amount and frequency of freshwater input, and distance of the wetland to the source of water input. As runoff has increased due to urbanization and wetlands have become isolated from tidal influences (e.g. via channelization, tide gates, etc.), the spatial distribution of vegetation within wetlands has changed. Weirs and tide gates modify the natural hydrology of a wetland and are also predictors of higher invasive plant cover (Fetscher et al., 2010).

If sediment accretion occurs at a rate comparable to the rate of sea level rise, the spatial distribution of coastal wetland habitats may not change significantly; however, Ballona Creek has low sediment supply (Inman and Jenkins, 1999), and it is likely sea-level rise will force habitats to transgress landward under the current conditions. Habitat migration at the BWER may not be possible under existing conditions due to urbanization of the surrounding land and hydrological modifications to the system. Restoration alternatives may account for sea level rise by including broad gentle slopes to allow many of the habitats to maintain similar acreages as they transgress towards higher elevations.

5.1 Existing habitat conditions

Types of estuarine habitats within the existing BWER (Figure 5.1) include subtidal, intertidal channels, mudflats, salt flats, low marsh, marsh plain (or mid marsh), high marsh, high marsh transition zone and brackish marsh. Each of these habitat types is associated with a particular plant community composition, and supports a range of wildlife species. Multiple factors that contribute to the types and acreages of habitats within the BWER include the inundation regime, the tidal prism, the excursion length and the characteristics of tributary streams. These processes are briefly discussed below.

Currently the BWER has muted tidal wetlands in Area B as a result of a Self-Regulating Tide gates (SRTs), which reduces the tidal range. The inundation regime can be modified by the SRTs, affecting the upper elevation of inundation. The vertical distribution of intertidal habitats can be estimated from a particular inundation regime because different plant species favor inundation at different frequencies. This muted system results in the compression of the intertidal habitat and a reduction of the habitats in the upper elevation range. Total intertidal habitat area would also be limited by reduced vertical range of habitats.

Along with a limited tidal range, muted tidal wetlands also experience a reduced tidal prism (the volume of water entering the wetland during each tide). The tidal prism affects the characteristics of channels, the source of tidal water, excursion length and the residence time.

Reduced channels, channel length, and ocean water all contribute to reduced intertidal habitats as evident at the BWER.

Natural, vegetated wetlands are usually drained by a series of branched, sinuous tidal channels which provide the necessary habitat for wildlife. The sinuous channels of the BWER have been largely replaced by a straightened and channelized drainage system lined with concrete. The separation of Ballona Creek from the marsh, the reduced inundation caused by the SRT gates, and the channelization of the creek and tributaries have all contributed to a severe reduction of wetland habitats at the BWER.

5.2 Proposed restoration habitat conditions

The project proponents and the scientific advisory committee, with stakeholder input have developed five restoration alternatives for the BWER, which have since been further refined based on existing infrastructure constraints. Alternative 5 (Alt5), which represents the most ecologically preferred option based on the Science Advisory Committee and with the greatest change from the existing conditions, was initially selected for analysis for this study. Subsequently during the development of this study, the restoration planning team revised Alternative 5 (RevAlt5), which was also included in this study for similar analysis.

Alternative 5 (Figure 5.2) and the Revised Alternative (Figures 5.3) are expected to yield the same habitat types as currently exist in the BWER, but with conditions more representative of a natural wetland with reduced impacts from urban development. Proposed changes made to the BWER will affect the hydrology and function of the wetland, and have implications for the location, quantity and quality of habitats. A summary of these changes and their potential effects to the wetland are discussed below.

Muted tidal habitats, such as those occurring in current conditions at the BWER, reduce tidal flow and range. Alt5 and RevAlt5 propose to create wetland connectivity through culverts, open breaches and removal of levees, allowing for the full oceanic tide to enter the portions of the site that will be tidal wetlands.

5.3 Model output and habitat distribution

HEC-HMS and EFDC were used to model the changes to the hydrology and hydraulics of the Ballona Watershed and Wetlands as a result of climate change and the resultant SLR. As discussed above (Section 4, Hydrology and Hydraulics), increased precipitation as a result of climate change has very little effect on the hydrology of the system when sea level rise is included in the scenario. Therefore, we can reasonably assume that the migration of wetland habitats is largely driven by SLR, and consider the implications of increased sea level only in this section.

Model outputs are discussed below, showing the impacts of SLR on the hydrology and habitat acreages and distributions within the BWER, based primarily on the predicted changes in inundation frequency and elevation. The effect of ponding water on habitat distributions was not investigated as part of this study. If the restoration alternatives move forward with large pond areas, further investigation and study of SLR and flooding effect to these features should be investigated.

Alternative 5 Habitat Conditions

For Alt5, the model was run to exhibit wetland hydraulic behavior for 1.0 m SLR and a 1.4 m SLR in the year 2100. These model outputs depict the new, sinuous creek with a collection of smaller intertidal channels across the BWER. The restoration alternative includes a large flat marsh plain (approximately 0.6 km^2) that is inundated approximately 10% of the time (Figure 5.4). This same area is inundated approximately 70% of the time with 1.0 m SLR, and 85% with 1.4 m SLR.

The effects of SLR on the distribution of wetland habitats were first investigated based on the elevation range of the habitat. This is done under the assumption that while wetland habitats are primarily associated with inundation frequency, elevation can provide a surrogate for inundation frequency. One exception could be a large wetland system. While inundation frequency will follow predictable elevations along the immediate coast, large wetlands with long channels in a complex network may display lag in the upper elevations or at the ends of channels.

Table 5.2 and Figure 5.6 display the effects of SLR on the habitat distributions based on elevations. With current SL conditions, Restoration Alternative 5 supports a large mid salt marsh plain (1.1 km^2) typical of southern California coastal wetlands. However, with SLR, this middle marsh habitat transitions to mudflat habitat (1.31 km^2 with 1.0 m SLR, and 1.38 km^2 with 1.4 m SLR) assuming static conditions of other physical influences such as scour or sedimentation. The transition from a vegetated middle marsh wetland system to a mudflat dominated system will cause dramatic shift in the species supported. For example, there may be a significant loss of Belding's savannah sparrow habitat with SLR due to the bird's dependency on marsh habitat for breeding.

The effect of SLR on the distribution of wetland habitats was also investigated based on the inundation frequency, and the results clearly validated the assumption that elevation can provide a surrogate for inundation frequency. Table 5.3 provides the results of EFDC model on habitat areas with current SL and the habitat area based on the inundation frequencies with 1.0 m and 1.4 m SLR. These habitat areas match exactly those determined using elevation except the habitats above high marsh. These habitats in the very upper limits of the transitional habitat extend beyond the extreme tides and cannot be determined using a surface water model alone. In addition, these results indicate minimal tidal lag, likely a result of the large connection to the ocean tides through Ballona Creek and the use of open unrestricted connections within the wetland.

Revised Alternative Habitat Conditions

RevAlt5 modified the previous Alt5 in order to accommodate existing infrastructure, and to address SLR impacts. The revision included a continuous slope throughout the marsh habitat that continues into the transitional and upland habitats. This minor change may provide significant benefits, including extending the persistence of intertidal marsh habitats based on the ability of those habitat types to transgress up the margins of the marsh.

Habitat distributions were investigated for the revised restoration alternative using similar methods to Alt5. Table 5.4 and Figure 5.7 display the effects of SLR on the habitat distributions based on elevations. With current SL conditions, the revised restoration alternative supports a range of vegetated marsh habitat (0.86 km^2) typical of southern California coastal wetlands. With SLR, this alternative also shifts toward a mudflat dominated system (0.86km^2 with 1.0m SLR, and 0.91 km^2 with 1.4m SLR). However, the revised alternative continues to support a significant area of diverse marsh habitats (0.41 km^2 with 1.0m SLR, and 0.31 km^2 with 1.4m SLR).

Similarly to Alt5, results of the EFDC model for the revised alternative also provide validation of the results developed using habitat elevations (Table 5.5). Subtidal, intertidal channel/mudflat, low and mid marsh habitat areas developed with inundation frequency closely follow those developed with elevations. However, the habitats above mid marsh extend beyond the tidal range of the model and do not allow estimation of the habitat area.

Table 5.1. Elevation range of intertidal habitats.

Habitat Type	Current SL NAVD (m)	1m SLR NAVD (m)	1.4m SLR NAVD (m)
	3.35	4.35	4.75
Upland			
	2.93	3.93	4.33
Transition Zone, Salt Pan			
	2.23	3.23	3.63
High Marsh			
	1.92	2.92	3.32
Mid Marsh			
	1.40	2.40	2.80
Low Marsh			
	1.11	2.10	2.50
Intertidal Channel/Mudflat			
	-0.06	0.94	1.34
Subtidal			
	-0.91	0.09	0.50

Table 5.2. Restoration Alternative 5 habitat area based on elevation.

Habitat Type	Current SL	Km^2	1m SLR	Km^2	1.4m SLR	Km^2
	15		15		15	
Upland		0.34		0.26		0.24
	2.93		3.93		4.33	
Transition Zone, Salt Pan		0.13		0.06		0.06
	2.23		3.23		3.63	
High Marsh		0.18		0.02		0.02
	1.92		2.92		3.32	
Mid Marsh		1.11		0.07		0.03
	1.40		2.40		2.80	
Low Marsh		0.04		0.09		0.04
	1.11		2.10		2.50	
Intertidal Channel/Mudflat		0.15		1.31		1.38
	-0.06		0.94		1.34	
Subtidal		0.38		0.52		0.55
	-5.00		-5.00		-5.00	

Table 5.3. Restoration Alternative 5 habitat area based on inundation frequency.

Habitat Type	Current SL	Inundation Frequency	Current SL Km^2	Inundation Frequency	1m SLR Km^2	Inundation Frequency	1.4m SLR Km^2
	15	0		0		0	
Upland			0.34		ND		ND
	2.93	0.00		0.00		0.00	
Transition Zone, Salt Pan			0.13		ND		ND
	2.23	0.00		0.00		0.00	
High Marsh			0.18		0.02		0.02
	1.92	3.15		3.45		3.00	
Mid Marsh			1.11		0.07		0.03
	1.40	19.04		20.24		18.89	
Low Marsh			0.04		0.09		0.04
	1.11	38.23		39.88		38.83	
Intertidal Channel/Mudflat			0.15		1.31		1.38
	-0.06	98.35		97.90		97.75	
Subtidal			0.38		0.52		0.55
	-5.00	100.00		100.00		100.00	

Table 5.4. Revised Restoration Alternative 5 habitat area based on elevation.

Habitat Type	Current SL	Km^2	1m SLR	Km^2	1.4m SLR	Km^2
	15		15		15	
Upland		0.76		0.52		0.44
	2.93		3.93		4.33	
Transition Zone, Salt Pan		0.27		0.14		0.12
	2.23		3.23		3.63	
High Marsh		0.18		0.10		0.06
	1.92		2.92		3.32	
Mid Marsh		0.58		0.19		0.17
	1.40		2.40		2.80	
Low Marsh		0.11		0.12		0.11
	1.11		2.10		2.50	
Intertidal Channel/Mudflat		0.11		0.87		0.91
	-0.06		0.94		1.34	
Subtidal		0.28		0.34		0.46
	-5.00		-5.00		-5.00	

Table 5.5. Revised Restoration Alternative 5 habitat area based on inundation frequency.

Habitat Type	Current SL	Inundation Frequency	Current SL Km^2	Inundation Frequency	1m SLR Km^2	Inundation Frequency	1.4m SLR Km^2
Upland	15		0.76	0	ND	0	ND
Transition Zone, Salt Pan	2.93	0.00	0.27	0.00	ND	0.00	ND
High Marsh	2.23	0.00	0.18	0.00	ND	0.00	ND
Mid Marsh	1.92	0.00	0.58	0.00	0.29	0.00	0.23
Low Marsh	1.40	17.88	0.11	18.44	0.12	17.88	0.11
Intertidal Channel/Mudflat	1.11	37.43	0.11	38.55	0.86	37.43	0.91
Subtidal	-0.06	97.21	0.28	96.65	0.35	97.21	0.46
	-5.00	100.00		100.00		100.00	

Figure 5.1. Existing habitat map of the wetlands. Figure courtesy PWA 2007.

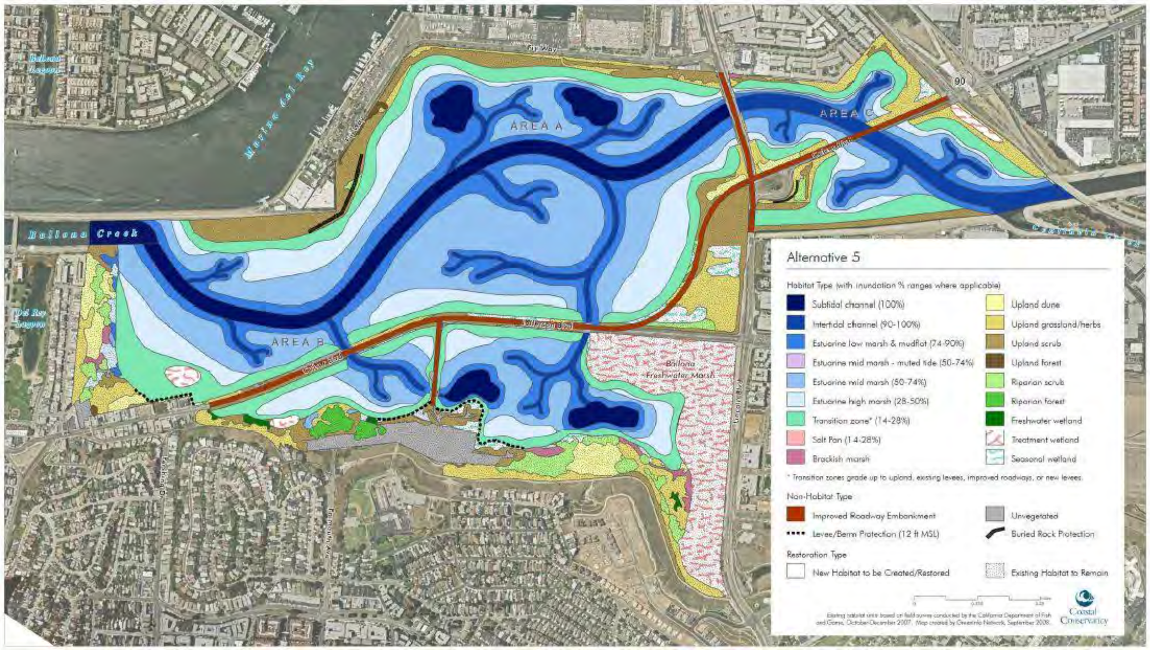


Figure 5.2. Alternative 5 restoration plan and habitat map.

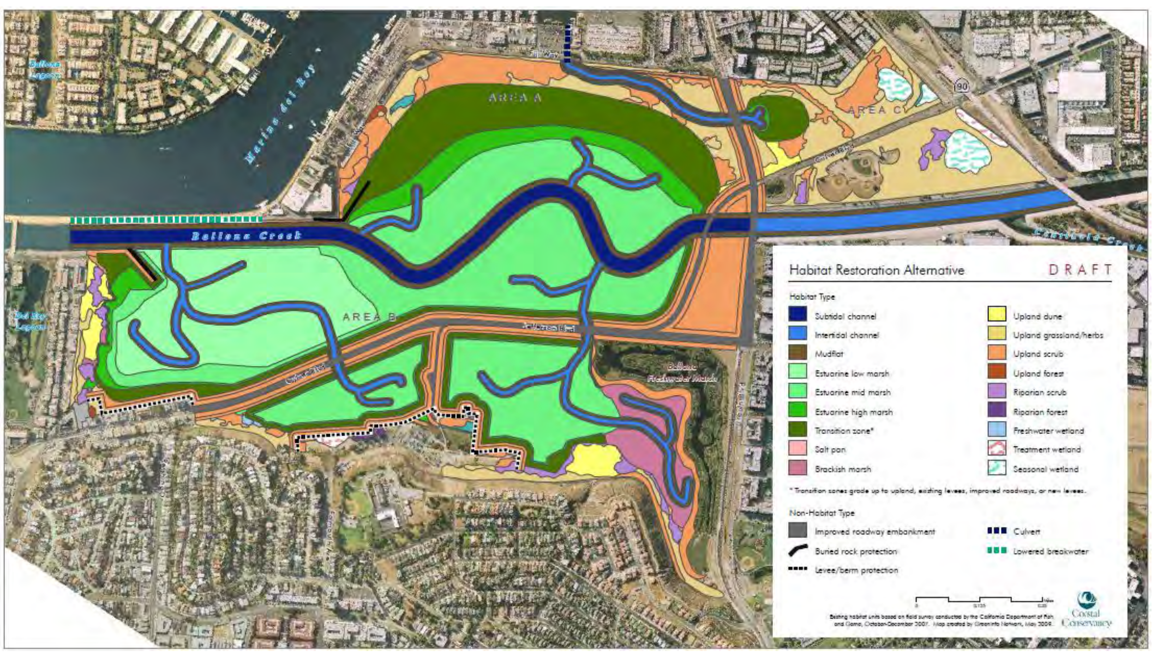


Figure 5.3. Revised Alternative 5 restoration plan and habitat map.

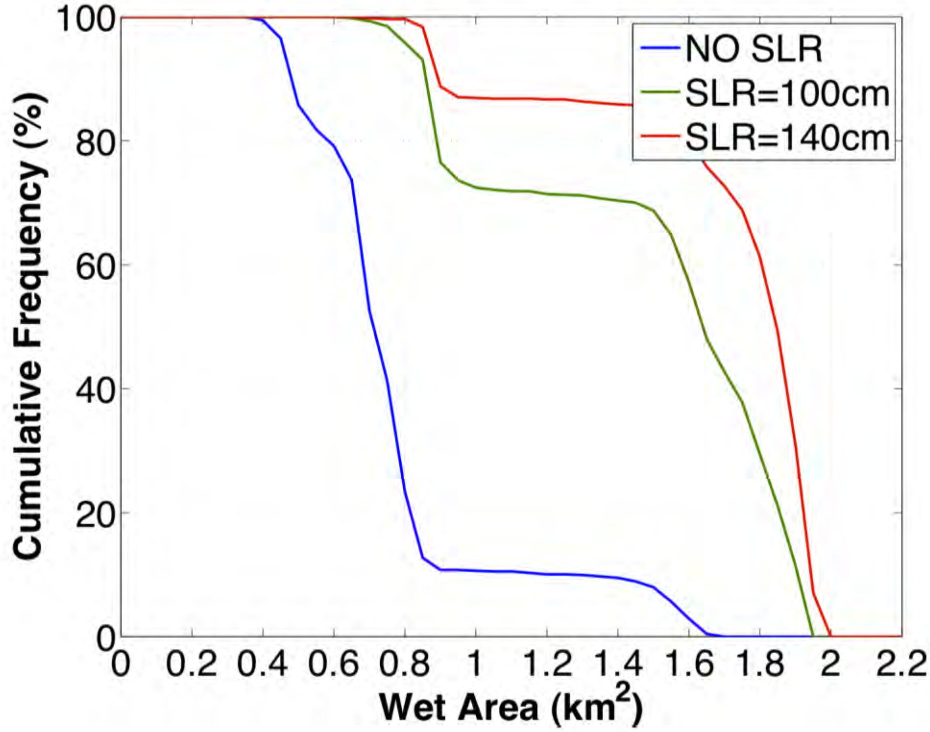


Figure 5.4. Wetted area vs. cumulative frequency for Alternative 5 with 0, 1.0m, and 1.4m SLR.

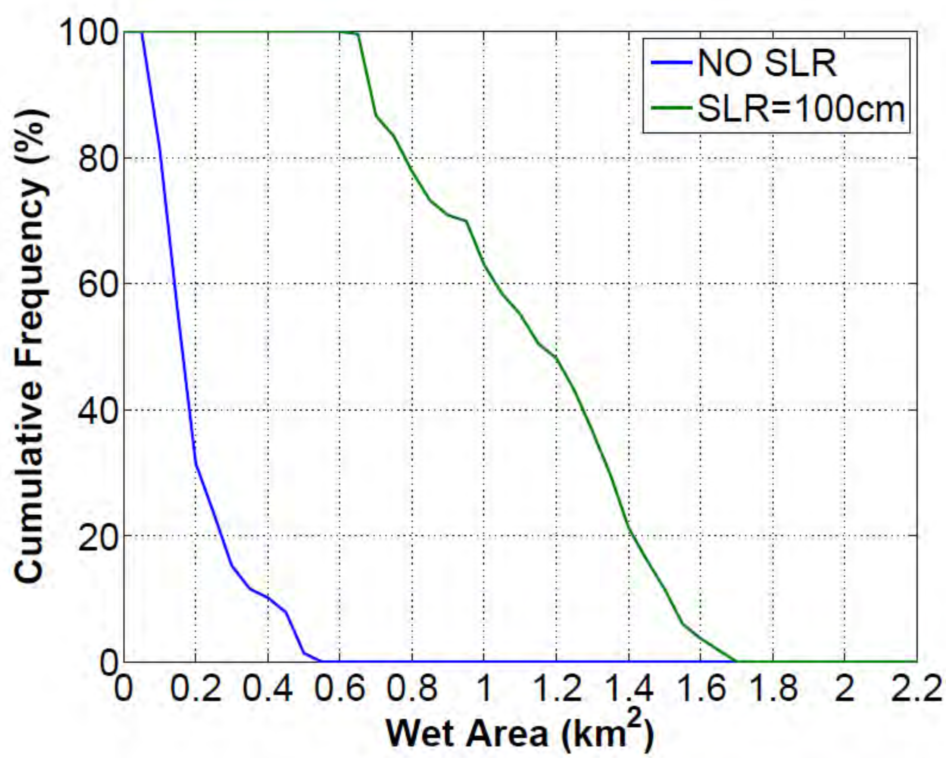


Figure 5.5. Weted area vs. cumulative frequency for the Revised Alternative with 0 and 1.0m SLR.

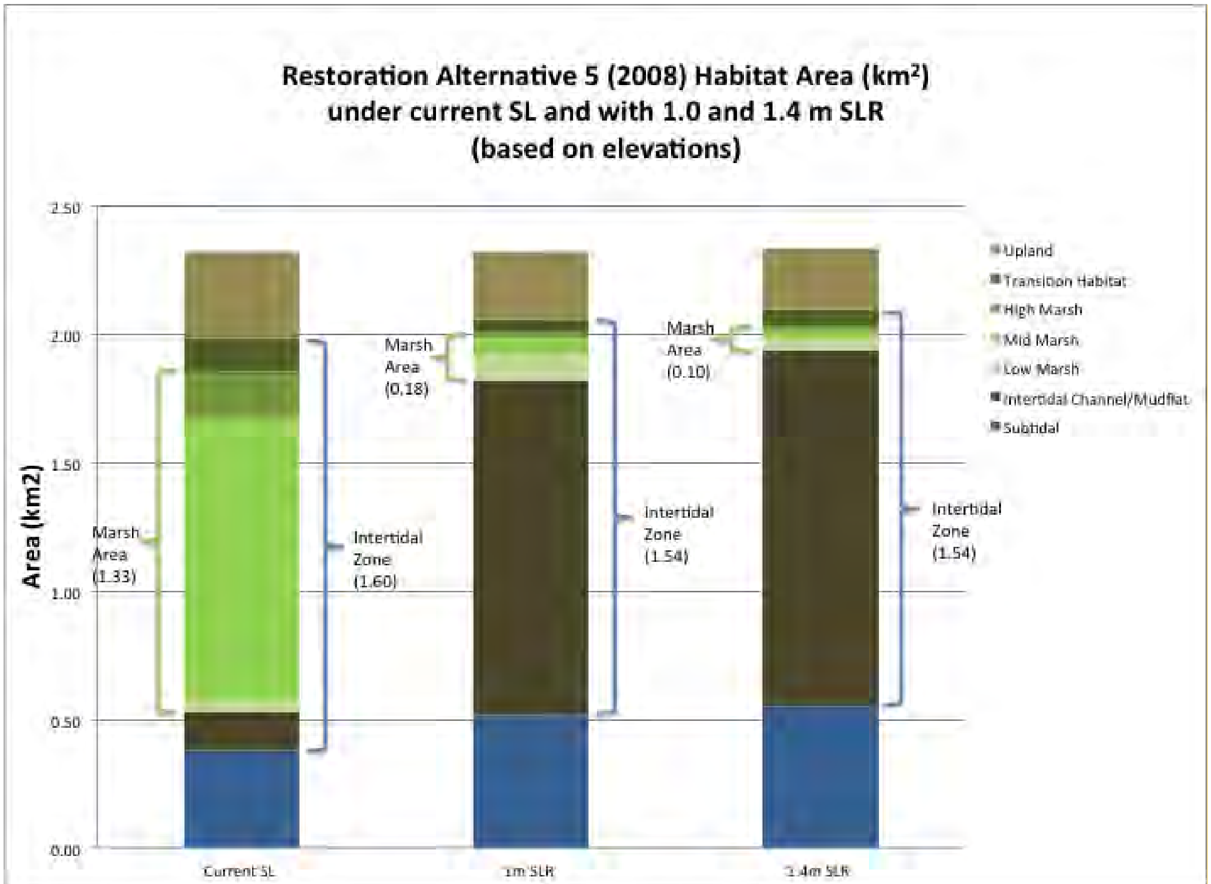


Figure 5.6. Restoration Alternative 5 habitat area with current SL and 1.0m and 1.4m SLR.

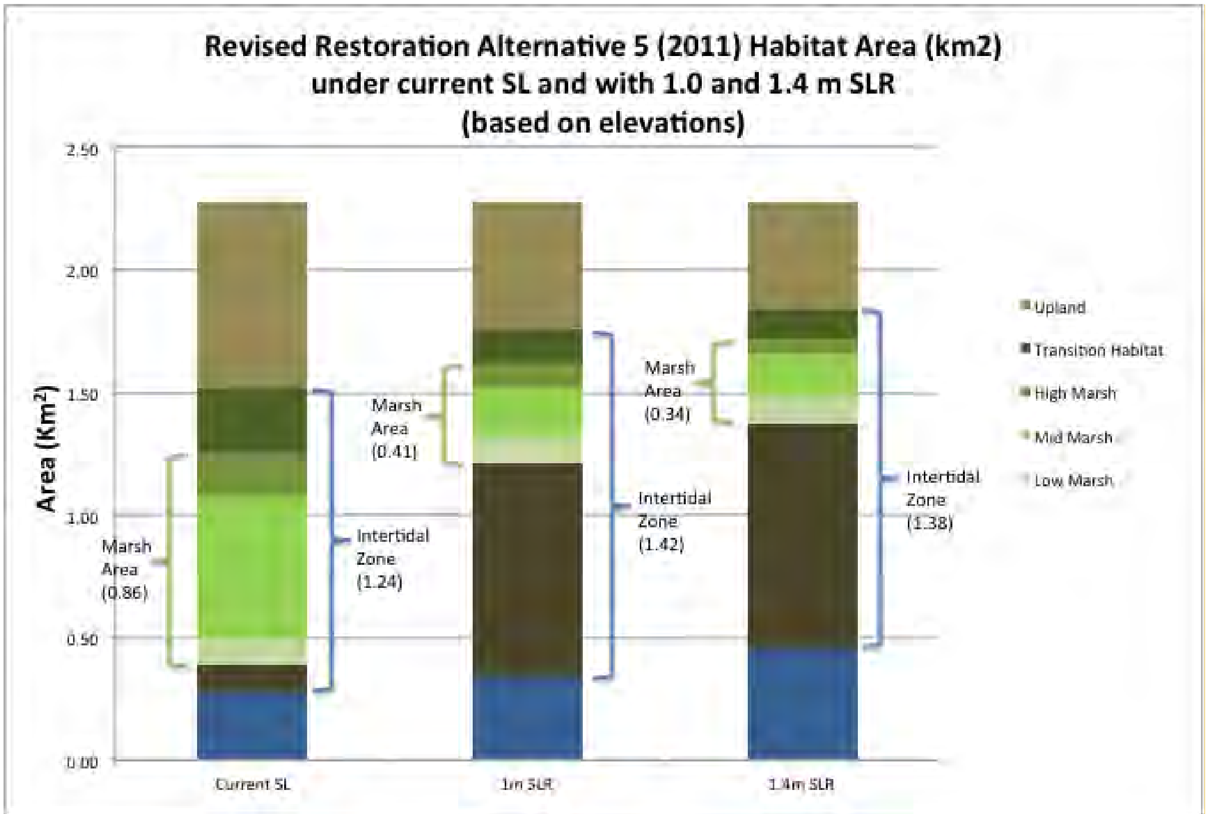


Figure 5.7. Revised Restoration Alternative 5 habitat area with current SL and 1.0m and 1.4m SLR.

6.0 Discussion

6.1. Modeling Results Implications

This study investigates the impacts of SLR and changes magnitude of precipitation event on two restoration alternatives being developed for the BWER. The results of the study demonstrate that in the event of SLR (with SLR estimates of 1.0 m and 1.4 m in the year 2100), habitats restored according to either alternative will experience various levels of impacts. A restoration alternative that can accommodate the transgression of habitats upslope may provide more sustainability in the long term. In future restoration planning for coastal habitats, it may be useful to model the impacts of sea level rise on designs that provide flat marsh areas on a stepped, rather than continuously sloped, gradient. Incremental steps of marsh at various elevations may maintain larger areas of a given marsh habitat as sea levels rise.

The results of this study validate one of the widely-held assumptions that tidal wetlands in southern California, including the BWER, are inherently highly vulnerable to SLR because they typically exist within a very narrow elevation range set primarily by the tidal frame (high and low tides), which is approximately 2 m in the region. A small change in the tidal frame due to SLR would result in migration of the vertical distribution of tidal habitats. On the other hand, the response of tidal wetlands to SLR also depends on many other factors that were not investigated under this study. One of the key factors is the availability of space for the transgression of wetland habitats to higher elevations. Another is sediment supply to the wetland and the associated rate of wetland accretion. If sediment is readily available, vertical accretion may keep pace with SLR and the spatial distribution of tidal habitats may not change significantly. If sediment supply is low, as in the urbanized Ballona Creek, accretion rates may be slower than SLR and habitats would transgress landward, if there is space for them to do so.

Another key factor that could further limit the ability of BWER to respond to the SLR impacts is the restriction on tidal flow caused by the existing tide gates in the creek levees. The existing condition at the BWER includes muted tidal flows into the wetland, such that the inundation by daily tides is relatively constant from day to day, because the tide gates prevent a full high tide from entering the wetlands and potentially flooding adjacent roads and properties. Tidal flows may be restricted even more with SLR as the tide gates will remain closed a greater amount of time to prevent flooding.

This study also investigated the impacts of climate change on the habitat structure and function in coastal wetlands, mainly as a result of increased inundation frequency due to SLR. The results indicate that with SLR, habitats supported by one restoration alternative (Alt5) will transition from a vegetated middle marsh wetland system to a mudflat dominated system. The revised restoration alternative (RevAlt5) shows some shifts toward a mudflat dominated system with SLR, but continues to support a significant area of diverse marsh habitats. These results are preliminary and in the future, an investigation of the species supported by these habitats and the potential change in species composition and diversity could be developed from the SLR projections.

6.2. Modeling System Constraints and Considerations for Further Application

In this study, a suite of simulations using both a watershed rainfall-runoff model (HEC-HMS) and a wetlands model (EFDC) were performed to investigate the potential impacts of climate change on two BWER restoration alternatives. While considerable and reliable information is provided from this suite of simulations, the results are preliminary, with several outstanding issues to be resolved.

As mentioned in Section 4.1, the basic HEC-HMS configuration was supplied by ACOE. Although extensive work has gone into calibrating the model for the Ballona Watershed and simulated hydrographs resulting from the 100-year precipitation event (and other return periods) match observations remarkably well, the configuration is still in a testing phase. It is possible that due to the limited sensitivity of the model, actual response of discharge to a change in precipitation in the watershed may not match the simulated response. ACOE is expected to release an official version of the model configuration when they finish their work on improving model parameters to better represent the rainfall-runoff processes of the watershed.

For the tidal simulations in this study, we used EFDC configuration and calibration developed by PWA to predict water levels over more or less the same two-week spring-neap tidal cycle. This configuration does not include processes for infiltration, evapotranspiration, and direct precipitation falling onto the wetlands. Given the low depth to water table in the wetlands, infiltration is generally small compared to inflow from tides and large storms, and perhaps can be considered negligible. Evapotranspiration is also small compared to inflow from tides, especially when no precipitation occurs during the period of simulation, as was the case in the weeks prior to and during the simulation period in this study. In addition, evapotranspiration is small compared to stormflow during large storms, such as those used for the flood simulations in this study. However, during inter-storm periods, evapotranspiration may be important especially from wetland areas outside of the tidal influence and impacted directly by precipitation. Similarly, direct precipitation falling onto the wetlands should be included when storms are considered as it is an important component of a wetland water budget.

A next step for this study would be a yearlong set of simulations that include infiltration, evapotranspiration, and direct precipitation. An ideal year would be the 1998 water year (October 1, 1997 to September 30, 1998), which included the largest El Nino Southern Oscillation (ENSO) event on modern record and generated considerable precipitation and stormflow into the wetlands. In this scenario, EFDC would be run continuously for the entire 1998 water year (plus any spinup period) using tidal and meteorological observations as well as the hydrographs coming from Ballona Creek. If hourly or better observations of discharge are available from Ballona Creek, these could be directly input into EFDC. If they are not available, which is likely the case, HEC-HMS would need to be run for each of the 1998 water year's precipitation events to generate the stormflow hydrographs entering the wetlands. HEC-HMS is well calibrated for large storm events, however, it may not perform well for smaller events.

The model predicted that with SLR, the wetlands are close 90% inundated in both of the restoration alternatives (Alt5 and Rev Alt5). Some of the inundation extends to the domain boundaries where there is a no flux condition imposed by EFDC. If this condition were not imposed, some of the water from the ocean and Ballona Creek inflow would inundate areas outside of the domain and perhaps into the surrounding community, as occurs under existing wetland conditions. To avoid this flooding in the surrounding community, RevAlt5 could be further revised to accommodate SLR. Additional experiments with a larger extended domain and/or flux boundaries should be performed to test the robustness of a revised RevAlt5. Alternatively, a restoration alternative with additional perimeter levees could be developed.

Large storm events typically coincide with storm surges. However, in this study, the peak of the 100-year storm flow hydrograph is timed such that it matches the peak of a typical tide, not a storm surge. Therefore the full impacts of the 100-year precipitation event may be underestimated in this study. A suite of idealized experiments could be designed to investigate the impacts of storm surges and storm events on the proposed wetland restoration alternatives. For example, a simulation could be performed imposing the 100-year precipitation event that coincides with the 10-year storm surge. A complimentary simulation could be performed with the 10-year precipitation event coinciding with the 100-year storm surge. With the current restoration alternatives, it is likely that the inundation levels from tidal conditions associated with the storm would be even more important.

The impacts of climate change were investigated in this study by imposing SLR and modified extreme precipitation events onto the wetlands. Output from regional climate model (RCM) simulations under the IPCC SRES A2 greenhouse gas emissions scenario was originally intended as input into the HEC-HMS and EFDC system. (RCMs are often forced by output from Global Climate Models (GCMs) to provide data for impacts studies such as this study.) An analysis of these RCM simulations found no statistically significant changes in extreme precipitation over the Ballona Creek and Los Angeles River watersheds. This result was confirmed by a review of the literature analyzing Southern California (See Section 2.1). For this reason, we investigated both increases and decreases in 100-year precipitation event magnitude. In the future, once the models are configured for the yearlong simulations, bias-corrected RCM meteorological data could be used as input for HEC-HMS and EFDC modeling system.

Obtaining EFDC model stability proved to be challenging. Generally speaking, finite-difference grid models require higher timesteps as the resolution increases. If the timestep is too large, transport processes can evacuate more mass (water in this case) over the given period of time (timestep) and distance (grid spacing) than a gridcell has available. This can result in negative mass and a model crash. The model crash could occur at any point in the simulation, i.e., not necessarily at the beginning. Reducing the timestep reduces amount of mass evacuated since there is less time to evacuate, and decreasing the grid spacing reduces the amount of mass available to evacuate. Consequentially, with grid models such as EFDC, doubling the resolution typically results in an eight-fold increase in computation time – two for each horizontal direction (x and y) and two for the reduction in timestep. The EFDC domains in these simulations have a variable mesh grid with grid spacing ranging from 10 m to 20 m. Therefore, the timestep must be adjusted to the high-resolution portion of the grid, i.e., 10 m.

Under normal tidal conditions, with the EFDC configurations we used, a timestep of 2 seconds provided numerically stable results. However, when SLR is incorporated, a timestep of 1 second is required for numerical stability, resulting in a two-fold increase in required computational time. The model crashes tended to occur early on in the simulations (first 30 minutes of wall time) since flow velocities do not change much with the different tidal cycles. In addition, the results varied slightly depending on the timestep. For example, running the model with no SLR at a 2 second timestep resulted in slightly different results than a 1 second timestep. Although the qualitative findings did not change with the varying timesteps, each tidal simulation was run (or in many cases rerun) at the same timestep for consistency reasons.

Prior to this study, a 50-year precipitation/flood event was the largest event for which the model was stable (PWA, 2008). Flood flows tend to move at higher velocities than tidal flows. As a result, the potential for the grid cell mass to be evacuated is greatly increased, requiring lower timesteps. The model configuration supplied by PWA for the 50-year precipitation event required a timestep of 0.25 seconds. In the 100-year precipitation/flood event simulations in this study, numerical instabilities occurred just before the peak of the flood hydrograph (day 6.8 or 2 days of wall time at a 0.25 second timestep). The model simulations did not crash as a result of the numerical instability producing no stoppage in simulation and appearance that the model simulations were successful, when in fact the results were invalid after the instability. It was not until months later when the results were being thoroughly analyzed that this problem was diagnosed. This required all 30 flood simulations to be rerun at a 0.125 second timestep. When the code was ported to the Linux cluster (described below), the compile settings were adjusted such that the model would crash whenever such numerical instabilities occurred. It was later ascertained that PWA was also unable to successfully perform the 100-year precipitation/flood event simulations and is the reason the 2008 Feasibility Report (PWA, 2008) included only 50-year precipitation/flood events. In this study, numerical stability was achieved with a 0.125 second timestep. Fortunately, a 0.125 second timestep was also appropriate for the 100-year precipitation event plus 25% simulation including 1.4 m of SLR.

EFDC water elevation initial conditions also proved to be a complicating factor on top of model timestep for obtaining model stability. More specifically, initializing simulations at water elevations different than the initial tidal levels tends to result in high-velocity flows due to large head differences, resulting in increased potential for more mass than is available to evacuate a grid box (as is the case with too large a timestep). Since this a problem of initial conditions, this would usually result in numerical instabilities within the first 15 to 30 minutes of model initialization. Given that symptoms for the numerical instabilities resulting from timesteps that are too large and water surface elevations differences that are substantially different appear the same, a considerable amount of effort was placed on obtaining a stable model timestep (see above). Model simulations were performed at timestep as low as 0.0125 seconds. While this finally resulted in model stability, the required computational time was well in excess of what was reasonable, particularly for the tidal simulations (around a 20-fold increase or 20 weeks of wall time per simulation). Furthermore, the high timestep in such a simulation is only required for the first several model minutes while water surface elevations stabilize, meaning most of the simulation would run at a timestep much lower than required.

To address this problem of water surface elevation and tidal level initial condition differences, all simulations are initialized with water surface elevations exactly at the tidal levels. For example, the tidal simulations with no SLR are initialized at day 10.88 with water elevations of 2.055 m, which is also the tidal height. The corresponding 1.0 m SLR simulations are initialized at 3.055 m. Fortran preproccesing routines were written to generate the necessary input files to accommodate these initial condition requirements.

There are some ramifications of initializing the model in such a manner. BWER areas not normally active and dry are potentially initialized as wet. Given that evaporation and infiltration are ignored, these areas remain wet throughout the simulations even if water entering from tidal flow and/or flood flow has no path to the area (discussed below). As a result, the initial wetland water levels can be considered as if a heavy rain event occurred over the wetlands immediately prior to the initialization of the simulations. For watershed flood simulations, this is often done to represent a worst-case scenario and therefore can be considered somewhat realistic. Furthermore, for the EFDC wetland flood simulations (and tidal simulations), no precipitation is assumed to fall on the wetlands despite the occurrence of a 100-year precipitation event. Initializing water elevations in regions of the BWER that are normally dry as wet partially compensates for the lack of precipitation falling on the wetlands during the flood simulations. This assumption of wet conditions in the non-active wetland areas also applies to the tidal simulations and impacts the results. The tidal simulations should be repeated, initializing these not-normally-wet BWER regions as dry.

The revised restoration alternative (RevAlt5) was made available by PWA midway through this project (mid-2011). As provided, the model configuration for RevAlt5 did not work in that it crashed during the initialization phase before the timestep loop began. Through trial and error, it was determined that 1) the model was not configured to properly receive the inflow stormflow hydrographs and 2) the initial water surface elevations and tidal levels were not similar enough for model stability (even in the default setup provided).

The addition of RevAlt5 to the project required a large number of new simulations (and hence additional computational time). The flood simulations needed to be rerun due to numerical instabilities, and to ensure the model did not crash when certain numerical instabilities occurred, the model was converted to work on the LMU Hydrology Linux cluster. Running the simulations on the cluster reduced the computational time for simulation by approximately a factor of two. In addition, 16 CPUs were made available for the computations, allowing the simulations to be performed in two waves taking approximately two weeks.

In summary, the lessons learned from the extra computer runs and simulations improved the model's capacity and stability for future use. The study explored a new approach to integrate climatic and hydrological models, and demonstrated its applicability in assessing the impacts of climate change on coastal wetland habitats. The applicability of this new modeling tool may be more important than the results of analysis on the two restoration alternatives, as at the time of this paper's publication the Ballona Wetland restoration planning process is still ongoing, and restoration alternatives are still evolving. New model runs for the updated restoration alternatives may provide more representative and reliable assessment of the climate change impacts.

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