Batiquitos Lagoon
Bridge Optimization Study

Final Report

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EXECUTIVE SUMMARY

For the past several years, the California Department of Transportation (Caltrans) and the San Diego Association of Governments (SANDAG) have been working on the development and implementation of a large-scale transportation improvement project in Northern San Diego County known as the Interstate 5 (I-5) North Coast Corridor (NCC) Project. Implementation of this project will require work within the major coastal lagoons of Northern San Diego County. The project will include new bridge structures across most of the lagoons, including Batiquitos Lagoon. The objective of this study is to evaluate a range of channel widths and depths under the I-5 and Railroad (RR) bridges. These evaluations will be used to determine bridge length and to identify a combination of channel widths and depths that provides the most favorable conditions for conveyance of tides and stormflows throughout the lagoon.

The TABS2 numerical modeling system, including the RMA-2 hydrodynamic model and the RMA-4 water quality model, was used for this study. A finite element numerical model grid was created based on a 2008 bathymetry survey of the lagoon. The RMA-2 model was calibrated and verified with tidal elevations recorded in the lagoon in July 2008. The calibrated and verified numerical model was then used in the channel dimensions optimization modeling. The RMA-4 model was used in this study to predict the residence time. The dispersion coefficients used in the RMA-4 model are based on modeling calibrations performed for other similar lagoons, as no data are available from Batiquitos Lagoon for calibration.

The selection of optimum channel widths and depths for bridge lengths was based on a sensitivity analysis conducted for each bridge crossing under: 1) typical dry weather tidal fluctuations and 2) extreme stormflow conditions (combined 100-year storm and 100-year water levels). Tidal range was used as the primary indicator for benefits to the wetland ecosystem. Extreme flood elevations were used to evaluate the high water surface elevations in the lagoon in comparison with bridge soffit elevations, although potential flooding of adjacent areas is not currently an issue at Batiquitos Lagoon. Using these indicators, the optimum channel width and depth at each bridge were identified as the point at which tidal range and flood conveyance are most favorable and further increases in channel width and depth result in only minimal benefit. The tidal inlet under the Carlsbad Boulevard bridges was originally sized and designed to achieve a stable tidal inlet as part of the Batiquitos Lagoon Restoration Project. The tidal inlet has been performing well since construction in 1995; therefore, no further optimization is required for that channel.

Table ES-1 presents the existing and optimum channel widths and depths for the I-5 and RR Bridges.

Table ES-1 Summary of Existing and Optimized Channel Dimensions

Infrastructure	Recommended Based on Optimization			Design Condition		
	Channel Invert (ft)		Bottom Width (ft)	Channel Invert (ft)		Bottom Width (ft)
	NGVD	MLLW		NGVD	MLLW	
Inlet	-8.0	-5.7	96	-8.0	-5.7	96
RR	-7.0	-4.7	202	-7.0	-4.7	162
I-5	-7.0	-4.7	134	-7.0	-4.7	66

Key findings from the optimization modeling study are summarized below:

- Dredging of the lagoon and channels under the bridges is an effective way to increase the tidal range and reduce tidal velocities under the bridges. Simply dredging the lagoon to its design condition will increase the tidal range by 0.4 feet in the Central Basin and by 0.7 feet in the East Basin, and will reduce the tidal velocity by more than 0.5 feet per second (fps). The tidal range will increase by an additional 0.17 feet in the Central Basin and by 0.21 feet in the East Basin with the optimized channel dimensions under both the I-5 and RR Bridges.

- With the optimized channel dimensions, the backwater effect created by the I-5 Bridge will be reduced and the flood elevation in the East Basin will be lowered. However, this will simply shift the backwater effect to downstream of the I-5 Bridge, resulting in an increase in flood elevations in the Central and West Basins compared to those under existing conditions.
- Tidal velocities at the bridge crossings, which are responsible for scour holes on both sides of the I-5 Bridge, will be reduced with the optimized channel dimensions. Reduced tidal flow velocities should significantly reduce the scour depth on both sides of the I-5 Bridge. Stormflow velocities will also be lowered at both the I-5 and RR Bridges; however, they will be slightly higher at the tidal inlet with channel optimizations. Fluvial sediment transport in the East Basin under the optimized condition should be slightly improved compared to existing conditions due to reduced backwater effects and the shortened flood travel time through the East Basin.
- Residence time is relatively short for Batiquitos Lagoon. In the West Basin the residence time is approximately 0.5 days, gradually increasing to approximately 1.5 days in the Central Basin and to approximately 5.5 days in the East Basin. A residence time of less than one week is considered relatively good for an estuary wetland system. While the tidal circulation in Batiquitos Lagoon is good, it can be further enhanced with maintenance dredging.
- The tidal inundation frequency curve under the optimized condition is very similar to that under existing conditions. The vertical range of the intertidal habitats would increase

slightly under the optimized channel dimensions condition. For Batiquitos Lagoon, the primary gain of intertidal habitat area will be mudflat.

- In the year 2100, with projected sea level rise (SLR), channels under both the existing and optimized I-5 and RR Bridges would pass the 100-year flood with more than 3-feet of freeboard. However, the soffit of the Carlsbad Boulevard Bridges will be below the 100-year flood water level. Flood velocities under the SLR scenario at all three bridge crossings will be lower than those under existing conditions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Caltrans	California Department of Transportation
CB	Central Basin (figure legends only)
cfs	Cubic Feet per Second
CSCC	California State Coastal Conservancy
EB	East Basin (figure legends only)
FEMA	Federal Emergency Management Agency
fps	Foot per Second
ft	Feet
GIS	Geologic Information System
GPS	Geological Position System
I-5	Interstate 5
ID	Identification
LOSSAN	Los Angeles – San Diego – San Luis Obispo Rail Corridor Agency
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
M&N	Moffatt & Nichol (Company)
MSL	Mean Sea Level
MTL	Mean Tidal Level
NAD	North American Datum
NAVD	North American Vertical Datum
NCC	North Coast Corridor
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
RMA-2	Resource Management Associates (2D numerical model for surface flow)
RMA-4	Resource Management Associates (2D water quality model)
RR	Railroad
SANDAG	San Diego Association of Governments
SED2D	2 Dimensional Sedimentation Model
SLR	Sea Level Rise
TABS2	The Open Channel Flow and Sedimentation (Numerical Modeling System)
TEA	Tidal Epoch Analysis
USACE	United States Army Corps of Engineers
WB	West Basin (figure legends only)
WRA	Wetland Research Associates, Inc. (Company)
WSE	Water Surface Elevation
2D	Two-dimensional

1.0 INTRODUCTION

Batiquitos Lagoon, located approximately 30 miles north of the City of San Diego and shown in Figure 1-1, is a coastal wetland restored in 1995 with significant biological and ecological resources.

Figure 1-1: Project Location Map

For the past several years, the California Department of Transportation (Caltrans) and the San Diego Association of Governments (SANDAG) have been working on the development and implementation of a large scale transportation improvement project in Northern San Diego County known as the Interstate 5 (I-5) North Coast Corridor (NCC) Project. Implementation of this project will require work within the major coastal lagoons of Northern San Diego County. The project will include new bridge structures across most of the lagoons, including Batiquitos Lagoon. The objective of this study was to evaluate a range of channel widths and depths under the I-5 and railroad (RR) bridges, which will be used to determine the bridge lengths, and identify a combination of channel widths and depths that provides the most favorable conditions for tidal range and flood conveyance throughout the lagoon. Channel dimensions, including both width and depth under the I-5 and RR Bridges, are optimized for both tidal and fluvial flows. The tidal inlet under the Carlsbad Boulevard East and West Bridges was sized and designed to achieve a stable inlet as part of the Batiquitos Lagoon Restoration Project. A stable tidal inlet is self-sustaining and remains open under most conditions. The tidal inlet has been performing well since construction in 1995. Therefore, no optimization is required for the tidal inlet.

However, the existing inlet is relatively narrow, resulting in tidal muting of 0.95 feet between the ocean and the east end of the inlet under existing conditions.

1.1 Scope of Work

The scope of work for this optimization study includes:

1. Gathering available data for model setup, calibration, verification, and alternative modeling runs.
2. Developing two dimensional numerical model (RMA-2) grids for both the post-construction condition and the existing condition (lagoon shoaled condition).
3. Calibrating and verifying the RMA-2 model by matching model-predicted tidal elevations to those measured in the lagoon in 2008 as part of long-term monitoring (Merkel & Associates 2009).
4. Performing RMA-2 hydrodynamic modeling runs to achieve the optimal tidal range in the lagoon and fluvial flood (stormflow) conveyance through the lagoon.
5. Performing RMA-4 water quality model runs to determine residence times in the lagoon.
6. Performing velocity and sedimentation pattern analyses based on RMA-2 hydrodynamic modeling results.
7. Preparing Draft and Final Reports of the methods, analyses, and results.

1.2 Modeling Bathymetry Conditions

Coastal lagoons with tidal connections to the ocean experience shoaling in the interior of the inlet as a result of tidal exchange between the ocean and the lagoon. Batiquitos Lagoon experiences such shoaling. Flood shoals have been gradually building up, first in the West Basin and then expanding into the Central Basin. To achieve the desired tidal exchange and maintain tidal inlet stability, the flood shoals have been partially removed on several occasions via maintenance dredging. Maintenance dredging will continue into the future. The bathymetric condition of Batiquitos lagoon has evolved between the dredged and shoaled lagoon conditions ever since. Therefore, for this study two bathymetric conditions were modeled: (1) the existing shoaled condition; and (2) the post-construction (dredged) lagoon condition. These two bathymetric conditions were selected to represent the two extreme tidal prism conditions.

(1) <u>Shoaled Lagoon Condition</u> - The bathymetry of the shoaled condition was based on the 2008 survey. As flood conveyance will be limited by shoals in the lagoon and channels under infrastructure crossings, this condition was the control condition in optimizing the channel widths and depths for lowering flood water levels in the lagoon.

(2) <u>Post-Construction (Dredged) Lagoon Condition</u> (Post-construction condition with material consolidation assumed to have occurred in the Central Basin) – Under this condition, the West and East Basins were assumed to be dredged to the post-construction condition. During original construction, the Central Basin was dredged deeper to create a disposal pit. The disposal pit was backfilled with silt/clay/fine sand

and topped with a 2-foot coarse sand cover to a finished elevation of -4.56 ft NGVD. According to the results of hydroprobing conducted in 2008 (Merkel & Associates 2009), an average of 2.2 feet of subsidence occurred in the disposal pit. Therefore, it is proposed to assume a lower shoal area in the Central Basin of -6.76 feet NGVD (-2.2 feet below the as-built elevation of -4.56 feet) for the modeling. The proposed shoal area is outlined in yellow in Figure 1-2. By lowering the shoal down to -6.76 feet, additional sediment storage will be created and the dredging interval may be extended. Based on the most recent survey conducted in 2008, the rest of the Central Basin is deeper than -4.56' NGVD and ranges from -5 to -7 feet due to consolidation. These depths were retained for modeling purposes. Table 1-1 shows shoals needing to be removed to return the lagoon to as-built conditions (Moffatt & Nichol, or M&N, 1997) except for the Central Basin. In the Central Basin the shoal volume estimate was limited to the dredging area shown in Figure 2-4, and the dredging area is assumed to be dredged down to -6.76 feet NGVD, as discussed earlier. For the West and East Basins, the shoal volume estimate was for the entire basin. All channels under infrastructure crossings were assumed to be dredged to dimensions shown on record design drawings. Table 1-2 shows the channel width and invert elevation for each bridge referenced to the NGVD vertical datum. Under this proposed dredged condition, the lagoon will have the largest tidal prism of any other scenario. Therefore, it will be the upper bound prism condition for the bridge optimization study to achieve the maximum tidal range.

Table 1-1: Shoal Volume Estimates

Basin	**West Basin**	**Central Basin (limited to the dredging area)**	**East Basin**
Volume (Cubic Yard)	59,000	125,000	464,000

Table 1-2: Channel Dimensions Shown on Record Drawings

West Carlsbad		**East Carlsbad**		**LOSSAN RR**		**I-5**	
Channel Invert (ft)	**Channel Width (ft)**	**Channel Invert (ft)**	**Channel Width (ft)**	**Channel Invert (ft)**	**Channel Width (ft)**	**Channel Invert (ft)**	**Channel Width (ft)**
-8	96	-8	109	-7	162	-7	66

Figure 1-2: Central Basin Dredging Area

2.0 NUMERICAL MODEL SETUP

This report section presents the model selection, description, set-up, and calibration/verification.

2.1 Model Selection and Description

The numerical modeling system used in this study is summarized herein. The TABS2 (McAnally and Thomas, 1985) modeling system was applied to this project because it realistically represents dynamic tidal and stormflow conditions to yield results most applicable to this evaluation.. TABS2 was developed by the U.S. Army Corps of Engineers (USACE), and consists of the following components:

1. Two-dimensional, vertically-averaged finite element hydrodynamics model (RMA-2);
2. Pollutant transport/water quality model (RMA-4); and
3. The sediment transport model (SED2D).

TABS2 is a collection of generalized computer programs and pre- and post-processor utility codes integrated into a numerical modeling system for studying 2D depth-averaged hydrodynamics, transport and sedimentation problems in rivers, reservoirs, bays, and estuaries. The finite element method provides a means of obtaining an approximate solution to a system of governing equations by dividing the area of interest into smaller sub-areas called elements. Time-varying partial differential equations are transformed into finite element form and then solved in a global matrix system for the modeled area of interest. The solution is smooth across each element and continuous over the computational area. This modeling system is capable of simulating tidal wetting and drying of marsh and intertidal areas of the estuarine system.

A schematic representation of the system is shown below. TABS2 can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. RMA-2 calculates water surface elevations and current patterns which are input to the pollutant transport and sediment transport models. The three models listed above are solved by the finite element method using Galerkin weighted residuals.

The hydraulic model RMA-2 and water quality model RMA-4 were applied to this study. The lagoon sedimentation models (SED2D) was not applied to this study due to limited input data, and the opportunity to use stormflow velocity as a surrogate for potential sedimentation..

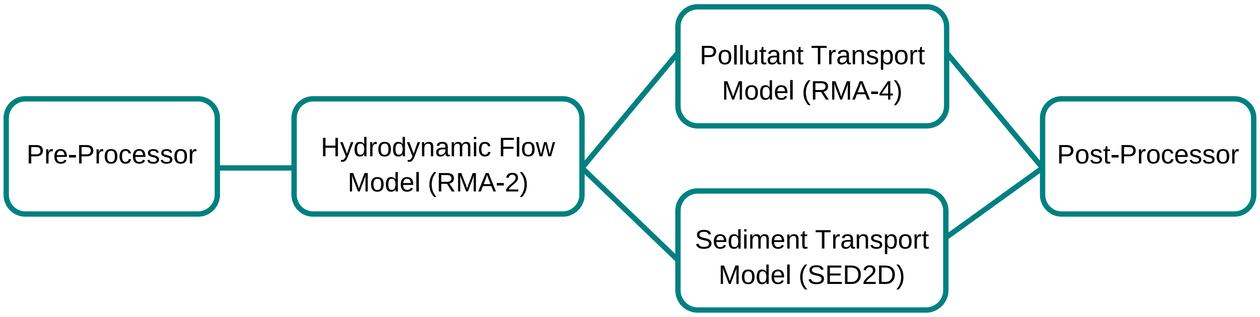

Figure 2-1: TABS2 Schematic

The hydrodynamic model simulates 2D flow in rivers and estuaries by solving the depth-averaged Navier Stokes equations for flow velocity and water depth. The equations account for friction losses, eddy viscosity, Coriolis forces and surface wind stresses. The general governing equations are:

$$h\frac{\partial u}{\partial t}+uh\frac{\partial u}{\partial x}+vh\frac{\partial u}{\partial y}+gh\frac{\partial a}{\partial x}+gh\frac{\partial h}{\partial x}-h\frac{\varepsilon_{xx}}{\rho}\frac{\partial^2 u}{\partial x^2}-h\frac{\varepsilon_{xy}}{\rho}\frac{\partial^2 u}{\partial y^2}+S_{f_x}+\tau_x=0$$

$$h\frac{\partial v}{\partial t}+uh\frac{\partial v}{\partial x}+vh\frac{\partial v}{\partial y}+gh\frac{\partial a}{\partial y}+gh\frac{\partial h}{\partial y}-h\frac{\varepsilon_{yx}}{\rho}\frac{\partial^2 v}{\partial x^2}-h\frac{\varepsilon_{yy}}{\rho}\frac{\partial^2 v}{\partial y^2}+S_{f_y}+\tau_y=0$$

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0$$

where:

- u,v = x and y velocity components, respectively
- t = time
- h = water depth
- a = bottom elevation
- Sf_x = bottom friction loss term in x-direction
- Sf_y = bottom friction loss term in y-direction
- τ_x = wind and Coriolis stresses in x-direction
- τ_y = wind and Coriolis stresses in y-direction
- ε_{xx} = normal eddy viscosity in the x-direction on x-axis plane
- ε_{xy} = tangential eddy viscosity in the x-direction on y-axis plane
- ε_{yx} = tangential eddy viscosity in the y-direction on x-axis plane
- ε_{yy} = normal eddy viscosity in the y-direction on y-axis plane

Wind stress is computed using the following formula:

$$\tau_S = 3.8\cdot 10^{-6} W^2$$

Where:

τ_s = wind stress (lb/ft^2) on the water surface, and

W = the wind speed in miles per hour at 10 meters (33 feet) above the water surface.

2.2 Model Setup

The setup for the hydrodynamic model included determination of the model area, bathymetry, channel dimensions, mesh selection, and boundary conditions. For this study, a new RMA-2 model was created for this site. The RMA-2 model setup includes all areas of interest and potential tidal influence, and contains the most current topographic and bathymetry data.

The horizontal coordinate system for the modeling work is North American Datum (NAD) 83, California state plan zone 6, and the vertical datum is NGVD 1929, which is equivalent to Mean Sea Level (MSL) at that time. As sea level has risen since 1929, NGVD is lower than existing MSL by approximately 0.44 feet. The NGVD vertical datum was selected to maintain consistency with other lagoon bridge optimization studies. Both horizontal and vertical units are in feet. Table 2-1 shows conversions between different vertical datums based on the 1983 to 2001 tidal epoch for the La Jolla tidal station.

Table 2-1 Datum Convertion Table at La Jolla (Based on 1983-3001 Tidal Epoch)

Description	Elevation	Elevation	Elevation	Elevation
	(ft, MLLW)	(ft, NGVD29)	(ft, MSL)	(ft, NAVD88)
Extreme High Water (11/13/1997)	7.65	5.36	4.92	7.47
Mean Higher High Water (MHHW)	5.33	3.04	2.60	5.15
Mean High Water (MHW)	4.60	2.31	1.87	4.42
Mean Tidal Level (MTL)	2.75	0.46	0.02	2.57
Mean Sea Level (MSL)	2.73	0.44	0.00	2.55
National Geodetic Vertical Datum 1929 (NGVD)	2.29	0.00	-0.44	2.11
Mean Low Water (MLW)	0.90	-1.39	-1.83	0.72
North America Vertical Datum 1988 (NAVD)	0.18	-2.11	-2.55	0.00
Mean Lower Low Water (MLLW)	0.00	-2.29	-2.73	-0.18
Extreme Low Water (12/17/33)	-2.87	-5.16	-5.60	-3.05

2.2.1 Model Area

The numerical model covers the nearshore ocean and the area below the +10 foot NGVD contour line of the site, as shown in Figure 2-2. The ocean boundary is approximately 1.5 miles offshore from the shoreline and the inlet location.

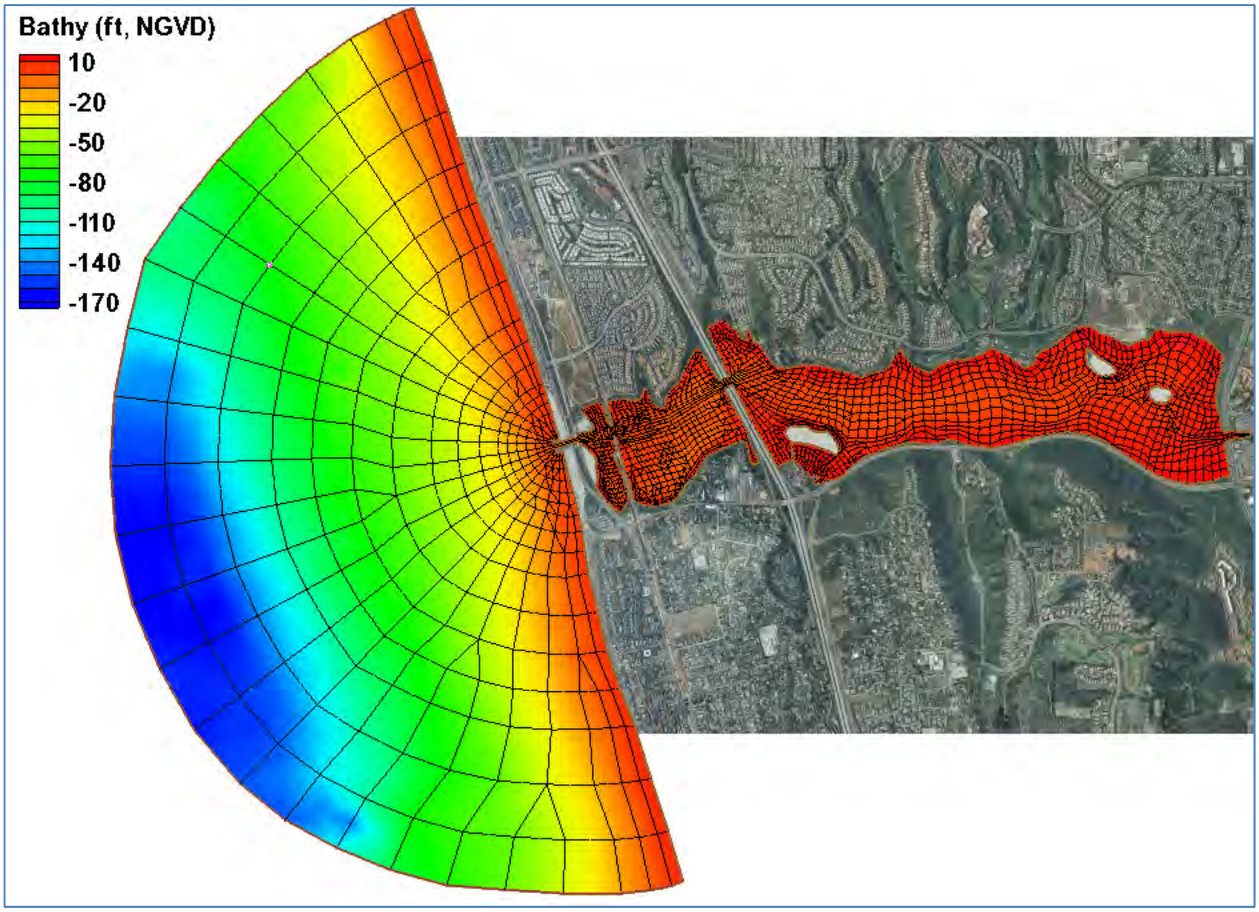

Figure 2-2: RMA-2 Modeling Area and Grid

2.2.2 Bathymetry

The ocean bathymetry used in the model is downloaded from the National Oceanic and Atmospheric Administration (NOAA) website (2005);it was originally compiled by the Pacific Marine Environmental Laboratory Center of NOAA for Tsunami Inundation Mapping Efforts. The bathymetry of the lagoon area for the existing shoaled condition was based on a GIS shape file provided by WRA, Inc. (2010). The GIS shapefile was based on three data sources: 1) a 2008 lagoon bathymetry survey (Merkel & Associates 2009) for areas below Mean High Water (MHW); 2) point elevations collected by WRA, Inc. (2010) with an Auto Level and a hand held Trimble GPS unit for a 2-foot elevation band above the MHW for the East basin, and 3) a topographic survey file provided by City of Carlsbad (provided by Caltrans through WRA in 2011). Figure 2-3 shows the modeling grid and existing bathymetry of the lagoon. The channel width under each bridge crossing was narrowed to account for flow constriction by bridge piers/columns together with growth of marine organisms.

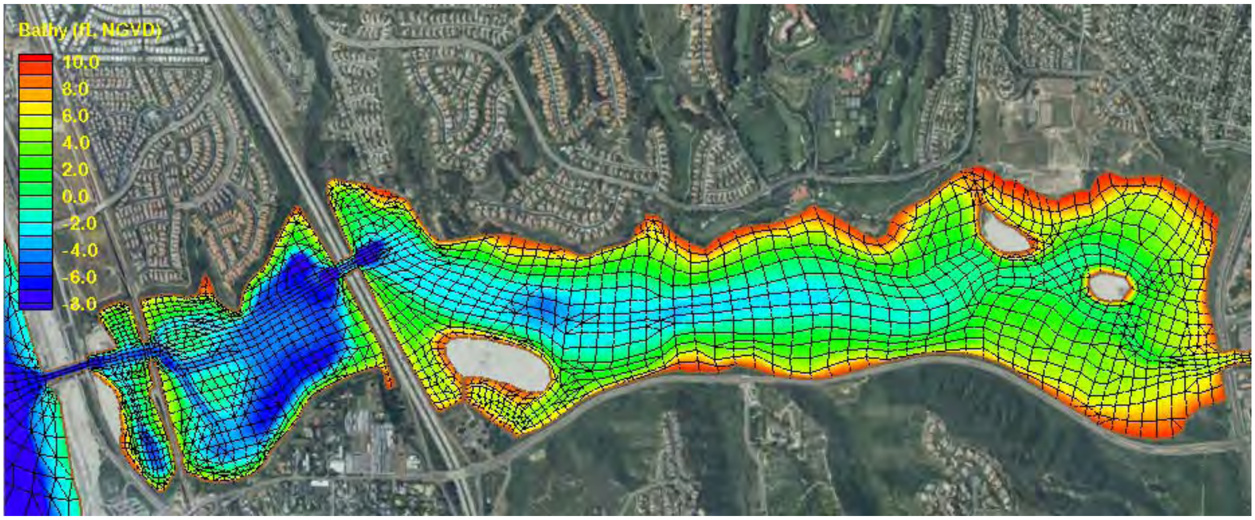

Figure 2-3: Modeling Grid and Bathymetry of the Existing Shoaled Lagoon

2.2.3 Finite Element Mesh

The RMA-2 modeling system requires that the estuarial system be represented by a network of nodal points and elements, points defined by coordinates in the horizontal plane and water depth, and areas made up by connecting these adjacent points, respectively. Nodes can be connected to form 1- and 2D elements, having from two to four nodes. The resulting nodal/element network is commonly called a finite element mesh and provides a computerized representation of the estuarial geometry and bathymetry.

It is noted that evaluations discussed herein correspond to 2D analyses. The two important aspects to consider when designing a finite element mesh are: (1) determining the level of detail necessary to adequately represent the estuary; and (2) determining the extent or coverage of the mesh. Accordingly, the bathymetric features of the estuary generally dictate the level of detail appropriate for each mesh. These concerns present trade-offs for the modeler to consider. Too much detail can lead the model to run slowly or even become unstable and "crash." Too little detail renders the results less useful. For this project, a balance was achieved with a stable and efficient model that yields the level of detail required for the study. The model described in this section is numerically robust and capable of simulating tidal elevations, flows, and constituent transport with reasonable resolution.

There are several factors used to decide the aerial extent of each mesh. First, it is desirable to extend mesh open boundaries to areas which are sufficiently distant from the proposed areas of change so as to be unaffected by that change. Additionally, mesh boundaries must be located along sections where conditions can reasonably be measured and described to the model. Finally, mesh boundaries can be extended to an area where conditions have been previously collected to eliminate the need to interpolate between the boundary conditions from other locations.

The same finite element mesh is used for both the dredged and shoaled lagoon scenarios, but the bathymetry differs between the two conditions. The bathymetry for the shoaled existing condition is shown in Figure 2-3, and that for the dredged lagoon condition described in Section 1.2 is shown in Figure 2-4. The mesh contains an area of ocean sufficiently large to eliminate potential model boundary effects. The wetland portion of the mesh is bounded by the ocean and dry land is considered to be at the outermost extents of tidal influence. The entire modeling area, approximately 5.43 square miles, is represented as a finite element mesh consisting of 2,950 elements and 8,530 nodes.

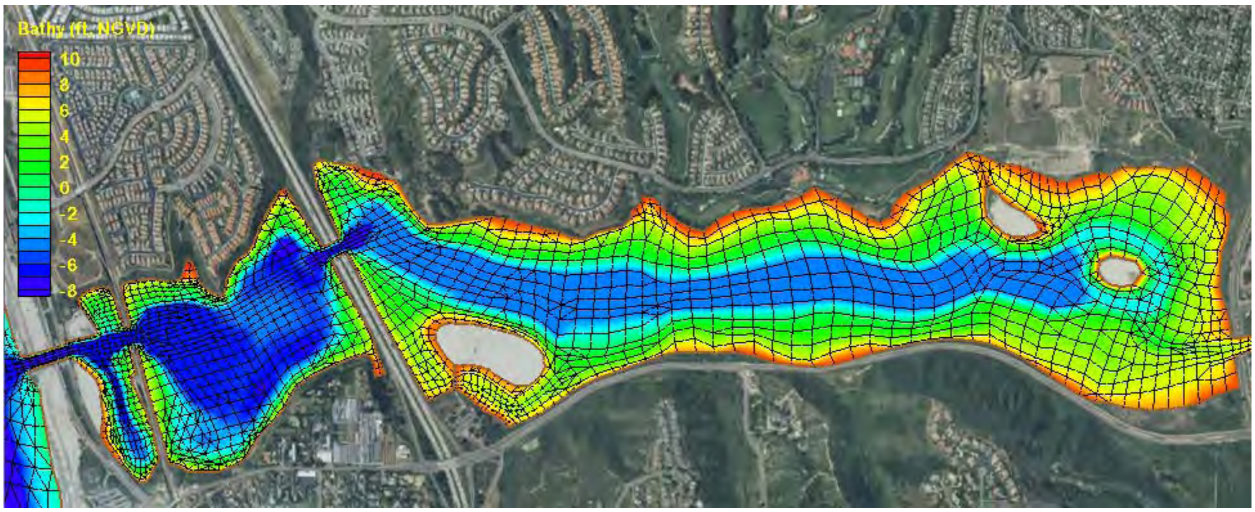

Figure 2-4: Bathymetry of the Dredged Lagoon

2.2.4 Boundary Conditions

Boundary conditions consist of the ocean driving tide and stormflows, both described below.

2.2.4.1 Ocean Tides

Since there are no tide stations at Carlsbad, the nearest La Jolla gage (NOAA Station ID: 9410230) was used to represent the ocean tide at the project site. As shown in Table 2-2, the diurnal tide range is approximately 5.33 feet MLLW to Mean Higher High Water (MHHW), and MSL is at +2.73 feet MLLW. Water level data records provide astronomical tides and other components including barometric pressure tide, wind setup, seiche, and the El Nino Southern Oscillation. Tidal variations can be resolved into a number of sinusoidal components having discrete periods. The longest significant periods, called tidal epochs, are approximately 19 years. In addition, seasonal variations in MSL can reach amplitudes of 0.5 feet in some areas. Superimposed on this cycle is a 4.4-year variation in the MSL that may increase the amplitude by as much as 0.25 feet. Water level gage records are typically analyzed over a tidal epoch to account for these variations and to obtain statistical water level information (e.g., MLLW and MHHW).

Table 2-2: Recorded Water Levels at La Jolla (1983-2001 Tidal Epoch)

Description	Elevation (feet, MLLW)	Elevation (feet, NGVD)
Extreme High Water (11/13/1997)	7.65	5.35
Mean Higher High Water (MHHW)	5.33	3.03
Mean High Water (MHW)	4.60	2.30
Mean Tidal Level (MTL)	2.75	0.46
Mean Sea Level (MSL)	2.73	0.44
National Geodetic Vertical Datum 1929 (NGVD)	2.30	0.00
Mean Low Water (MLW)	0.91	-1.39
North America Vertical Datum 1988 (NAVD)	0.19	-2.11
Mean Lower Low Water (MLLW)	0.00	-2.30
Extreme Low Water (12/17/33)	-2.87	-5.16

2.2.4.2 TEA Tidal Series

The tide series used for modeling was a representative period from June 7 to 21, 2011. Modeling long-term hydrologic conditions is typically done using a synthetic (artificially created) tide series that represents average spring tide conditions over the most recent 19-year tidal epoch, referred to as a Tidal Epoch Analysis (TEA) tide series. The benefit of using a statistical tide is that the long-term condition can be modeled over a shorter time period with less computation time.

Significant effort (beyond the scope of this study) is required to prepare a new TEA tide for this site. Therefore, a real tide series was used that matched average spring tide data available from National Oceanic and Atmospheric Administration (NOAA 2011).

Not using a statistical TEA tide for modeling does not create a serious information gap. To address this potential shortcoming, the modeler evaluated existing tide data from NOAA for San Diego at Scripps Pier (NOAA 2011). NOAA began publishing spring high and spring low tidal elevations of all tidal cycles in January of 2008. The modeler averaged the spring high and spring low tidal elevations of all tidal cycles from January of 2008 through July of 2011 (42 months), then examined the existing data to identify a real two-week tidal cycle that matched them. Tides during the period of June 7 through June 21, 2011 reached nearly the exact same spring high and spring low tidal elevations of NOAA’s longer 42-month record. Also, the average tidal elevation of that June 7 through June 21, 2011 period compared with the average tidal elevation of the 19-year tidal epoch and was within 0.01 foot. Therefore, the modeler concluded that tides during the period of June 7 through June 21, 2011 sufficiently matched long-term tides at the site, and use of this record poses no implications for analyses. The modeling tide includes both spring and neap tidal ranges, as shown in Figure 2-5.

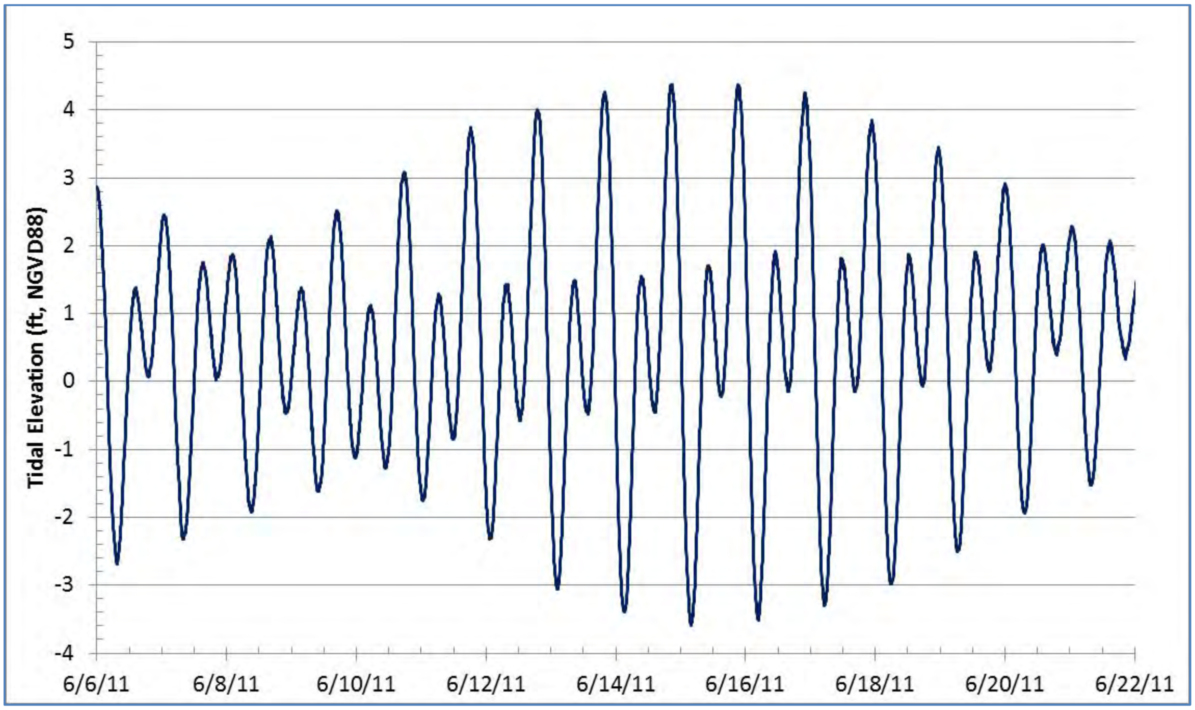

Figure 2-5: TEA Modeling Tidal Series

2.2.4.3 Flood Hydrographs

The watershed of Batiquitos Lagoon encompasses 52.3 square miles. The primary stream that drains into Batiquitos Lagoon is San Marcos Creek which begins in the mountains east of the lagoon and drains much of the watershed. A dam impounds San Marcos Creek about 5 miles upstream from its confluence with the lagoon and creates Lake San Marcos. The other primary stream in the watershed is Encinitas Creek which drains Green Valley and the Olivenhain Road area. Several other small creeks drain into the lagoon from its north and south shores. The 100-year and 50-year peak stormflow rates for San Marcos Creek are 12,050 and 6,707 cfs, respectively; and those for Encinitas Creek are 4,520 and 2,511 cfs, respectively (M&N, 1990). The hydrographs shown in Figure 2-6 and Figure 2-7 were based on the equations cited in Flood Plain Information (USACE 1971) and the Batiquitos Lagoon Watershed Sediment Control Plan prepared by the California State Coastal Conservancy (CSCC 1987).

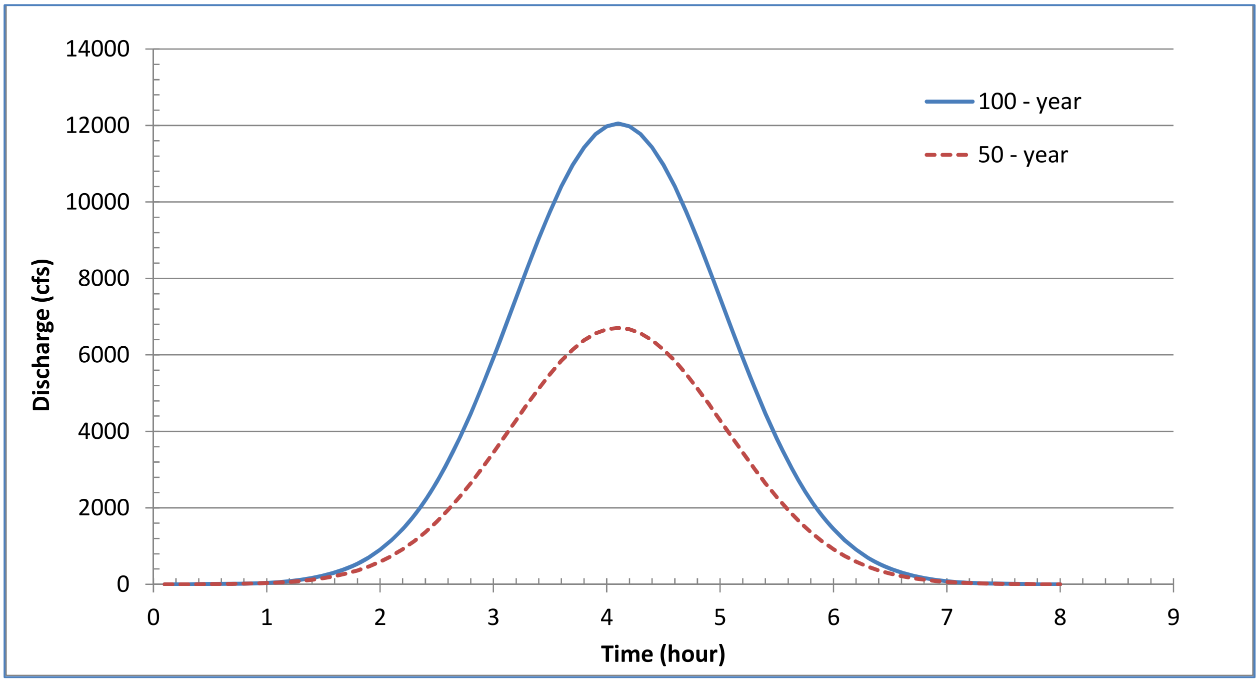

Figure 2-6: 100-Year and 50-Year Hydrographs for San Marcos Creek

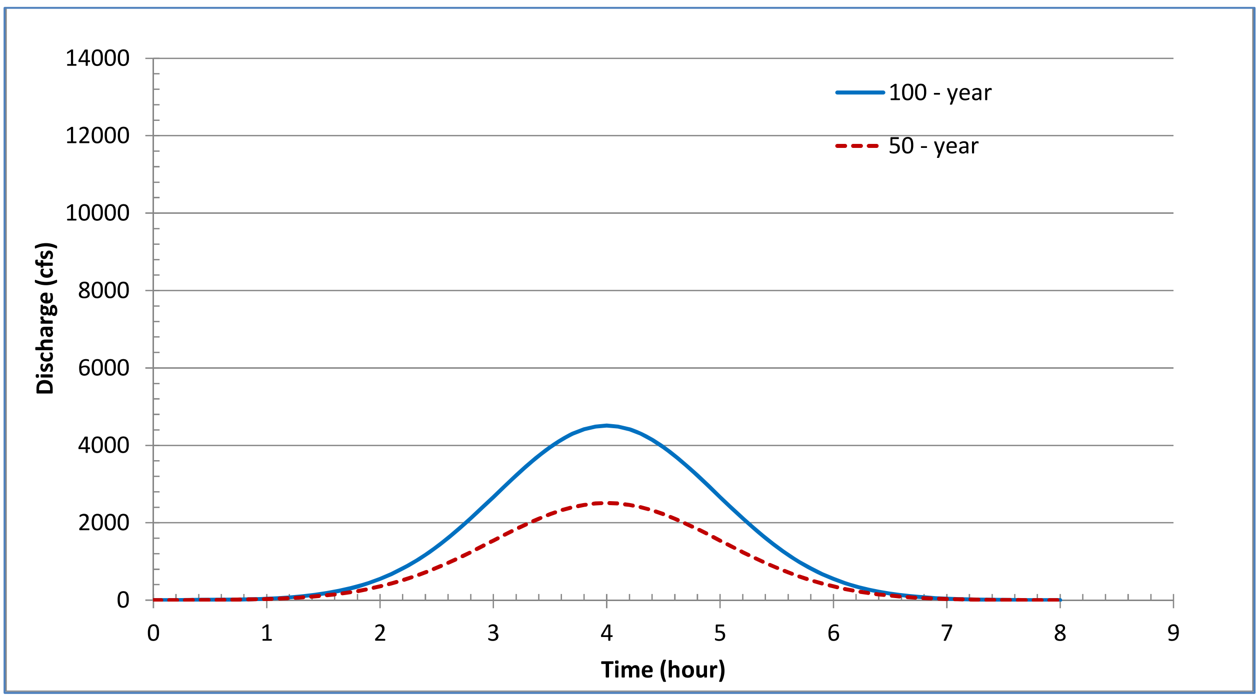

Figure 2-7: 100-Year and 50-Year Hydrographs for Encinitas Creek

2.3 RMA-2 Model Calibration and Verification

RMA-2 calibration involves matching model predictions with measured data by selecting appropriate variable input values (e.g., Manning's roughness coefficient - n, peclet numbers, and marsh porosity) to the model. A two-week period of measured tidal elevations in the lagoon that occurred very close in time period to the date of the lagoon bathymetry survey was selected for model calibration and verification. Tidal elevations were recorded by Merkel & Associates, Inc. (2009) at three gage locations shown in Figure 2-8. The two-week period covers both spring and neap tidal cycles. Instead of running the RMA-2 model separately for the spring and neap tidal cycles, the model was run continuously over the two-week period. Results for the first week served as model calibration and the second week results served as model verification.

Figure 2-8: Gage Locations with Recorded Tides and for Model Calibration

The tidal series used as the offshore model boundary input over the model calibration period was downloaded from the nearest La Jolla tide gage (NOAA Station ID: 9410230) as discussed in Section 2.2.4.1.

2.3.1 Model Setup for Calibration

The RMA-2 User's Manual recommends ranges of values for Manning's roughness coefficient (n) and eddy viscosity to be used in the model (USACE 2009). The value of Manning's roughness coefficient (n) is a function of the physics of the hydraulic system and represents the roughness of the channel bed. As discussed in Chaudhry (1993), values can range from 0.011 to 0.075 or higher for natural rivers and estuaries. Relatively high values (0.04 to 0.05) are specified for rough surfaces, such as channels with cobbles or large boulders. Mid-range values (0.03) represent clean and straight natural streams. Low values (0.013 to 0.02) are specified for smooth surfaces, such as concrete, cement, wood, or gunite. The depth dependent method is used in assigning the Manning's roughness coefficient (n) for this analysis. The roughness coefficient is higher in areas with shallow water depths and lower for areas with deeper water.

The modeling grid size depends on and is limited by the Peclet number and eddy viscosity. The Peclet number is defined as,

$$\frac{\rho V \Delta X}{E_{ij}}$$

in which ρ, V, ΔX, and E_{ij} are the water density, velocity, grid size and eddy viscosity, respectively. In order for the solution to be stable, the Peclet number has to be less than 50. The Peclet number can be reduced by increasing the mesh density or by increasing the eddy viscosity. However, it is unrealistic and time-consuming to perform this modeling with a very fine grid. Eddy viscosity is another variable often specified in modeling. It represents the degree of turbulence in the flow. A higher value represents greater turbulence, while a low value suggests less turbulence. The modeling approach can either be based on use of the Peclet number or eddy viscosity. This modeling was based on specifying the Peclet number to maximize model stability and to minimize "crashing." Peclet numbers were adjusted until model results approximated field measurements. The resulting Peclet numbers for various areas are presented in Table 2-3.

Table 2-3: Setup Values For Model Calibration

Model Area	Peclet Number
Offshore Area	20
Nearshore Area	5
Tidal Inlet and Main Channels	5
Secondary Channels	5
Low Marsh	2
High Marsh	1
Lower Riparian Area	0.8
High Riparian Area	0.5

The time step is another important parameter in the modeling. Sensitivity tests were conducted and results showed that the RMA-2 model becomes unstable with increasing time steps, if tidal wetting and drying processes are considered in the model. Therefore, a relatively fine time step of 0.1 hour was used in order for the solution to be stable and to reflect the dynamic tidal series and flood flow hydrograph.

2.3.2 *Calibration and Verification Results*

Model calibration and verification were done over a two-week period for each basin from July 3 to 19, 2008. The first week of the model run serves as the model calibration and the second week of the model run serves as the model verification. Model predictions of tidal elevations were compared to measured tides at all three gage locations shown in Figure 2-8. The results are shown in Figure 2-9 through Figure 2-11. Tidal elevations simulated by the model correspond reasonably well with those measured in the field both in terms of tidal phase (timing) and range (elevation) for gages located in all three basins. The ocean tide is also included in the figures as reference. The tidal elevation differences between the ocean and those recorded in the lagoon especially during the low tide indicate tidal muting in the lagoon. The calibration and verification results indicate that the model can reasonably replicate (predict) the existing tidal conditions in all three basins of the lagoon as compared with measured values, and is, therefore, suitable for bridge optimization simulations for this study.

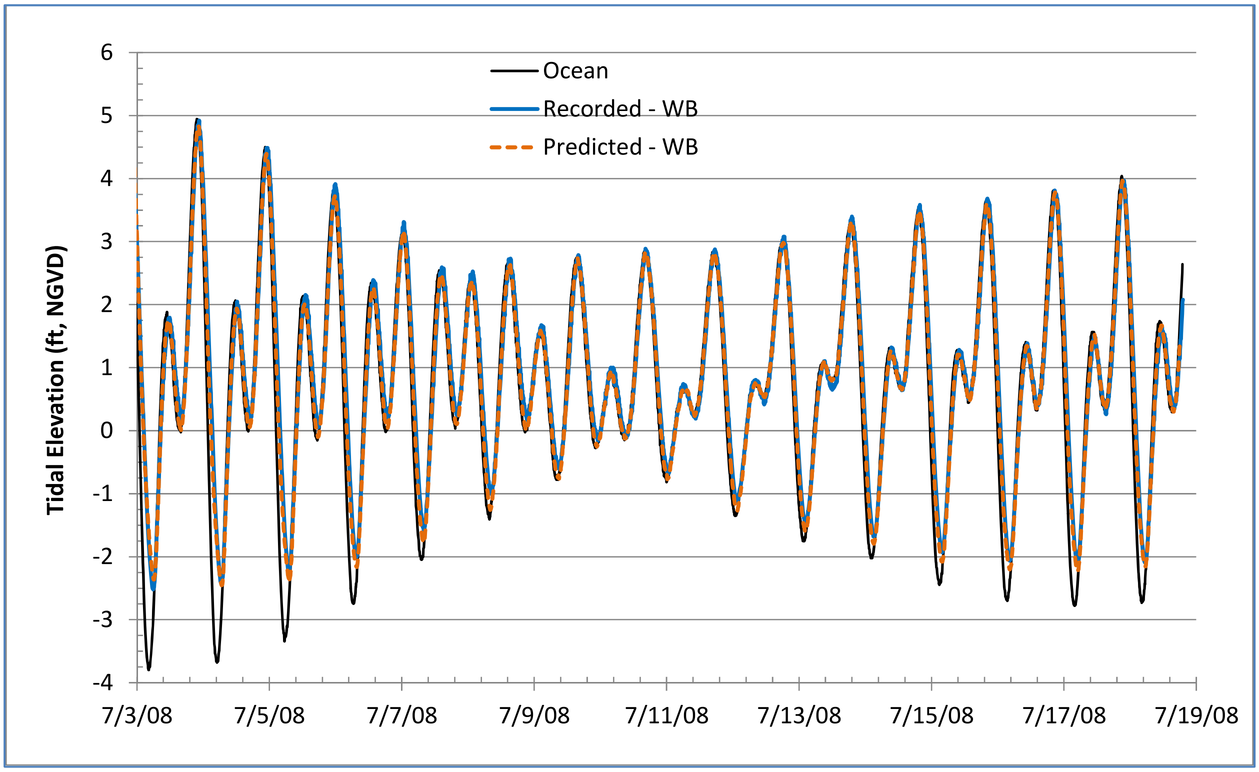

Figure 2-9: RMA-2 Model Calibration and Verification Results in the West Basin

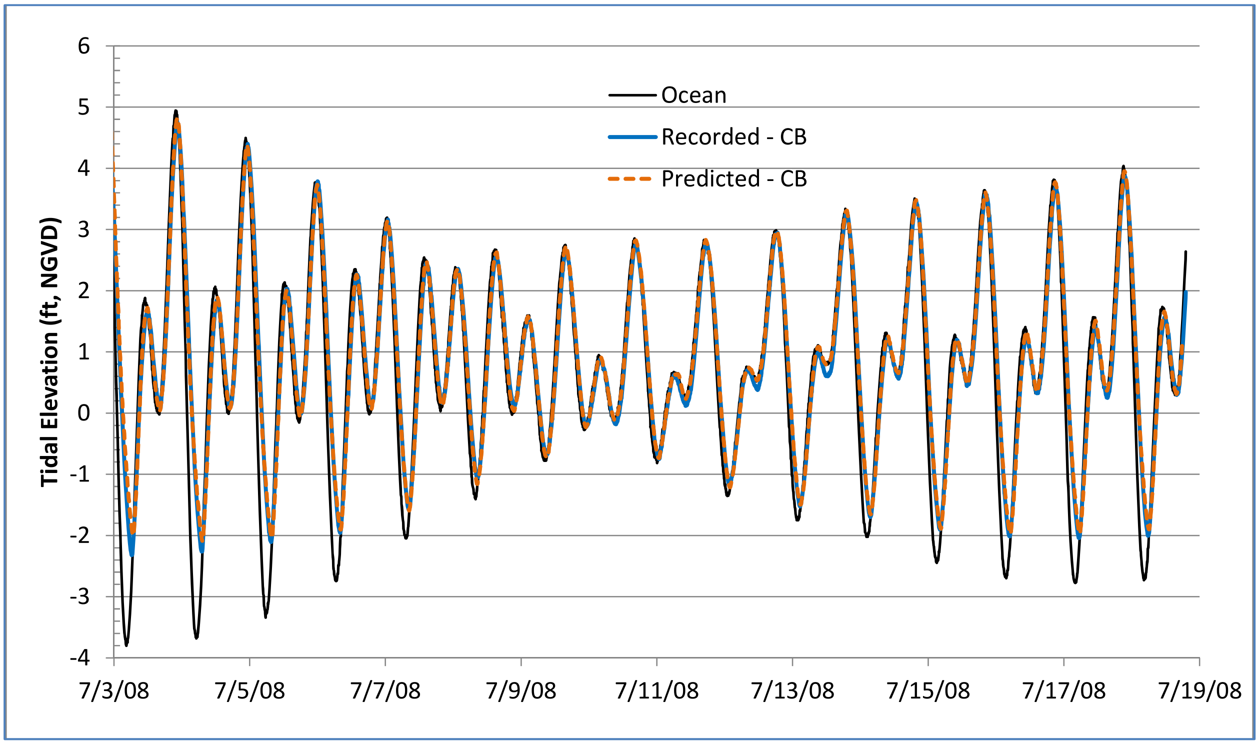

Figure 2-10: RMA-2 Model Calibration and Verification Results in the Central Basin

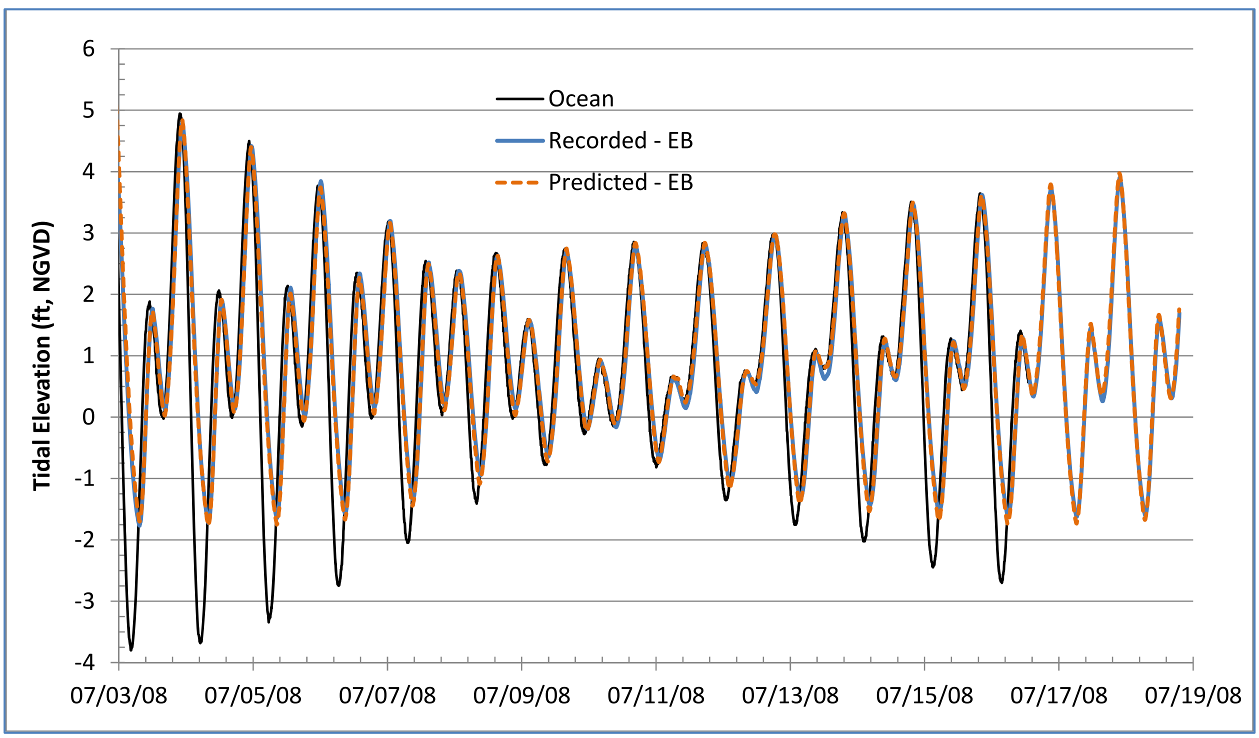

Figure 2-11: RMA-2 Model Calibration and Verification Results in the East Basin

3.0 ANALYSES TO ACHIEVE OPTIMAL TIDAL RANGE

The modeling parameters of roughness coefficients and Peclet numbers determined in model calibration and verification were assigned for the hydrodynamic modeling of Batiquitos Lagoon for both the shoaled and dredged lagoon bathymetry conditions. The two lagoon bathymetry conditions were described in Section 1.2.

The goal of this hydrodynamic modeling section is to determine the channel width and depth under the RR and I-5 Bridges required to achieve the optimal tidal range in both the Central and East Basins. The benefit of a larger tidal range is that it can support a broader vertical range of intertidal habitats.

The spring high tide has the largest tidal range and would experience the worst tidal muting if muting were to occur. Therefore, the spring high tidal series shown in Figure 3-1 is applied at the model offshore boundary in the tidal range optimization modeling. No storm flood flows were applied to the tidal modeling effort. Dry weather base flow has a negligible effect on the tidal range.

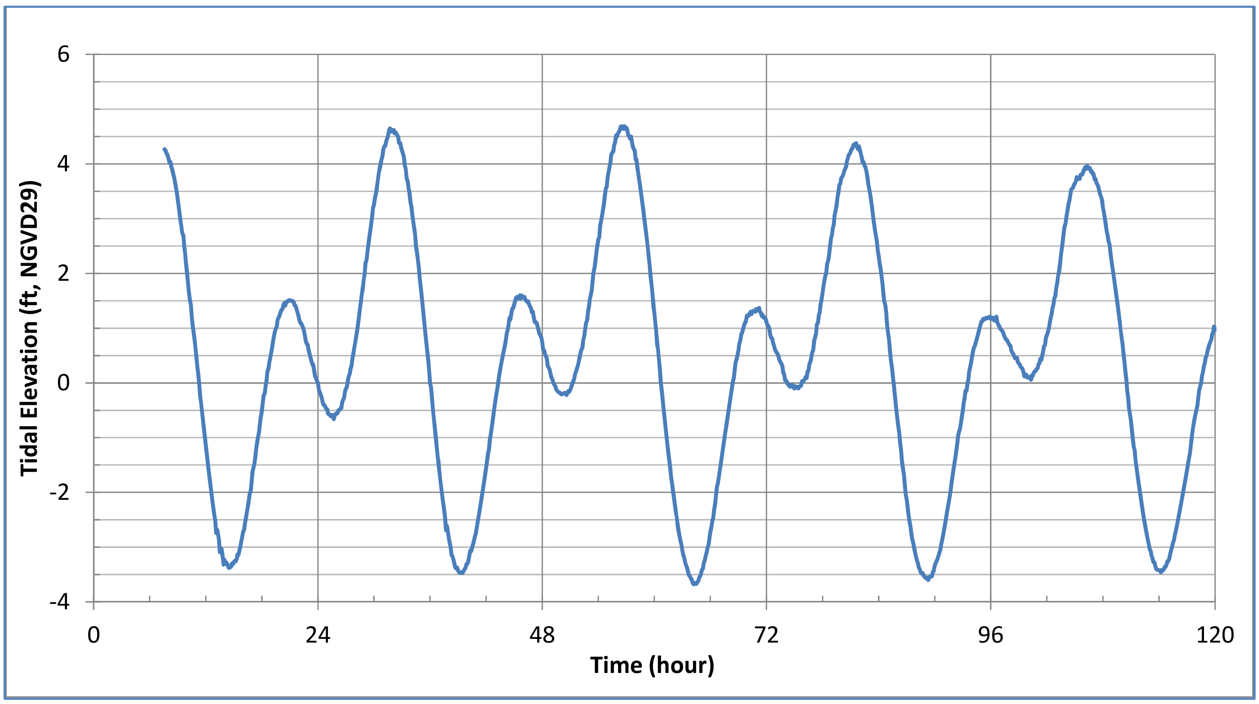

Figure 3-1: Spring High Tide Series for Tidal Optimization Modeling

A series of numerical modeling runs were performed to optimize channel dimensions under both RR and I-5 Bridges. The modeling approach was to begin upstream and work downstream. First, the channel dimensions under I-5 Bridge were optimized while artificially specifying that the channel under the RR Bridge as large enough to not pose a hydraulic constraint. Next, the channel dimensions under the RR Bridge were optimized with an artificially large channel cross-section under the I-5 Bridge. Then the model runs of nine combinations of different channel widths under the RR and I-5 Bridges were performed to determine the optimal channel dimensions. Figure 3-2 shows locations where tidal ranges were calculated from the RMA-2 modeling results for comparison.

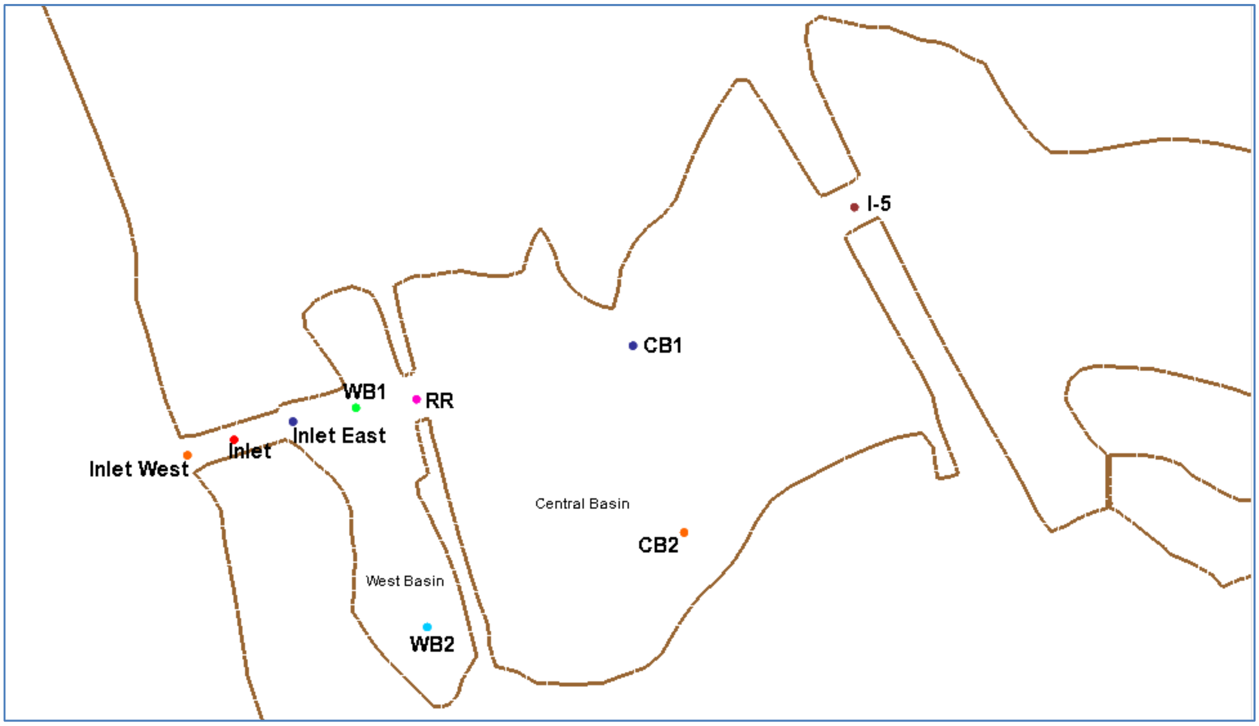

Figure 3-2: Virtual Gage Locations for Tidal Range Comparison

Table 3-1 shows tidal ranges from the ocean to the East Basin for existing conditions (assumed as post-construction or dredged) and the optimized bridge condition. An optimized channel width of 202 feet is specified under the RR Bridge and an optimized width of 134 feet is specified under the I-5 Bridge. The results indicate:

- Tides are muted through the relatively long and narrow tidal inlet, and the tidal range decreases from 8.37 feet in the ocean to 7.29 feet for the existing (post-construction dredged) condition and to 7.42 feet in the West Basin for the optimized condition.
- The tidal range at gage location WB1 is the same as that at WB2, and there is no muting from WB1 to WB2. Therefore, the tidal range may not vary throughout the Basin and gages WB1 and WB2 are representative of the West Basin.
- The tidal range at CB1 is the same as that at CB2. The tidal range may not vary throughout the Basin and gages CB1 and CB2 are representative of the Central Basin.
- The tidal range at EB1 shown in Figure 3-3 is slightly different from that at EB2. Therefore, the tidal range may vary throughout the Basin and results at both gages are calculated and reported.

Table 3-1: Comparison of Tidal Ranges (ft) in Each Basin

Bridge Condition	Ocean	Inlet West	Inlet	Inlet East	WB1	WB2	RR	CB1	CB2	I-5	EB1	EB2
Existing	8.37	8.31	7.78	7.41	7.29	7.29	7.26	7.23	7.23	7.17	7.12	7.14
Optimized	8.37	8.32	7.83	7.51	7.42	7.42	7.41	7.4	7.4	7.4	7.35	7.38

Figure 3-3: Virtual Gage Locations for Tidal Range Calculations

3.1 I-5 Channel Dimensions Optimization Results

An over-sized channel with a width of 600 feet and a depth of 7 feet was assumed under the RR Bridge for optimizing the channel dimensions under the I-5 Bridge. A lagoon with a larger tidal prism will typically experience more tidal muting than a lagoon with a smaller tidal prism if both lagoons have an identical tidal inlet that limits tidal exchange (as is the case at Batiquitos Lagoon). Therefore, the dredged lagoon bathymetry condition was modeled since the lagoon storage or tidal prism is bigger under the dredged condition than that under the shoaled condition with the same tidal inlet. Figure 3-4 shows the model predicted tidal ranges with various channel widths under the I-5 Bridge, while the lagoon condition and other bridge dimensions are kept the same. Figure 3-5 shows the model predicted tidal ranges with various channel invert elevations under the I-5 Bridge, while all other parameters are held constant including the channel width under the I-5 Bridge. The results indicate the existing channel invert elevation of -7 feet under the dredged condition is appropriate.

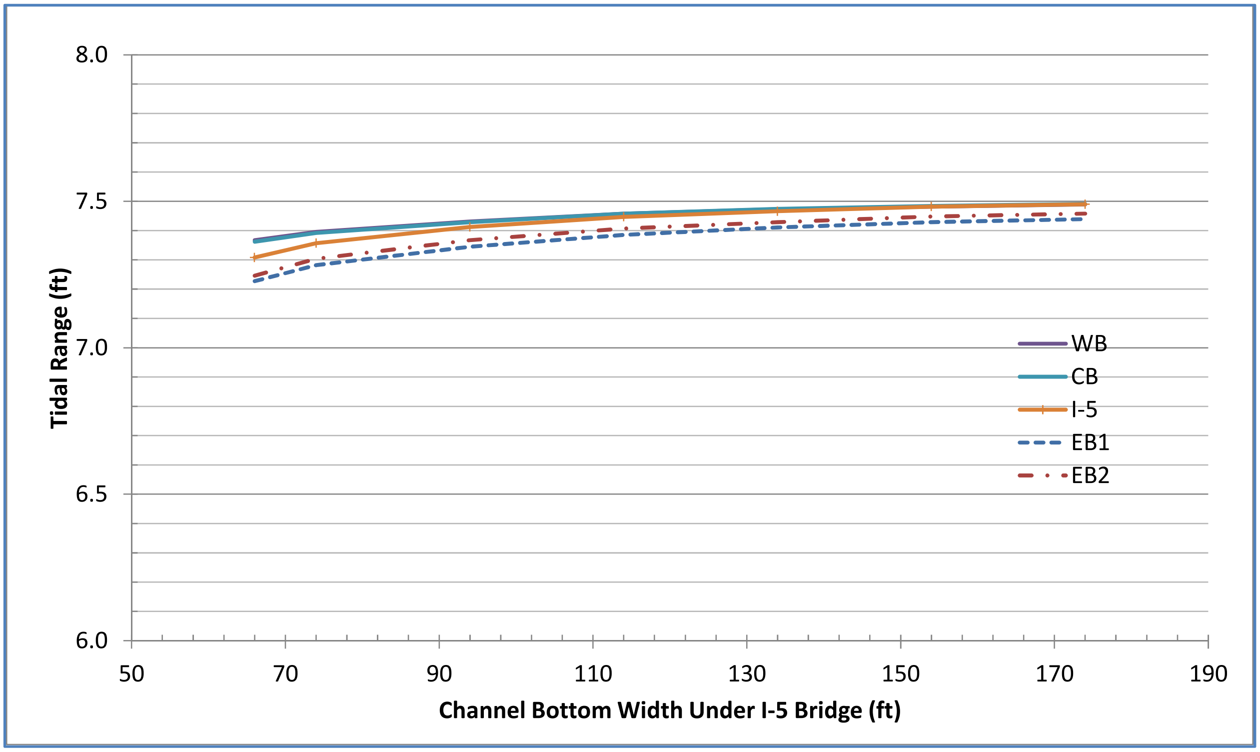

Figure 3-4: I-5 Optimization Results with Different Channel Widths

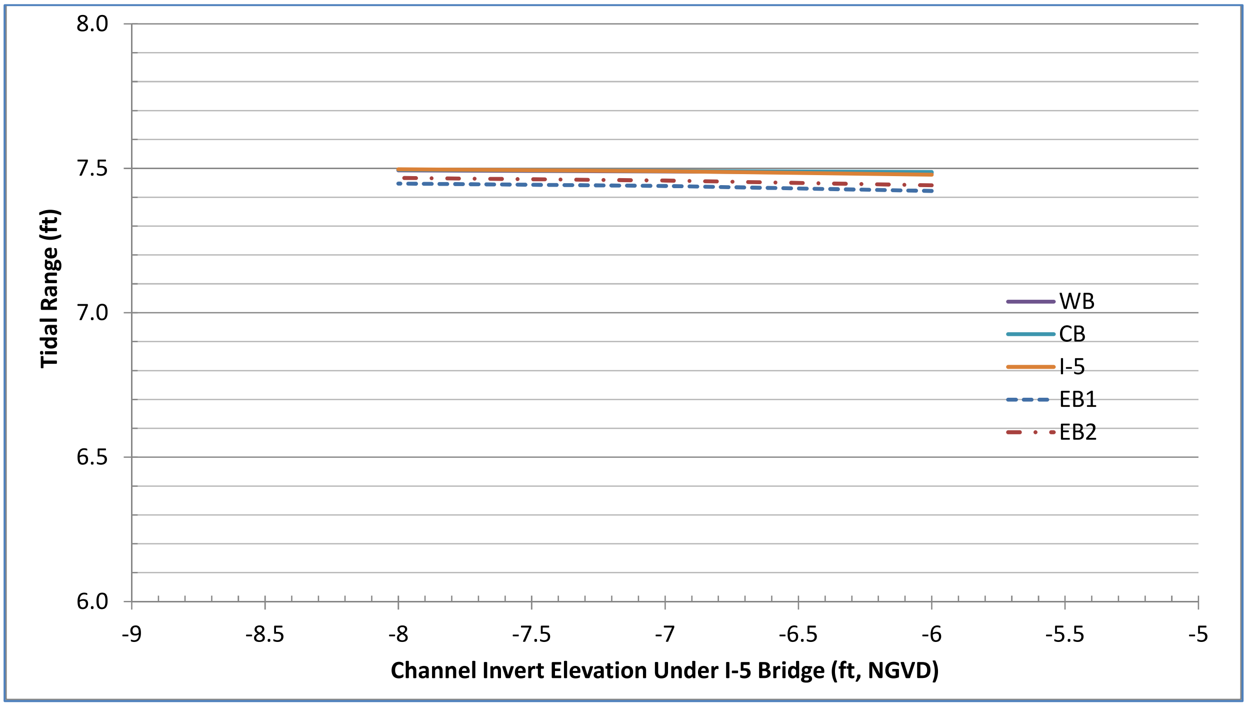

Figure 3-5: I-5 Optimization Results with Different Channel Depths

Table 3-2 summarizes the results of all dimension optimization modeling of the channel under the I-5 Bridge. The yellow highlighted row shows the tidal range under the existing baseline condition with a shoaled lagoon and channels under the bridges. The second row shows the result under the dredged condition of the existing lagoon and channels under the bridges. Dredging would increase the tidal range by approximately 0.4 feet in the Central Basin and 0.7 feet in the East Basin. Increasing the width of the channel has some benefit, but the benefit diminishes if the width is increased beyond 134 feet.

Table 3-2: Summary of I-5 Optimization Results

Run Description	I-5 Dimensions (ft)		Tidal Range (ft)							
	Width	Invert	Ocean	Inlet	WB	RR	CB	I-5	EB1	EB2
Existing shoaled condition	**66**	**-5.3**	**8.37**	**7.75**	**4.59**	**6.96**	**6.79**	**6.73**	**6.47**	**6.48**
Existing dredged condition	66	-7	8.37	7.78	7.29	7.26	7.23	7.17	7.12	7.14
RR Longer, I-5 Existing	66	-7	8.37	7.81	7.37	7.36	7.36	7.31	7.23	7.25
RR Longer, I-5 8 ft longer	74	-7	8.37	7.82	7.40	7.39	7.39	7.36	7.28	7.30
RR Longer, I-5 20 ft longer	94	-7	8.37	7.83	7.43	7.43	7.43	7.41	7.35	7.37
RR Longer, I-5 40 ft longer	114	-7	8.37	7.85	7.46	7.46	7.46	7.45	7.39	7.41
RR Longer, I-5 60 ft longer	134	-7	8.37	7.85	7.47	7.47	7.47	7.47	7.41	7.43
RR Longer, I-5 80 ft longer	154	-7	8.37	7.86	7.48	7.48	7.48	7.48	7.43	7.45
RR Longer, I-5 100 ft longer	174	-7	8.37	7.86	7.49	7.49	7.49	7.49	7.44	7.46
RR Longer, I-5 100 ft longer	174	-6	8.37	7.86	7.48	7.48	7.49	7.48	7.42	7.44
RR Longer, I-5 100 ft longer	174	-7	8.37	7.86	7.49	7.49	7.49	7.49	7.44	7.46
RR Longer, I-5 100 ft longer	174	-8	8.37	7.86	7.49	7.49	7.50	7.50	7.45	7.47

3.2 RR Dimensions Optimization Results

An over-sized channel with a width approximately 174 feet and a depth of 7 feet under the I-5 Bridge were assumed in optimizing the channel dimensions under the RR Bridge. The dredged lagoon bathymetry condition was modeled since the tidal prism is larger and will experience more muting due to tidal prism under the dredged condition than the shoaled condition. Figure 3-6 shows the model-predicted tidal ranges with various channel widths under the RR Bridge while the lagoon condition and other bridge dimensions are held constant. There is a relatively significant gain in the tidal range when the channel width increases from the existing 162 feet to 202 feet; however, the gain in tidal prism diminishes with furthering widening of the channel.

Figure 3-7 shows the model-predicted tidal ranges with various channel invert elevations under the RR Bridge while all other parameters are held constant, including the width of the channel under the RR Bridge. The results indicate the existing channel with an invert elevation of -7 feet under the dredged condition is appropriate. Further deepening of the channel invert does not provide much additional benefit.

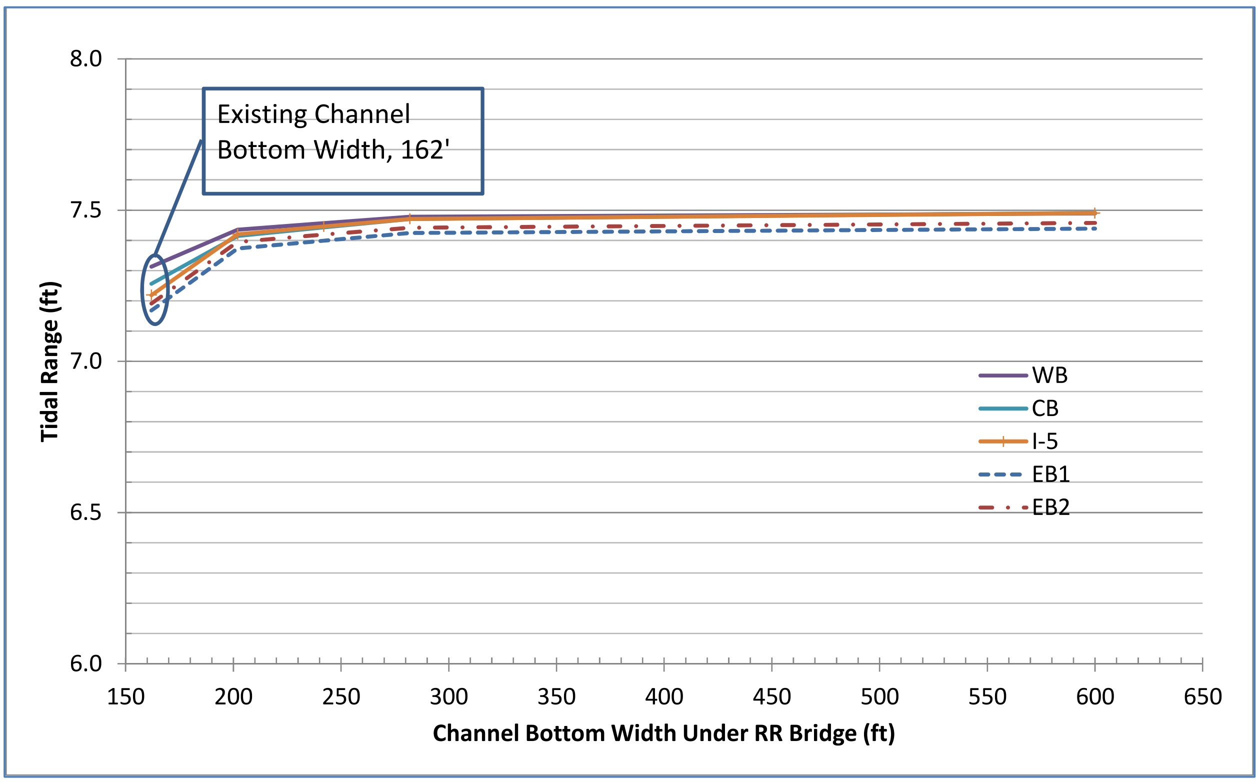

Figure 3-6: RR Optimization Results with Different Channel Widths

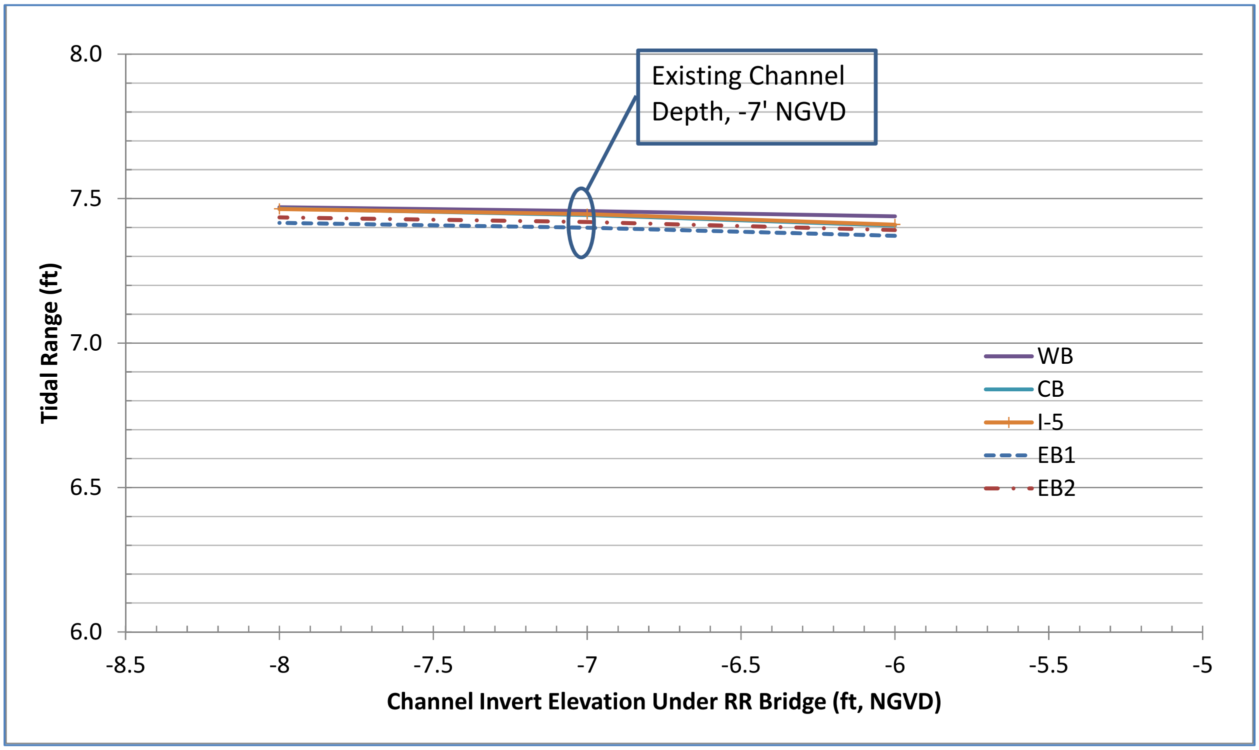

Figure 3-7: RR Optimization Results with Different Channel Invert Elevations

Table 3-3 summarizes the results of optimization modeling of the channel under the RR Bridge. The yellow highlighted row shows the tidal range under the existing baseline condition with a shoaled lagoon and channels under the bridges. The second row shows the result under the dredged condition of the existing lagoon and channels under the bridges. Dredging would increase the tidal range by approximately 0.5 feet in the Central Basin and 0.7 feet in the East Basin. Increasing the width of the channel has some benefit, but the benefit diminishes if the width is increased beyond 202 feet. The lower part of the table shows tidal ranges under different channel invert depths. The results indicate that modifying channel depths does not significantly increase tidal range and the current design invert elevation of -7 feet NGVD is appropriate.

Table 3-3: Summary of RR Optimization Results

Run Description	RR Dimensions (ft)		Tidal Range (ft)							
	Invert (NGVD)	Width	Ocean	Inlet	WB2	RR	CB2	I-5	EB1	EB2
Existing shoaled condition	**-6.35**	**162**	**8.37**	**7.75**	**7.15**	**6.96**	**6.80**	**6.73**	**6.47**	**6.48**
Existing dredged condition	-7	162	8.37	7.78	7.29	7.26	7.23	7.17	7.12	7.14
RR 40 ft Longer	-7	202	8.37	7.85	7.44	7.43	7.41	7.42	7.37	7.40
RR 80 ft Longer	-7	242	8.37	7.86	7.46	7.45	7.44	7.45	7.40	7.42
RR 120 ft Longer	-7	282	8.37	7.86	7.48	7.47	7.47	7.47	7.42	7.44
I-5 100 ft longer	-7	600	8.37	7.86	7.49	7.49	7.49	7.49	7.44	7.46
RR 80 ft Longer	-6	242	8.37	7.86	7.44	7.43	7.41	7.41	7.37	7.39
RR 80 ft Longer	-7	242	8.37	7.86	7.46	7.45	7.44	7.45	7.40	7.42
RR 80 ft Longer	-8	242	8.37	7.86	7.47	7.47	7.47	7.46	7.42	7.44

3.3 Results of Combined I-5 and RR Dimensions Optimization

Sections 3.1 and 3.2 presented the optimization results of one bridge at a time, while keeping the other bridge dimensions over-sized and constant. This section presents modeling results of a combination of different channel widths under the I-5 and RR Bridges. The modeling results in the previous sections indicate that the channel invert elevation of -7 feet is the optimized elevation. Therefore, the invert elevation of -7 feet is used for all remaining modeling runs.

Table 3-4 shows model-predicted tidal ranges in the Central and East Basins with various channel widths under the I-5 and RR Bridges. The dredged bathymetry condition was used for all modeling runs. Yellow highlighted cells show the tidal range with the existing channel dimensions with the channels dredged. The results indicate the optimal channel width is 134 feet under the I-5 Bridge and 202 feet under the RR Bridge. Green highlighted cells in Table 3-4 show the tidal range with the optimized bridge dimensions. The increase in tidal range is less than 0.05 feet if channels are widened beyond the recommended dimensions of 202 feet under the RR Bridge and 134 feet under the I-5 Bridge. The tidal range increase of 0.05 feet (or 0.6 inches) is insignificant when compared with the ocean tidal range of 8.37 feet.

Table 3-4: Tidal Range (ft) in the Central and East Basins

I-5 Channel Bottom Width (ft)	RR Channel Bottom Width (ft)							
	Central Basin				East Basin			
	162	202	242	282	162	202	242	282
66	***7.23***				***7.14***			
94		7.36	7.39	7.41		7.29	7.32	7.34
134	7.35	7.40	7.43	7.46	7.31	7.35	7.38	7.40
174		7.41	7.44	7.47		7.37	7.4	7.42

4.0 ANALYSES TO ACHIEVE OPTIMAL FLOOD CONVEYANCE

The goal of this hydrodynamic modeling section is to determine the optimal channel width and depth under the RR and I-5 Bridges for lowering the storm flood elevation in the lagoon. As discussed in the previous sections, the tidal inlet under Carlsbad Boulevard Bridges was sized and designed to achieve a stable inlet as part of the Batiquitos Lagoon Restoration Project. The tidal inlet has been performing well since construction in 1995. Therefore, no optimization was performed for the tidal inlet.

The calibrated and verified RMA-2 numerical model was used in predicting flood water surface elevations throughout the lagoon. The average spring high tide elevation is approximately 4.69 feet NGVD and the highest tidal elevation measured in this area is 5.35 feet NGVD. To be consistent with the optimization study of San Elijo Lagoon (M&N 2012), the spring high tidal series was raised vertically up such that the spring high tidal elevation is 7.00 feet. This 7-foot elevation is the FEMA base flood elevation along the shoreline of San Elijo Lagoon and it includes the water level rise due to wave runup. It is a very conservative elevation for the flood conveyance optimization. Using this value would affect the flood water level in the lagoon, but would not affect the optimization results when considering the head loss or the backwater effect through each bridge.

The resulting tidal series is shown in Figure 4-1 and applied at the model offshore boundary for the flood optimization modeling. The elevation of the tidal series would affect the flood water surface elevation in the lagoon, but it would not affect the optimized channel dimensions. The flood hydrographs of San Marcos and Encinitas Creeks discussed in Section 2.2.4.3 were superimposed to form one hydrograph and the resulting hydrograph was applied in the model upstream boundary.

The RMA-2 model is an unsteady hydrodynamic model. Both the offshore tidal boundary (downstream boundary) and the upstream boundary input are time varying. The time when the peak of flood hydrograph is superimposed on top of the high tide is important and affects the modeling result. Therefore, a series of modeling runs were performed by adjusting the phase of the flood hydrograph such that both the spring high tide and the peak of the flood occur simultaneously at the I-5 Bridge.

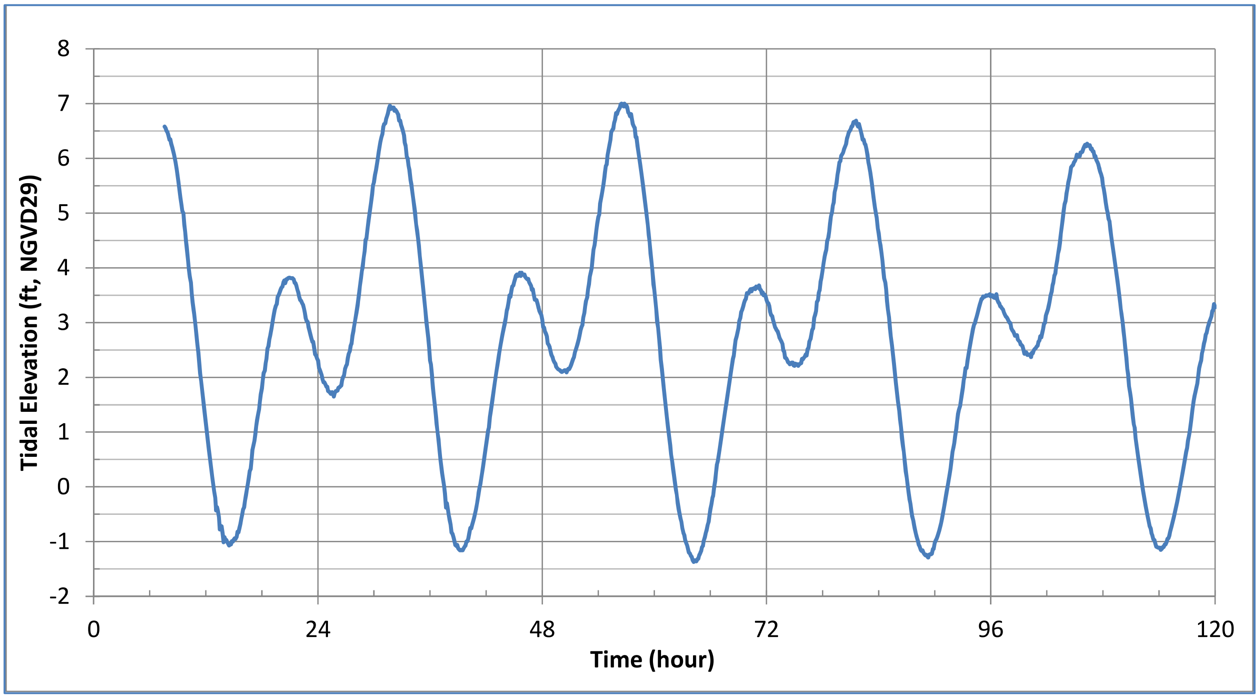

Figure 4-1: Spring High Tidal Series for Flood Optimization Modeling

The RMA-2 model predicts water surface elevation and velocity at every node point of the model grid. Figure 4-2 shows virtual gage locations where the maximum water surface elevation is extracted from the RMA-2 modeling results for plotting the maximum water surface profile. The maximum water surface profile is plotted for each model run. The maximum water surface elevation at different gage locations occurs at different times while the peak of the flood travels throughout the lagoon from east to west. The maximum water surface profile is not an instantaneous profile like those produced by a steady state model run. A steady state model run simplifies natural processes by assuming both the downstream tidal elevation and the flood elevation remain constant. The water surface profile from a steady state model run is an instantaneous profile.

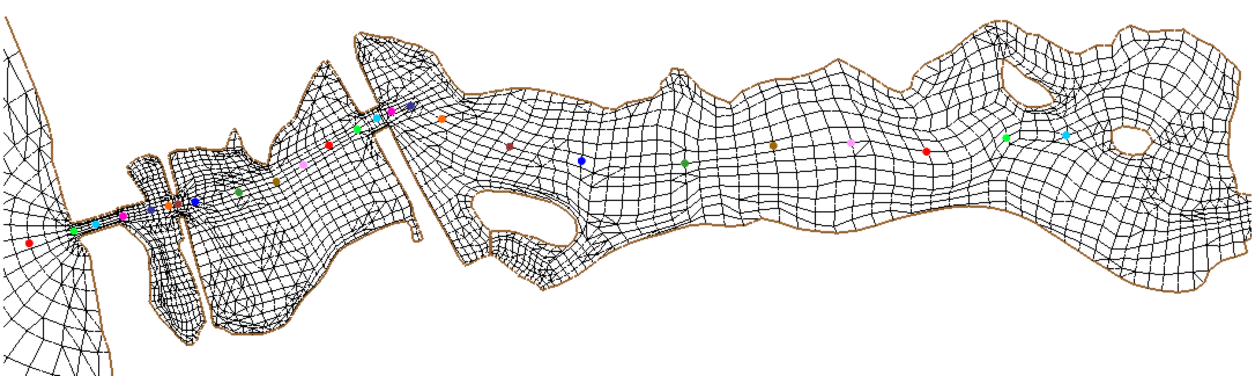

Figure 4-2: Virtual Gage Locations for Plotting Surface Water Profiles

For the channels under the I-5 and RR Bridges to achieve optimal flood conveyance throughout the lagoon, the 100-year stormflow event is modeled with the extreme spring tide. Figure 4-3 compares 100-year water surface profiles under different lagoon and channel conditions. The modeling results indicate that under the existing shoaled condition, the water surface elevation is backed up by approximately 0.8 feet in the East Basin by the I-5 Bridge, by approximately 0.4 feet in the Central Basin by the RR Bridge, and by approximately 0.7 feet in the West Basin by Carlsbad Boulevard Bridges. Clearing sedimentation from the channel under the bridge crossings will reduce the backwater effect at the I-5 and RR Bridges, and lower the water surface elevation in the East Basin, but will increase the water surface elevation in the Central and West Basins. The lagoon sedimentation condition (shoaled or dredged) assumed in the modeling has little effect on the water surface elevation. The water level is slightly lower under the dredged lagoon condition than that under the shoaled lagoon condition. Therefore, the shoaled lagoon condition is modeled for fluvial optimization modeling.

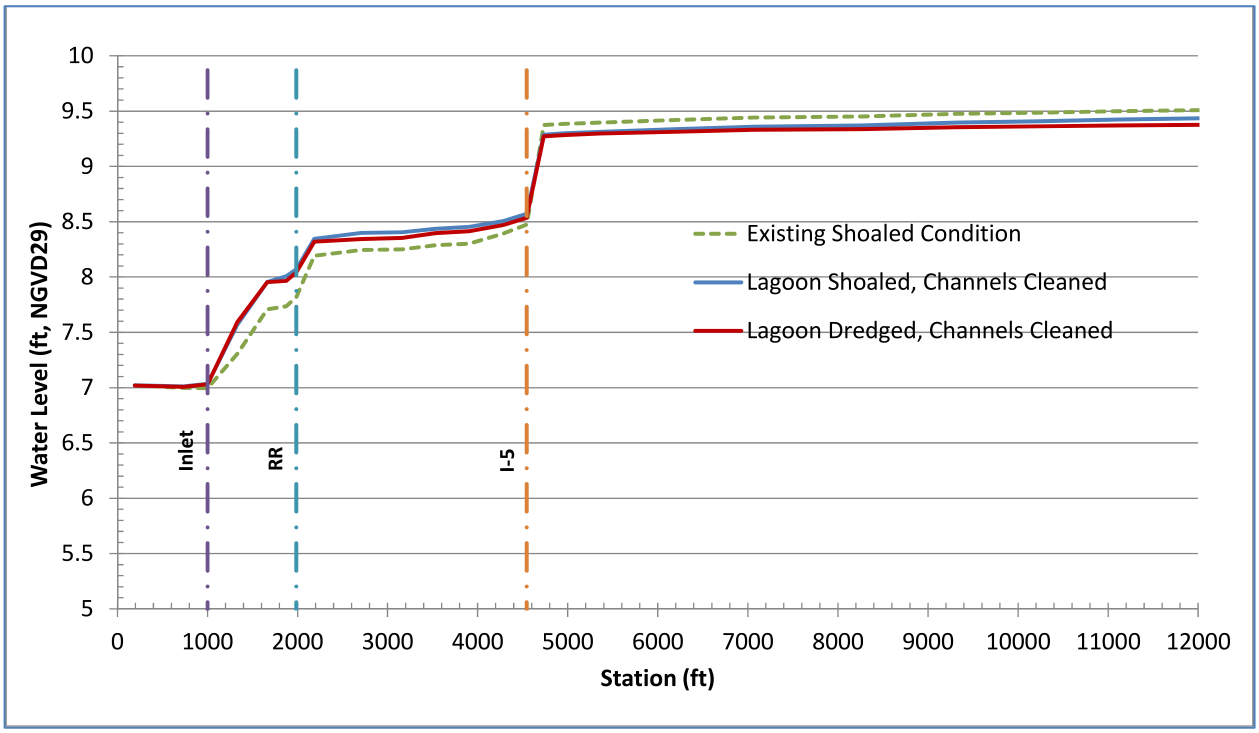

Figure 4-3: Comparison of 100-Year Surface Profile for Different Lagoon Sedimentation Conditions

4.1 I-5 Channel Dimensions Optimization Results

Figure 4-5 presents 100-year water surface profiles through the lagoon for different channel widths under I-5 Bridge while keeping the RR Bridge channel in its design condition. Modeling results indicate widening the channel under the I-5 Bridge will reduce the backwater effect created by the I-5 Bridge and lower the water surface elevation in the East Basin. However, it will also shift the backwater effect to downstream of the I-5 Bridge and increase the water surface elevation in the Central and West Basins.

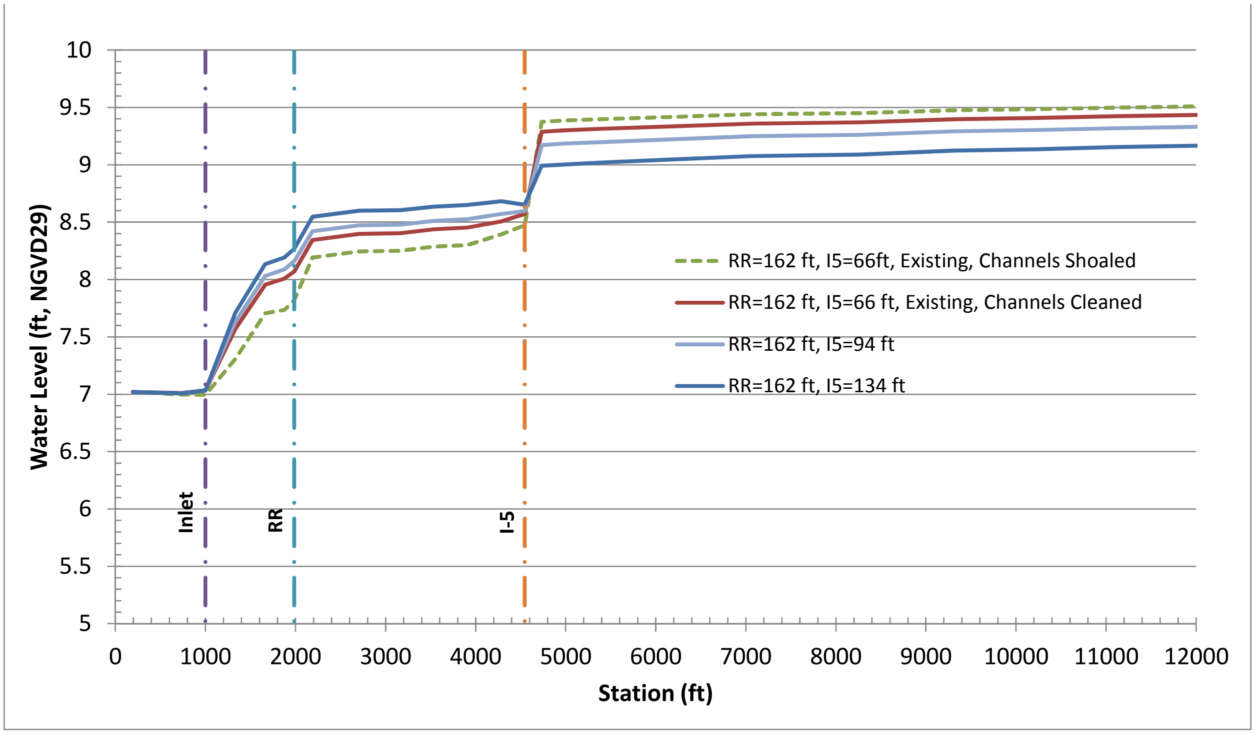

Figure 4-4: 100-Year Surface Profiles Under Different I-5 Channel Widths

4.2 RR Dimensions Optimization Results

Figure 4-6 illustrates 100-year water surface profiles through the lagoon under different RR Bridge channel widths while keeping the I-5 Bridge channel width under its optimized condition based on tidal range modeling. Modeling results indicate widening the channel under the RR Bridge will only slightly reduce the backwater effect created by the RR Bridge and will lower the water surface elevation in the Central and East Basins. However, this action will also shift the backwater effect to downstream of the RR Bridge and increase the water surface elevation in the West Basin.

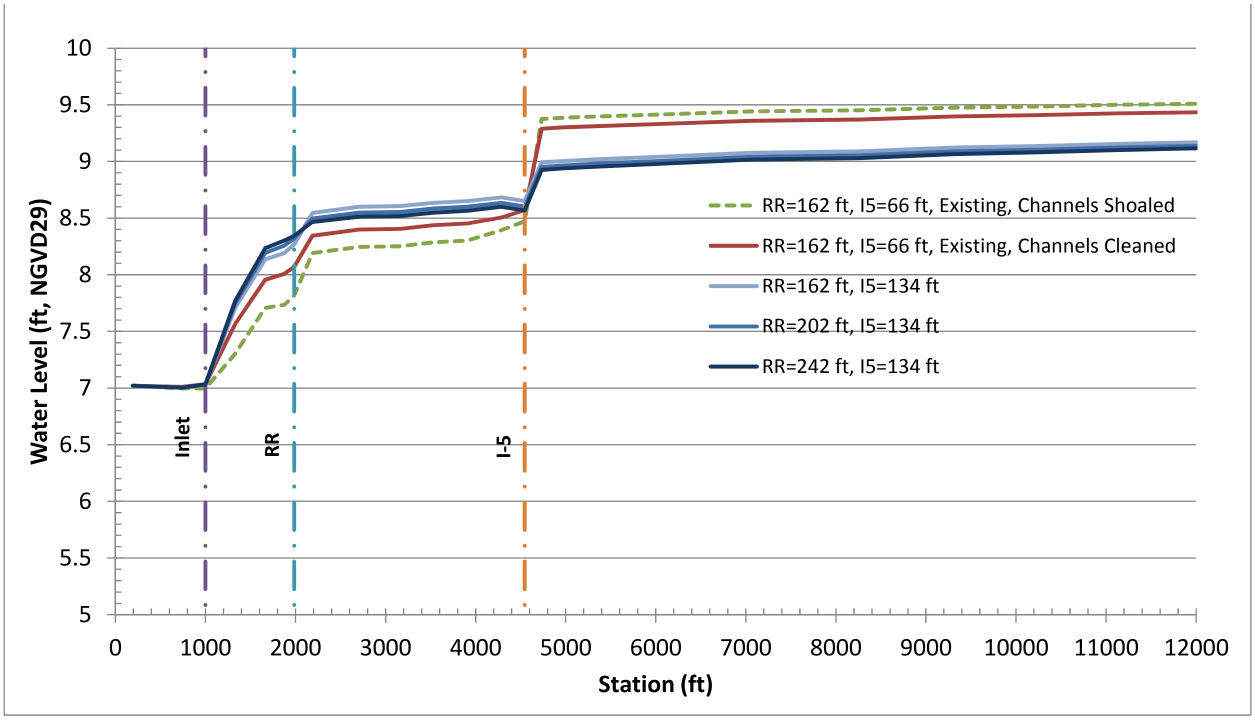

Figure 4-5: 100-Year Surface Profiles Under Different RR Channel Widths

4.3 Results of Combined Channel Dimensions Optimization for I-5 and RR Bridges

Figure 4-6 illustrates 100-year water surface profiles for various channel widths under the I-5 and RR Bridges. Table 4-1 summarizes the 100-year water surface elevations under different channel dimensions. In general, widening the channels under the I-5 and RR Bridges would reduce the backwater effects and slightly lower the water level in the Central and East Basins, but would shift the backwater effect to the West Basin upstream of the Carlsbad Boulevard Bridges and slightly increase water surface elevations in the West Basin. Since flooding is not currently an issue for Batiquitos Lagoon, the channel widths optimized for the tidal range also work for flood conveyance.

The green highlighted cells in Table 4-1 show the 100-year water levels under the optimized channel conditions. The yellow highlighted cells in the Table show the 100-year water levels under the existing channel conditions, assuming the channels are dredged to conditions shown in the design drawings.

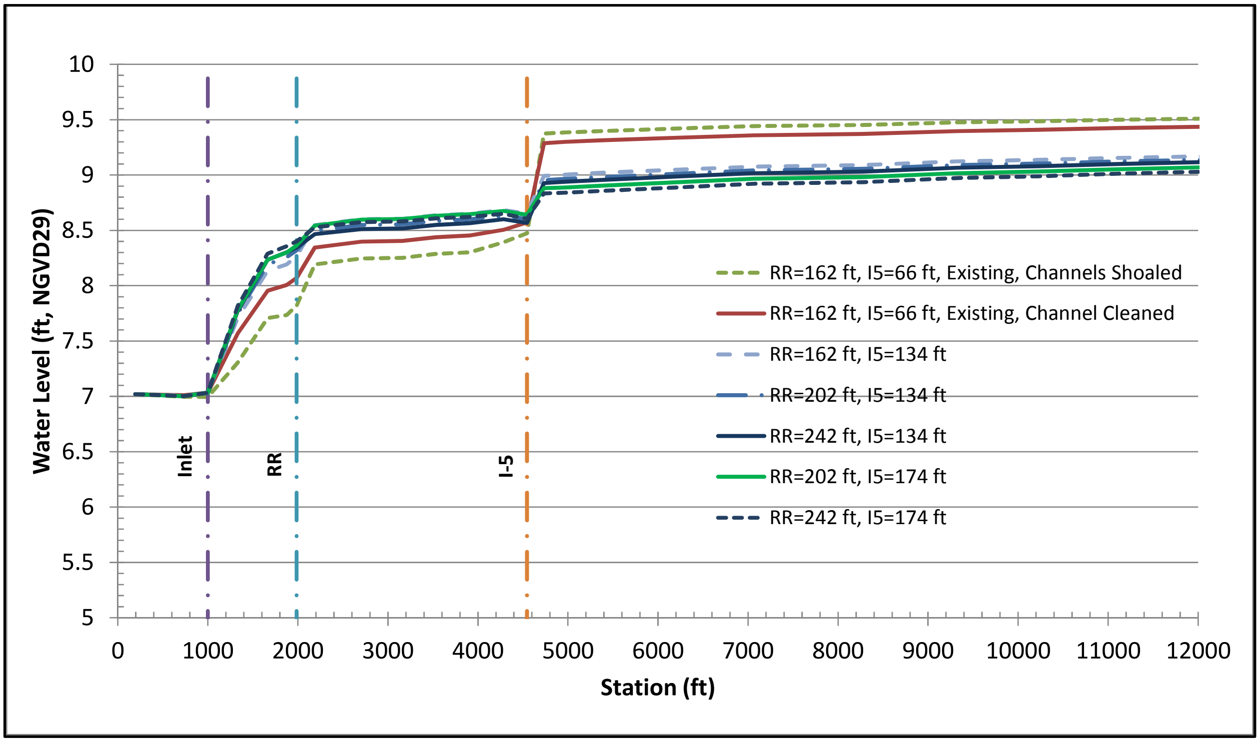

Figure 4-6: 100-Year Surface Profiles for Combined Channel Optimization Under I-5 and RR Bridges

Table 4-1: Summary of 100-Year Flood Levels in Each Basin

I-5 Channel Bottom Width (ft)	RR Channel Bottom Width (ft)								
	West Basin			Central Basin			East Basin		
	162	202	242	162	202	242	162	202	242
66	***7.9***			***8.4***			***9.4***		
94	8.0	8.1		8.5	8.4		9.3	9.2	
134	8.1	8.2	8.2	8.6	8.6	8.5	9.1	9.1	9.0
174		8.2	8.3		8.6	8.6		9.0	8.9

4.4 Hydrodynamic Modeling Results of the 50-Year Storm Event

Hydrodynamic modeling runs were also performed for the 50-year storm event. The same offshore tidal boundary used in the optimization of fluvial conveyance was used and is shown in Figure 4-1. The 50-year water surface profiles calculated from the RMA-2 modeling results are shown in Figure 4-7 in “warm” color lines. The 100-year water surface profiles shown in “cold” color lines are also included for relative comparison.

The water surface elevations for the 50-year flood are much lower than those under the 100-year storm event; however the pattern of change in water surface elevation is very similar to that under the 100-year storm event. The water surface elevations will be lower in the East Basin but higher in the Central and West Basins with optimized bridge dimensions.

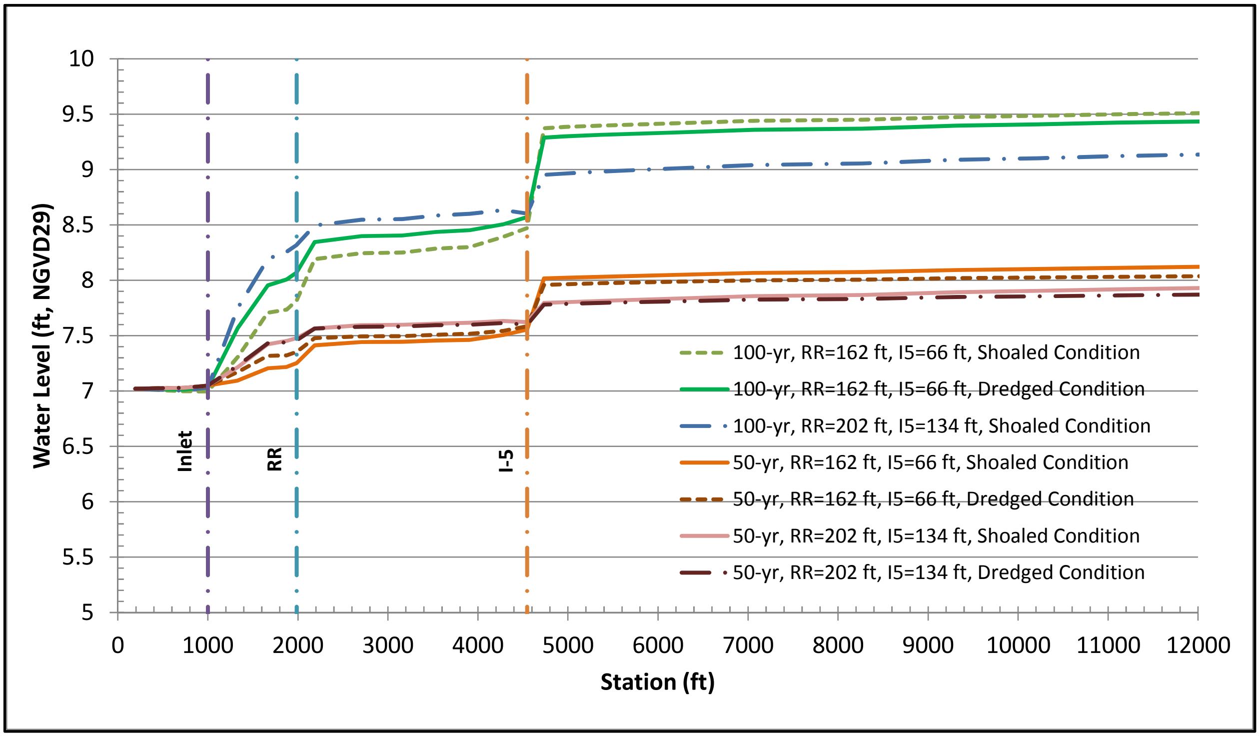

Figure 4-7: 50-Year Water Surface Profiles

5.0 SUMMARY OF EXISTING AND OPTIMIZED CHANNEL DIMENSIONS UNDER BRIDGES

The existing channel widths below the I-5 and RR Bridge crossings provided a starting point for the optimization modeling. The following section provides a brief description of each bridge and the range of channel dimensions evaluated in the optimization study.

5.1 Carlsbad Boulevard Bridges

The Carlsbad Boulevard Bridges, shown in Figure 5-1, cross over the Batiquitos tidal inlet. The existing tidal inlet under the Carlsbad Boulevard Bridges was sized and designed to achieve a stable inlet as part of the Batiquitos Lagoon restoration project. The tidal inlet has been performing well since construction in 1995. Therefore, no further optimization is required for the tidal inlet. As-built drawings (M&N 1993) indicate a channel bottom width of 96 feet at an invert elevation of -8 feet, NGVD. The channel under the East Carlsbad Boulevard Bridge is concrete lined as shown in Figure 5-2 and Figure 5-4, and the West Carlsbad Boulevard Bridge is lined with armor rocks as shown in Figure 5-3. Both bridges slope from north to south. The road surface profile grade of the East Carlsbad Boulevard Bridge is about 1.8 feet lower than that of West Carlsbad Boulevard Bridge. The soffit elevation of the East Carlsbad Boulevard Bridge is approximately +9.2 feet scaled from the as-built drawing.

Figure 5-1: Image of Carlsbad Boulevard and Railroad Bridges (source: California Coastal Records Project, 2012)

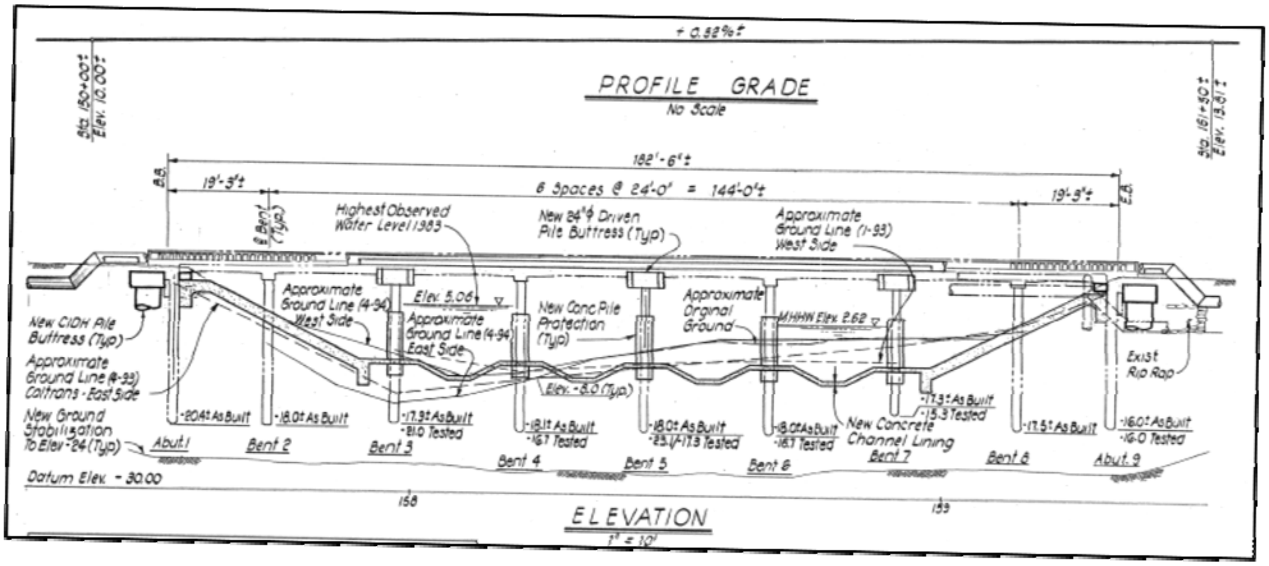

Figure 5-2: East Carlsbad Boulevard Bridge As-Built Drawing (Looking from Lagoon to Ocean)

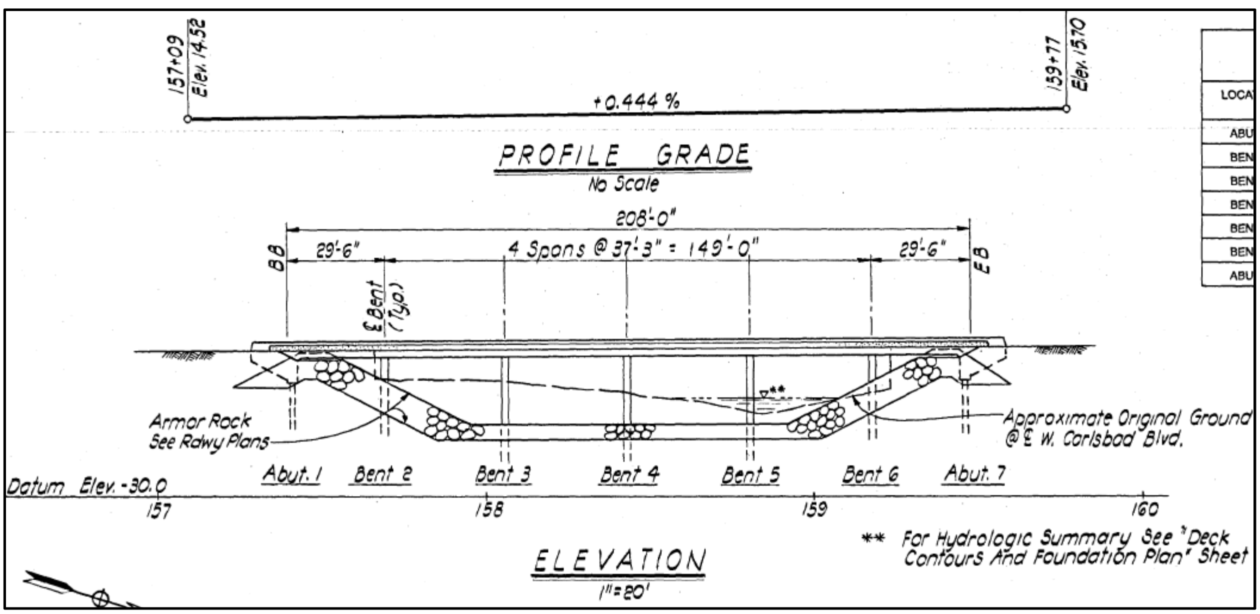

Figure 5-3: West Carlsbad Boulevard Bridge As-Built Drawing (Looking from Lagoon to Ocean)

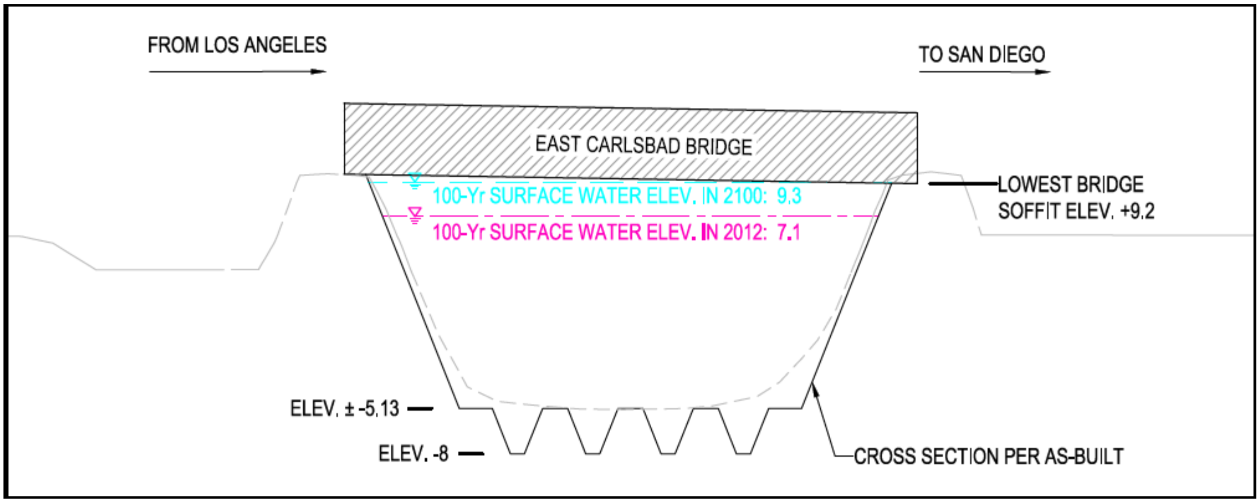

Figure 5-4: Channel Cross Section Under East Carlsbad Boulevard Bridge

Figure 5-4 also shows the model-predicted 100-year water surface elevations under the current horizon and for year 2100, taking into consideration 55-inches of SLR. The water surface elevation in year 2100 touches the bridge soffit in the east end of the bridge, but it does not create a flow situation that would require a specialized modeling approach called “pressure flow modeling.” Existing modeling results should accurately portray future conditions.

5.2 Railroad Bridge

The RR Bridge, shown in both Figure 5-1 and Figure 5-5, runs just east of and parallel to Carlsbad Boulevard Bridges across the Batiquitos Lagoon. As-built drawings (M&N 1993) show the total bridge length is 308 feet and the channel bottom width is approximately 162 feet at an invert elevation of -7 feet, NGVD. The entire channel bottom is lined with a 2-feet thick layer of 400-lb riprap underlined with a 0.5-feet thick layer of bedding rock. The RR Bridge slopes from south to north. The top of rail elevation at the north end of the RR Bridge is 22.9 feet. The soffit elevation is approximately 17.3 feet scaled from the as-built drawing.

The optimization modeling focused on a range of channel bottom widths between 162 feet and 282 feet. The recommended optimal channel bottom width is 202 feet, which is 40 feet wider than its current bottom width of 162 feet. The increase in tidal range is less than 0.05 feet if the channel under the RR Bridge is widened to beyond the recommended width of 202 feet. For flood conveyance, widening the channel would only lower the water level in the Central Basin by approximately 0.1 feet, however, it would raise the water level in the West Basin by approximately the same amount. The optimization modeling also indicates that the channel invert elevation of -7 feet under the as-built (or dredged) condition is appropriate.

Figure 5-5: Image of the Existing Railroad Bridge

Figure 5-6 shows the channel cross-section under the Railroad Bridge for both existing and optimized channel dimension conditions. It also shows the model predicted water surface elevations under the current time horizon and for year 2100, taking into consideration 55-inches of SLR. Sufficient freeboard exists above the maximum flood elevations for the RR Bridge under both current and future SLR scenarios.

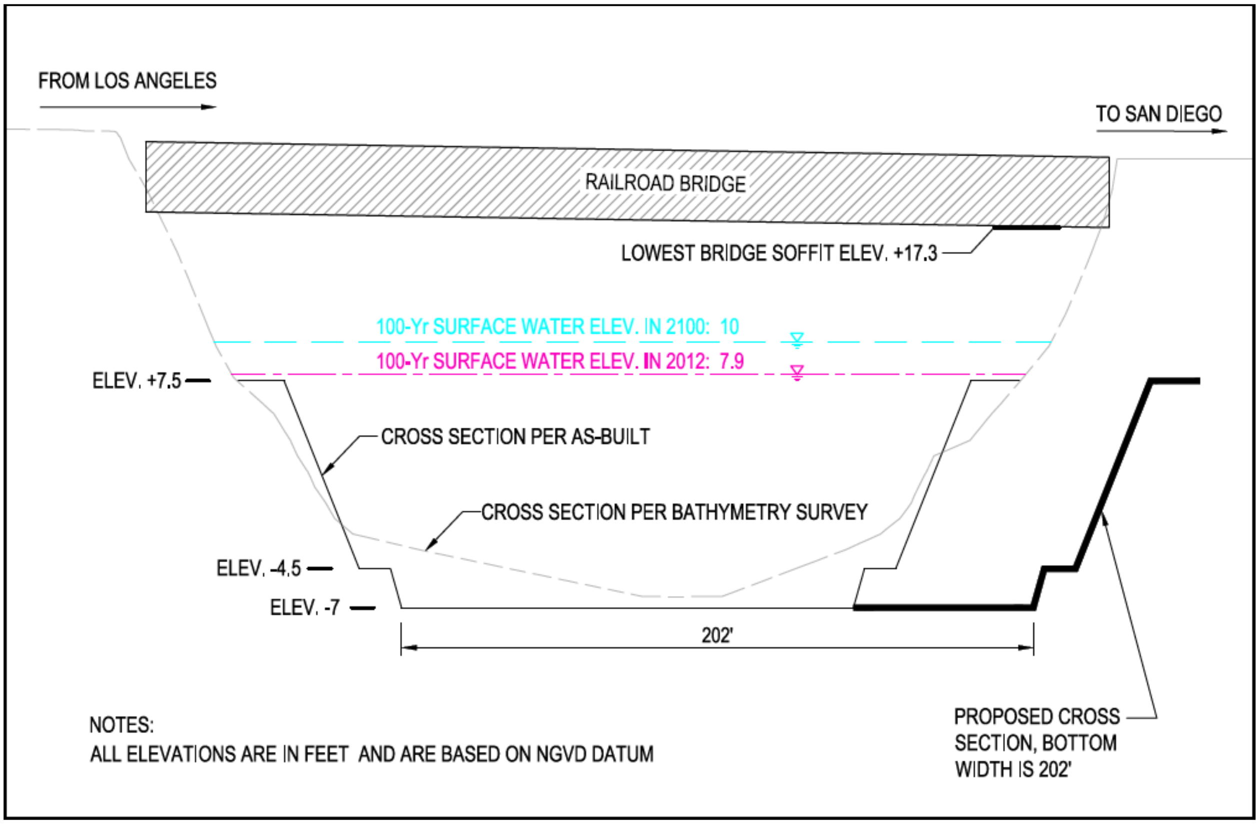

Figure 5-6: Channel Cross-Section Under the Railroad Bridge

5.3 I-5 Bridge

The I-5 freeway runs north to south across the Batiquitos Lagoon. The I-5 Bridge, shown in Figure 5-7, crosses near the middle of the lagoon serving as the boundary between the Central and East Basins. The as-built drawings indicate that the total bridge length is 219 feet and the channel bottom width under the I-5 Bridge is 66 feet at an invert elevation of -7 feet, NGVD. The entire channel is lined with a 3.5 feet thick layer of 400 lb riprap. The lowest bridge soffit elevation, indicated on the as-built drawings, is 16.14 feet, NGVD.

The I-5 Bridge optimization modeling focused on a range of channel widths between 66 feet and 174 feet. The recommended optimal channel bottom width is 134 feet, which is 68 wider than its current width of 66 feet. The increase in tidal range is less than 0.05 feet if the channel is widened to beyond the recommended width of 134 feet for the I-5 Bridge. With the recommended channel width, the 100-year flood water level in the East Basin will be lowered by 0.3 feet, however, the 100-year flood water level in the Central and West Basins will rise about 0.3 feet. The existing channel is very narrow and results a scour hole of more than 20 feet deep on both sides of the bridge. With the recommended channel width, the tidal velocity will be significantly reduced and therefore the scour depth will also diminish.

Figure 5-7: Image of Existing I-5 Bridge

Figure 5-8 shows the channel cross-section under the I-5 Bridge for both existing and optimized channel dimension conditions. It also shows the 100-year water surface elevations under the current time horizon and for year 2100, taking into consideration 55-inches of SLR. Sufficient freeboard exists above the maximum flood elevations for the I-5 Bridge under both current and future SLR scenarios. Figure 5-9 is an exhibit prepared by the Caltrans (2012) for the proposed I-5 Bridge.

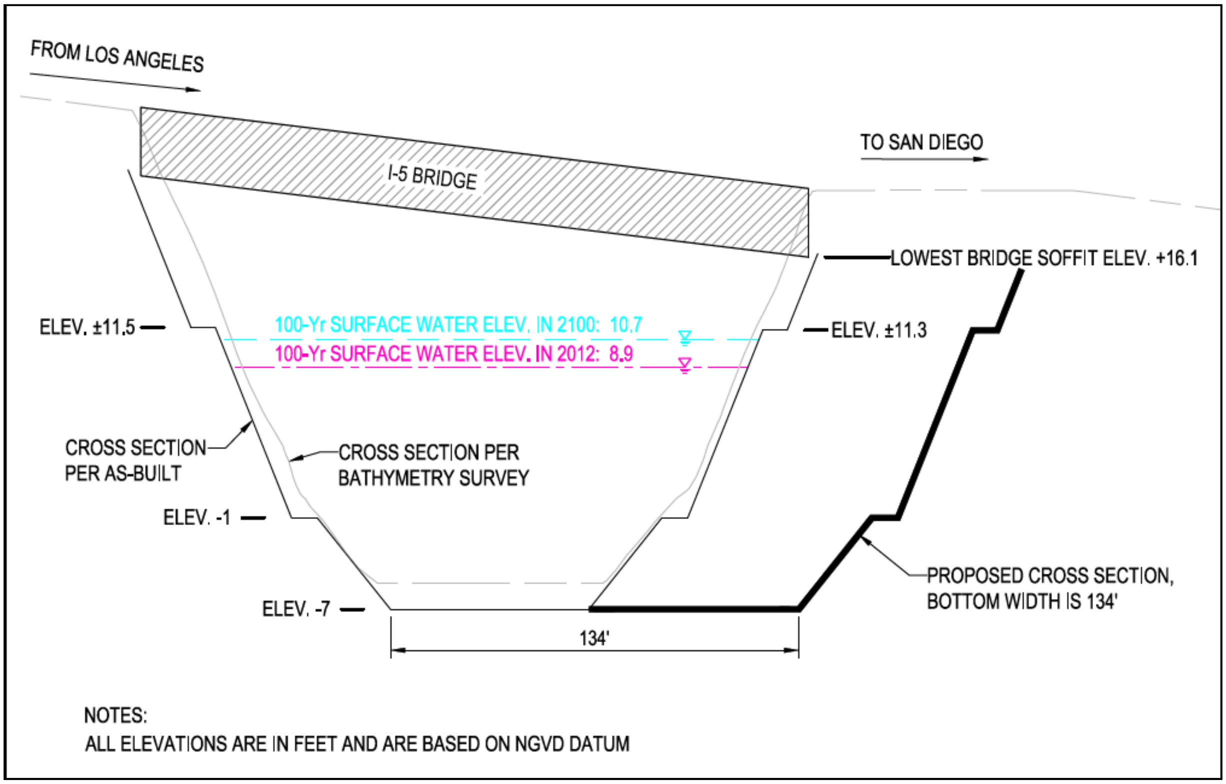

Figure 5-8: Channel Cross-Section Under I-5 Bridge

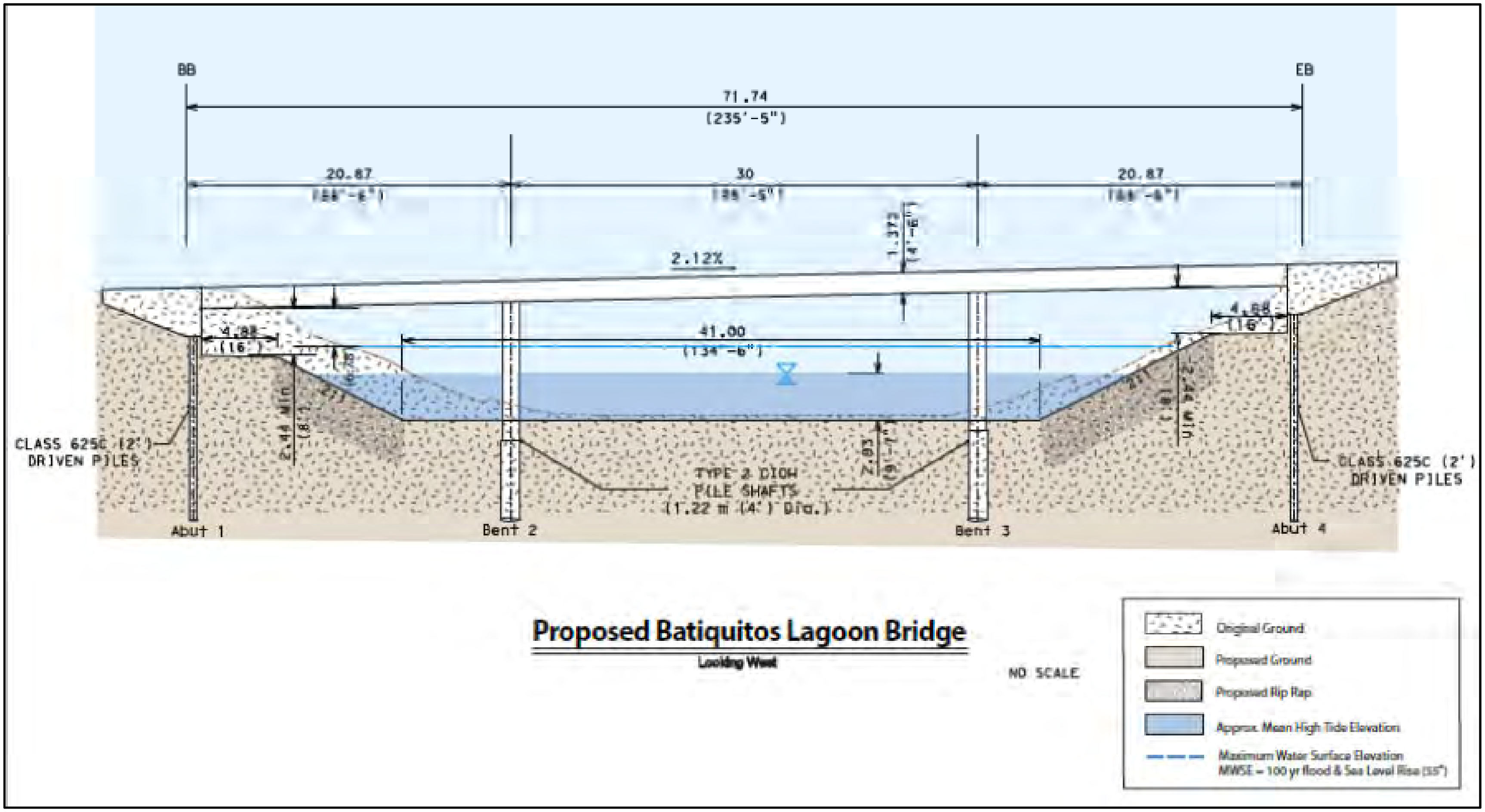

Figure 5-9: Proposed I-5 Bridge Exhibit (Looking from Lagoon to Ocean)

5.4 Summary of Channel Dimensions

Table 5-1 summarizes the recommended new channel dimensions (referred as the ‘optimized channel dimensions’) based on the tidal and flood optimization modeling results discussed in previous sections. The existing channel invert elevations are appropriate when they are dredged to the design condition. The dimensions of the tidal inlet channel are also included for reference although no optimization modeling is required or performed. The dimensions under the current design condition shown on record drawings are also included for each bridge.

The optimized channel dimensions are used in the following sections for analyses of flow velocity at bridge crossings, sedimentation patterns in the lagoon, tidal inundation frequency and residence time under the dry weather condition, and hydraulic impacts of predicted sea level rise.

Table 5-1: Summary of Existing and Optimized Channel Dimensions

Infrastructure	Recommended Based on Optimization			Design Condition		
	Channel Invert (ft)		Bottom Width (ft)	Channel Invert (ft)		Bottom Width (ft)
	NGVD	MLLW		NGVD	MLLW	
Inlet	-8.0	-5.7	96	-8.0	-5.7	96
RR	-7.0	-4.7	202	-7.0	-4.7	162
I-5	-7.0	-4.7	134	-7.0	-4.7	66

6.0 ANALYSES OF VELOCITY AND SEDIMENTATION

Analyses of velocity and sedimentation are performed for the following four lagoon bathymetry and bridge dimension conditions:

1. **Scenario1 - Shoaled Lagoon and Shoaled Existing Channels:** Both the lagoon and channels under existing bridge crossings are at the condition surveyed 2008.
2. **Scenario 2 - Dredged Lagoon and Dredged Existing Channels**: The lagoon is assumed to be dredged to the design condition, and assuming subsidence in the Central Basin as discussed in Section 1.2. The existing channels are dredged to their design conditions.
3. **Scenario 3 - Dredged Lagoon and Dredged Optimized Channels:** The lagoon is assumed to be dredged to the design condition assuming subsidence in the Central Basin as discussed in Section 1.2. The channels under the I-5 and RR Bridges with the optimized channel dimensions shown in Table 5-1 are at their design condition with no shoaling. The inlet entrance channel is also dredged to the design condition.
4. **Scenario 4 - Shoaled Lagoon and Dredged Optimized Channels:** The lagoon with the optimized channel dimensions under the I-5 and RR Bridges is assumed to be shoaled to the condition similar to that surveyed in 2008 since the shoaling pattern in the West and Central Basins will likely be similar to current conditions. Shoaling in the channels with optimized channel dimensions is expected to be different from that under the current condition. Because of largely unknown conditions, the channels under the I-5 and RR Bridges with the optimized channel dimensions shown in Table 5-1 are assumed to be at their design conditions with no shoaling. The inlet entrance channel is also assumed to be dredged to the design condition.

A comparison of Scenarios 1 and 2 would show the impact of shoaling in the lagoon. Comparison of Scenarios 2 and 3 would show the benefits of optimized channel dimensions when compared to the existing channel dimensions.

6.1 Analyses of Tidal Velocity Under Bridges

The section summarizes velocities under the bridges for both the dry weather (tidal only) and extreme storm (50-year and 100-year) conditions. Table 6-1 displays the spring high tide velocities at the infrastructure crossings during the dry weather condition under the four modeling scenarios, with their associated variations in lagoon bathymetry and bridge dimensions. The results indicate that the peak flood and ebb tidal flow velocities, especially under the I-5 Bridge, are generally lowered under the optimized bridge condition when compared to the existing condition. The peak velocities under the I-5 Bridge are lowered by at least 1 foot per second (fps) and are lower than those under the RR Bridge for the currently shoaled condition. Therefore, the lagoon bed erosion on both sides of the I-5 Bridge is expected to be significantly reduced compared to the existing condition. The velocities at the

RR Bridge are also reduced, but remain approximately the same at the tidal inlet. Maintaining a velocity at the tidal inlet which is similar to the existing condition is essential for inlet stability.

A comparison of modeling Scenarios 1 and 2 indicates that for existing bridge conditions lagoon dredging will also reduce tidal velocities at the I-5 and RR Bridge crossings as shown in Table 6-1. Therefore, more frequent channel dredging will also reduce erosion around the I-5 Bridge.

Scenarios 2 and 3 show effects of optimizing the channels under bridges. Both assume the lagoon is clear of sand (dredged). Tidal flow velocities decrease throughout the lagoon, with the exception of the tidal inlet.

Tidal velocities under Scenario 4 (shoaled condition) are lower than those under Scenario 3, the dredged lagoon bathymetry condition, since shoaling would reduce the tidal prism and consequently, the tidal flow velocities under bridges.

Table 6-1: Tidal Velocity (fps) at Bridge Crossings During the Dry Season

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	Inlet		RR		I-5	
			Flood	Ebb	Flood	Ebb	Flood	Ebb
1	Shoaled	Existing Shoaled	4.4	5.6	3.7	4.3	4.3	3.9
2	Dredged	Existing Dredged	3.9	5.5	3.1	3.5	3.7	3.6
3	Dredged	Optimized Dredged	4.1	5.6	2.7	2.9	2.4	2.3
4	Shoaled	Optimized Dredged	3.8	5.1	2.6	2.7	2.2	2.0

6.2 Analyses of Extreme Flood Velocities Under Bridges

Table 6-2 summarizes the velocities at bridge crossings under the 100-year storm event superimposed on the 7-foot spring high tide scenario discussed in Section 4.0. The modeling runs were performed to determine the maximum water surface elevations for flood protection, but not to determine the potential maximum velocities at the bridge crossings. The maximum water surface elevation occurs at the high tidal elevation, while the maximum velocity occurs during the low tide. However, the velocities summarized in Table 6-2 still provide relative comparison between different lagoon and bridge conditions.

Velocities under both the I-5 and RR Bridges for the optimized bridge condition are lower than those under the existing bridge condition due to widening of the channels. However, the potential peak flood velocities will be higher than those shown if the peak flood arrives in a spring low tidal condition. Additional modeling analysis, which is beyond the scope of this study, is required to determine the maximum scour velocity and scour depth. With the magnitude of velocities at the bridge crossings, riprap protection of the bridge abutments and the entire channel under both the RR and I-5 Bridges will still be required, similar to their current conditions. The storm flow velocity in the tidal inlet is expected to be higher under the optimized condition of the I-5 and RR Bridges since some backwater effects in the Central and East Basins are shifted to the West Basin. A slight increase in velocity in the inlet channel may not cause additional scour problems since the channel under the bridges is riprap protected.

Velocities under the dredged lagoon condition are lower than those under the shoaled condition. Frequent dredging of the lagoon will also improve flood conveyance and reduce peak flood velocity.

Table 6-2: 100-Year Peak Flood Velocity (fps) at Bridge Crossings

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	Inlet	RR	I-5
1	Shoaled	Existing Shoaled	9.2	5.9	7.1
2	Dredged	Existing Dredged	7.6	5.0	6.6
3	Dredged	Optimized Dredged	8.0	4.5	4.8
4	Shoaled	Optimized Dredged	7.9	4.2	4.7

Table 6-3 summarizes velocities under a lesser frequency 50-year storm event. The conclusions are similar to those found for the 100-year storm event. Velocities under the I-5 and RR Bridges under the optimized bridge dimensions condition are lower than those under the existing bridge conditions. For the existing bridge dimensions condition, dredging of the lagoon and channels would also reduce the flood flow velocities. Under the 50-year storm event, the peak velocity in the tidal inlet also increases slightly.

Table 6-3: 50-Year Peak Flood Velocity (fps) at Bridge Crossings

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	Inlet	RR	I-5
1	Shoaled	Existing Shoaled	7.6	5.3	5.2
2	Dredged	Existing Dredged	6.5	4.2	4.8
3	Dredged	Optimized Dredged	6.6	3.6	3.4
4	Shoaled	Optimized Dredged	6.4	3.3	3.3

6.3 Analyses of Sedimentation

Fluvial sedimentation has been gradually accumulating in the East Basin of Batiquitos Lagoon. With the current maintenance dredging program in place for the Lagoon, coastal sedimentation is not expected to pass beyond the Central Basin. On the other hand, coastal sedimentation is dominant in the Central and West Basins. The sediment accumulation in the Central and West Basins will be removed via maintenance dredging even if there is fluvial deposition in these areas. Analysis of coastal sedimentation is beyond the scope of this study. Another sedimentation-related issue for Batiquitos Lagoon is formation of deep scour holes present on both sides of the I-5 Bridge. This study therefore focuses discussion on fluvial sedimentation in the East Basin and sedimentation around the I-5 Bridge.

6.3.1 Dry Weather Sedimentation

The coastal sedimentation (shoaling) in the West and Central Basins is expected to be similar to that under existing conditions. The tidal inlet velocities under Scenario 3 (optimized channel dimensions) are slightly higher than those under Scenario 2 (existing channel dimensions). Therefore, the tidal inlet will be relatively more stable.

As shown in Table 6-1, both ebb and flood tidal velocities, which are believed to be responsible for the scour holes on both sides of the I-5 Bridge, are significantly reduced under Scenario 3 (optimized channel dimensions) compared to those under Scenario 2 (existing channel dimensions). Therefore, the erosion conditions are expected to be improved and scouring depths on both sides of the I-5 Bridge should be reduced under Scenario 3 (optimized channel dimensions).

As discussed previously, lagoon dredging will also result in lower tidal velocities at the I-5 and RR Bridge crossings. Consequently, more frequent channel dredging should also reduce erosion around the I-5 Bridge.

6.3.2 Extreme Storm Event Sedimentation

This section summarizes changes in the sedimentation pattern and potential sediment transport in the East Basin. Figure 6-1 and Figure 6-2 show the velocity contours in the lagoon during the 100-year stormflow event. The velocity increases slightly under the optimized bridge dimension condition. Therefore, the flood conveyance and sediment transport capacity will be slightly improved in the East Basin, which should reduce fluvial sedimentation in the East Basin. As shown in Table 6-4, the 100-year peak flood travel time through the East Basin is reduced from 0.7 hours to 0.6 hours with a widened channel under the I-5 Bridge, which would reduce the time for sediment to settle in the lagoon. Therefore, the flood conveyance and sediment transport capacity under the optimized bridge condition should be slightly improved compared to the existing condition, and may likely result in slightly reduced sedimentation in the East Basin. Dredging of the lagoon should also reduce flood travel time in the Central and West Basins

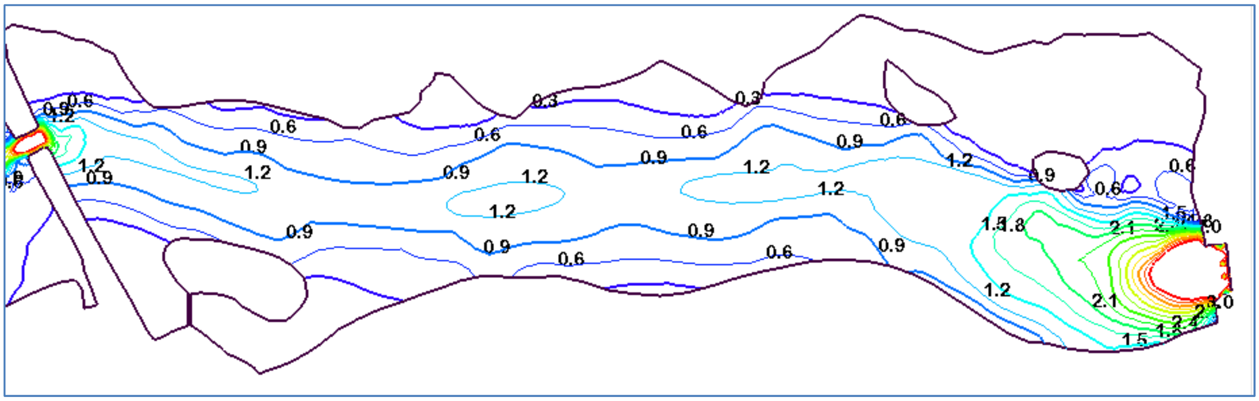

Figure 6-1: 100-Year Velocity Contours for Dredged Lagoon and Existing Bridge Dimension Condition

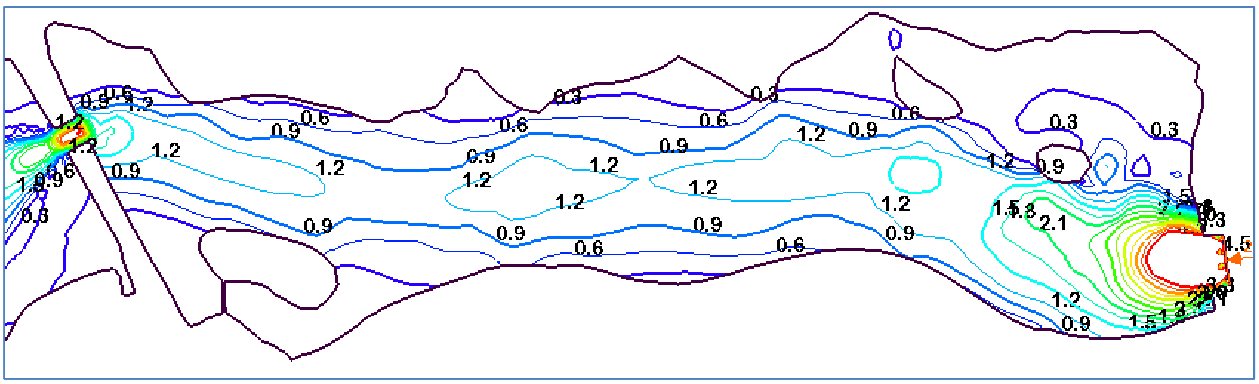

Figure 6-2: 100-Year Velocity Contours for Dredged Lagoon and Optimized Bridge Dimension Condition

Table 6-4: Duration (Hour) of Stormflow Drainage Under a 100-Year Storm

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	East Basin	Central Basin	West Basin
1	Shoaled	Existing Shoaled	0.8	1.2	0.5
2	Dredged	Existing Dredged	0.7	0.8	0.4
3	Dredged	Optimized Dredged	0.6	0.6	0.2
4	Shoaled	Optimized Dredged	0.6	0.6	0.2

7.0 RESIDENCE TIME ANALYSES

The RMA-4 model is used in the study to calculate the residence time. The dispersion coefficients used in the RMA-4 model are based on modeling calibrations performed for other similar projects as no data are available for the model calibration. This is adequate for the purpose of comparison between existing and optimized project conditions.

7.1 Methodology

Changes in constituent concentrations in a water body reflect a balance between the rate of constituent supply and the rate of constituent removal by tidal flushing. Residence time (i.e., average time a particle resides in a hydraulic system) provides a useful measure of the rate at which waters in the hydraulic system are renewed. Accordingly, residence time provides a means for assessing the water quality of the hydraulic system.

Consider the reduction of a tracer concentration in a tidal embayment due to flushing after being released (Fisher et al., 1979), in which C_0 is initial concentration, K is a reduction coefficient and C(t) is the concentration at time t.

$$C(t) = C_0 e^{-Kt} \qquad (7.1)$$

The residence time of the tracer in the embayment is determined as follows:

$$T_r = \frac{\int_0^\infty t\,C(t)\,dt}{\int_0^\infty C(t)\,dt} = \frac{1}{K}. \qquad (7.2)$$

Since the concentration at t = T_r is

$$C(T_r) = C_0 e^{-1} = \frac{C_0}{e} \qquad (7.3)$$

T_r can be calculated from a regression analysis of the tracer concentration time series computed by the numerical model RMA-4.

Based on the above methodology, the general procedure for computing residence times for different parts of a tidal embayment is as follows:

- Assign an initial constituent concentration of one over the entire embayment element mesh (wetlands for this study) and a value of zero at the open water boundaries to simulate an instantaneous release of a new constituent into an embayment.
- Run the numerical model RMA-4 for an adequate number of tidal cycles until substantial reduction of constituent concentrations have occurred due to tidal flushing at the locations of interest.
- Analyze the computed concentration results by regression analysis to obtain the constituent reduction distributions at the locations of interest.

- Find the residence times for the locations of interest from the distribution curves according to Equations 7.1 through 7.3.

Figure 7-1 shows an example of how the method works, where the zigzagging solid blue line shows the direct results from RMA-4 and the dashed green line shows the daily moving average results. An arrow points to the amount of time it takes for the moving average to fall below the threshold concentration of 1/e, which in this example represents a residence time of approximately 173 hours. This method was used in the project study for all scenarios.

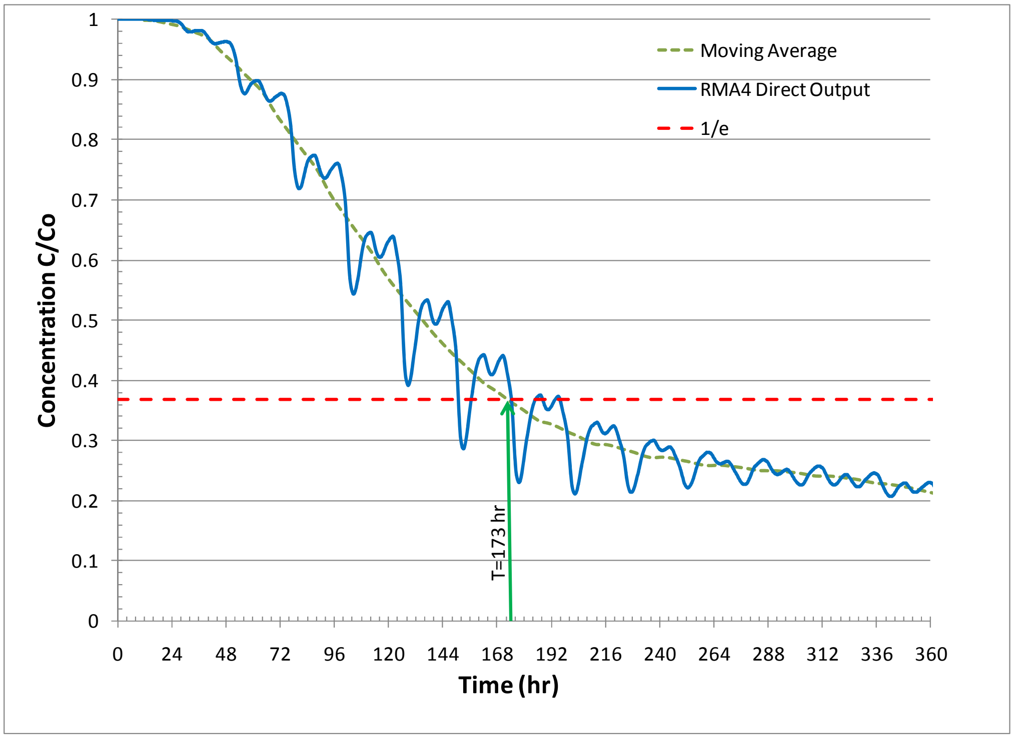

Figure 7-1: Example of a Residence Time Plot

7.2 Boundary Conditions

7.2.1 Hydraulic Input

The 15-day modeling tidal series, representing the average spring and neap tidal cycle, as described in Section 2.2.4.2 is applied as the offshore driving tide. No runoff from the fresh water boundary is considered, as the base flow of the creek is negligibly small.

7.2.2 Concentration Input

An initial constituent concentration of one is specified for the entire lagoon. No constituent concentration is assigned at the open water boundaries. Also, it is assumed that ocean water is clean and does not supply additional constituents, or "contaminants."

7.3 Residence Time Results

Residence times are calculated at representative gage locations shown in Figure 7-2. The lagoon is well circulated in both the West and Central Basins. The difference in residence time between Gages WB1 and WB2 is very small and less than 0.1 day. Similarly, the residence time at Gage CB1 is very similar to that at CB2. Therefore, since the residence time value at each station is the same within a basin, only one residence time value is reported. Table 7-1 summarizes residence times under the four scenarios described in Section 6.0. The residence times are very similar for existing and optimized channel dimension conditions. The overall residence times are short, being less than one week, indicating that tidal waters within Batiquitos Lagoon circulate well. However, dredging of the lagoon will reduce residence times in the East Basin by one half of a day and further enhance lagoon circulation.

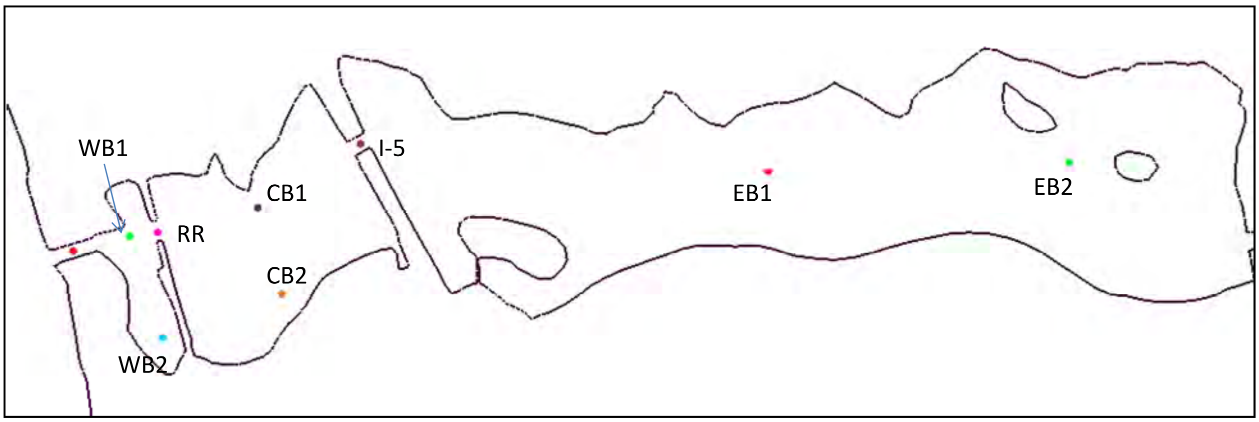

Figure 7-2: Gage Locations for Residence Time Calculations

Table 7-1: Summary of Residence Time (Days)

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	West Basin	Central Basin	East Basin	
					EB1	EB2
1	Shoaled	Existing Shoaled	0.6	1.6	4.3	5.8
2	Dredged	Existing Dredged	0.6	1.6	3.8	5.4
3	Dredged	Optimized Dredged	0.5	1.6	3.8	5.4
4	Shoaled	Optimized Dredged	0.5	1.6	4.5	5.9

8.0 TIDAL INUNDATION FREQUENCY ANALYSES

Tidal inundation frequency is analyzed and plotted with tidal elevation data from the TEA tidal model runs. The tidal range difference within each basin is very small, so only one inundation frequency is plotted for each basin. Figure 8-1 through Figure 8-4 show the inundation frequency plots. There is no high tide muting in Batiquitos lagoon. However, the lagoon does experience low tidal muting, especially under the shoaled lagoon condition. Dredging would reduce muting by 0.4 feet in the Central Basin and by 0.7 feet in the East Basin, and increase the vertical range of the intertidal habitat zone. Optimizing the channel dimensions under the RR and I-5 Bridges would further reduce tidal muting by approximately 0.2 feet and add to the increase in vertical range of the intertidal habitat zone. For Batiquitos Lagoon, the primary gain of intertidal habitat area will be mudflat. Mudflat lies from an inundation frequency of approximately 100 to 40 percent.

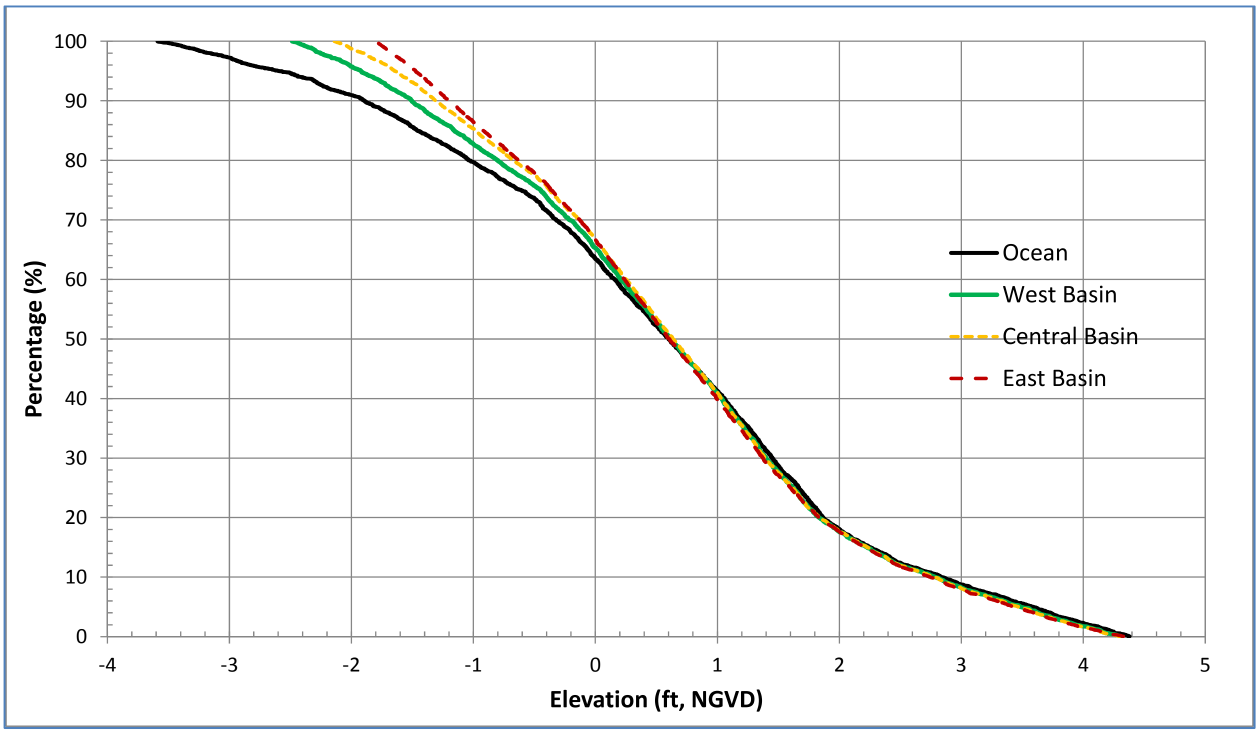

Figure 8-1: Inundation Frequency for Shoaled Existing Condition

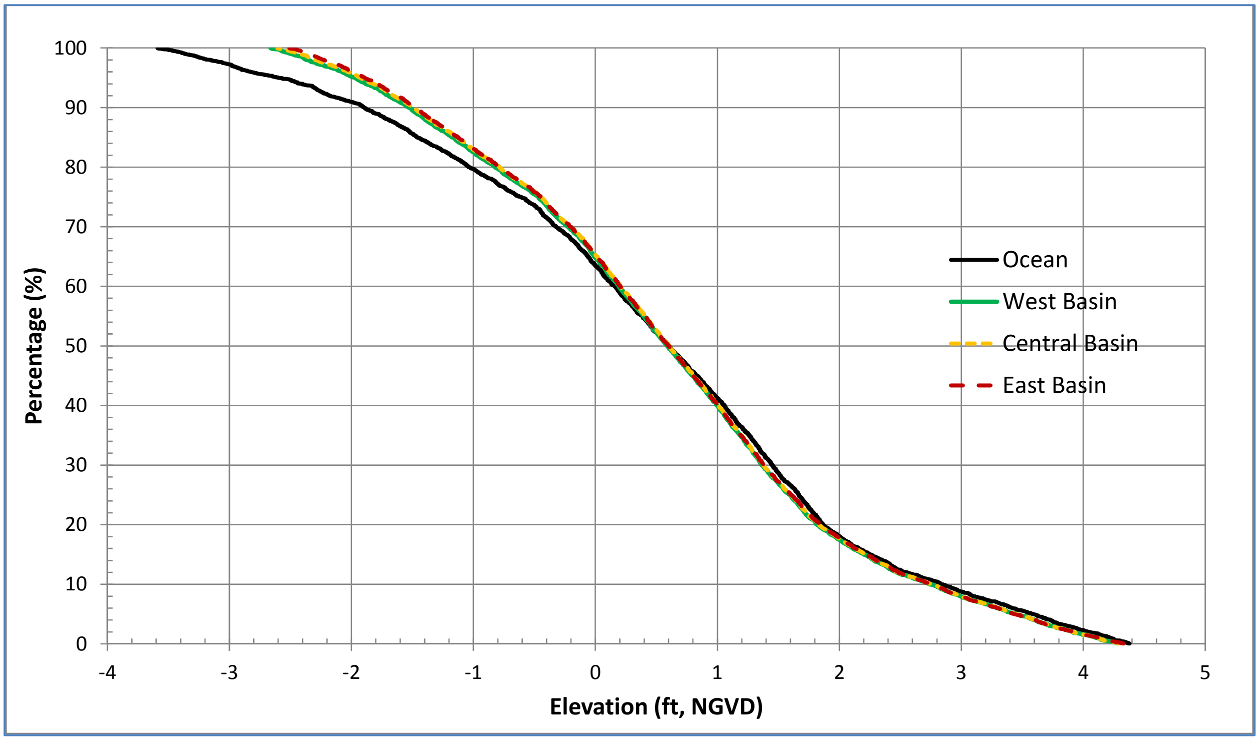

Figure 8-2: Inundation Frequency for the Dredged Existing Condition

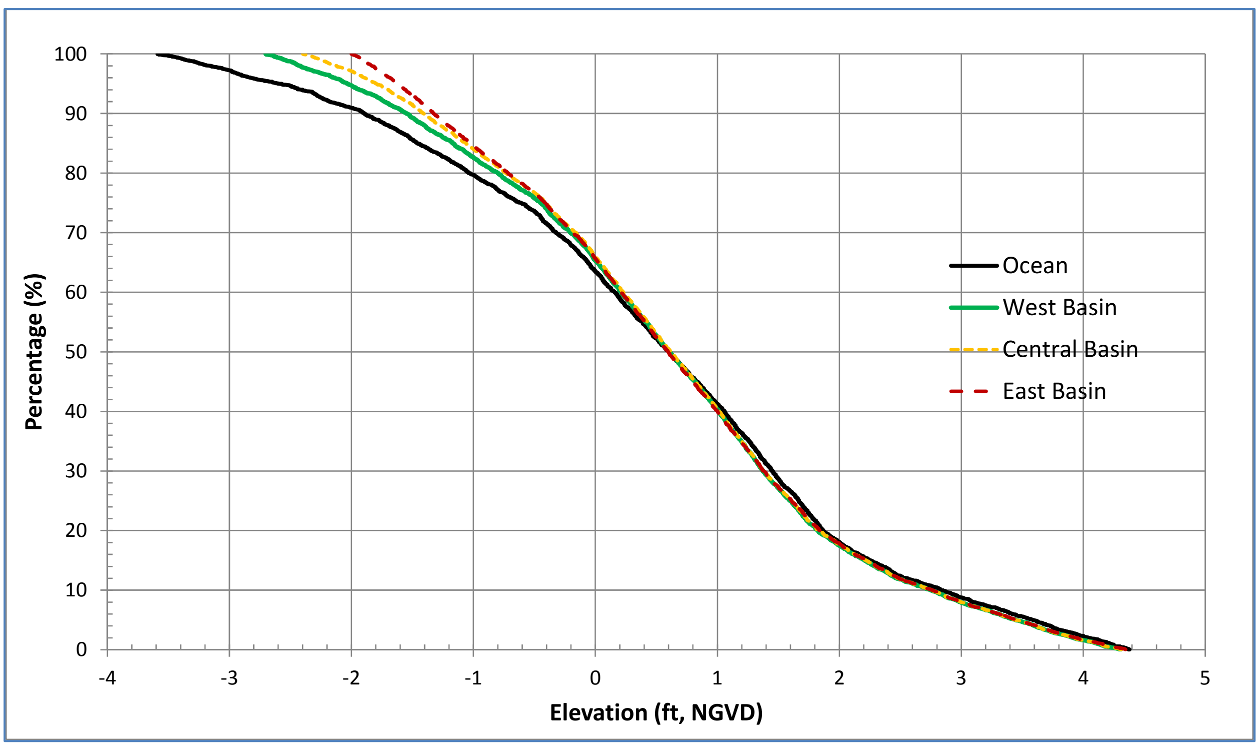

Figure 8-3: Inundation Frequency for the Shoaled Optimized Condition

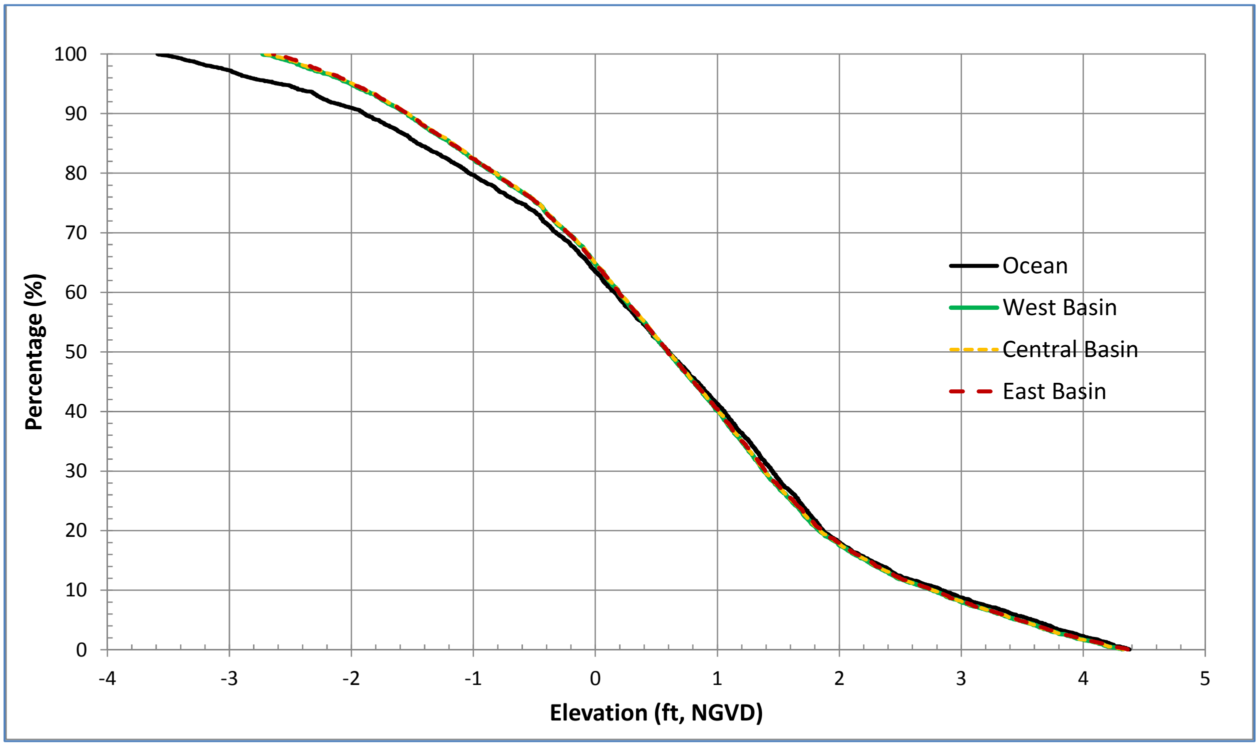

Figure 8-4: Inundation Frequency for the Dredged Optimized Condition

9.0 HYDRAULIC EFFECTS OF SEA LEVEL RISE

Hydrodynamic modeling runs were performed to consider sea level rise (SLR) predicted for the year 2100. A 55-inch SLR estimate was considered in the modeling study based on the guidance provided by Caltrans internal guidance (Caltrans 2011) and the California State Coastal Conservancy on its web site (CSCC 2012) for horizon year 2100. The offshore spring high tide series (with a high tide elevation of 4.69 feet NGVD) was raised linearly upward by 55 inches to form the spring high tide series in year 2100 (future high tide elevation of 9.27 feet NGVD).

The offshore high tide base level of 4.69 feet used for modeling of SLR compares to a base level of 7.0 feet used for stormflow modeling under existing conditions. The ocean base level for SLR modeling is therefore different, and 28 inches lower, than that assumed for existing conditions stormflow modeling. The difference is the omission of the value of wave run-up from the SLR modeling base level. Wave run-up is not included because it is too conservative to assume that breaking waves would exist at the Lagoon mouth during combined maximum high tide and SLR conditions based on engineering judgment. Water depths at the Lagoon mouth are estimated to be sufficient to preclude wave breaking within the tidal inlet channel.

The resulting tidal series is shown in Figure 9-1. It is also assumed that the 100-year stormflow condition, as shown in Figure 2-6, will be the same as it is today.

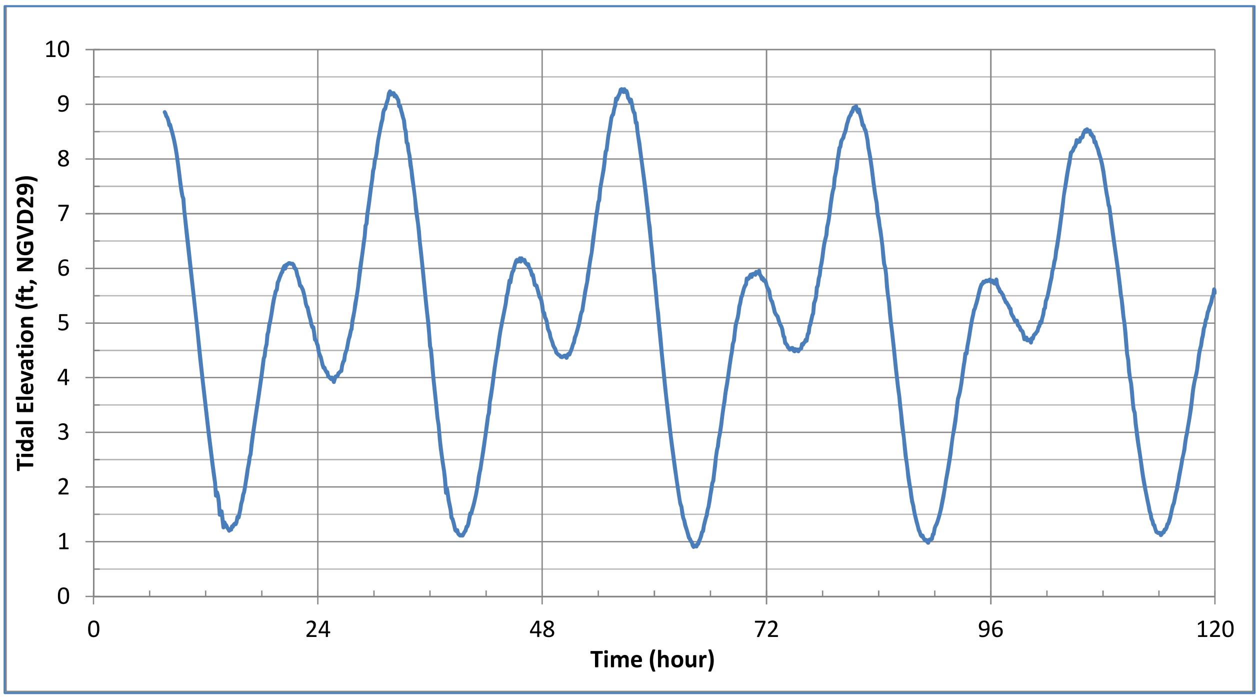

Figure 9-1: Spring High Tidal Series for Year 2100

Figure 9-2 compares 100-year water surface profiles shown in “warm” color lines in the year 2100 with predicted sea level rise. The 100-year water surface profiles in the year 2012, shown in "cold" color lines, are also included for relative comparison. The water surface elevation will be higher, but head losses through each bridge will be less than those under the current condition. The water surface elevation in the East Basin will be lower with optimized bridge dimensions than with existing bridge dimensions. However, the water surface elevation in the Central and West Basins will be higher with the optimized bridge dimensions than with existing bridge dimensions.

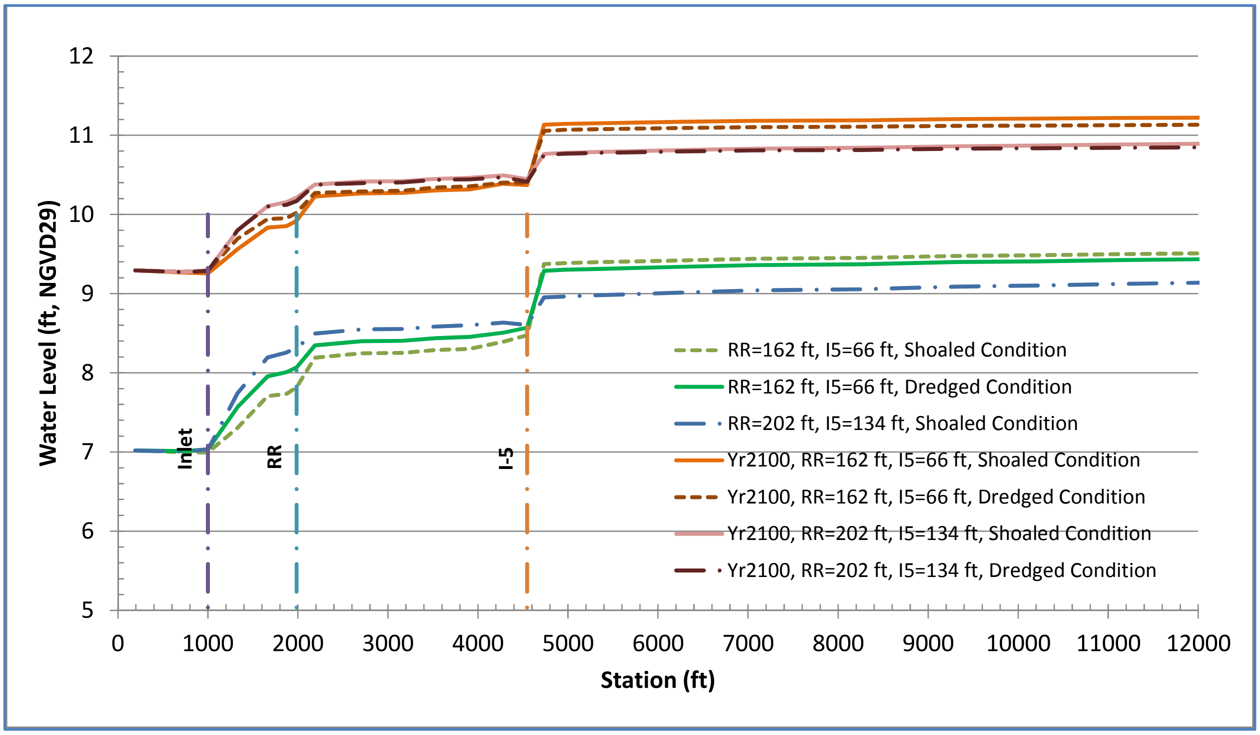

Figure 9-2: 100-Year Surface Profile Comparison with Sea Level Rise

In order to predict the maximum flood water elevation at the I-5 Bridge, a series of iterative modeling runs were performed by adjusting the phase of the flood peak to arrive simultaneous with the spring high tide. The same procedure was also repeated separately for both the RR Bridge and the Carlsbad Boulevard Bridges, such that the water levels at the RR and the East Carlsbad Boulevard Bridge are maximized since the flood travel time from the model upstream boundary to each bridge crossing is different. The maximum water surface elevations at the upstream side (eastside edge of the bridge) of the bridges were extracted from the modeling results and summarized in Table 9-1. The last row of the table summarizes the existing bridge soffit elevations (M&N 1993). The soffit elevation of the East Carlsbad Boulevard Bridge is used for the inlet constraint since the West Carlsbad Boulevard Bridge is about 1.8 feet higher in elevation. The 100-year water surface elevations in both year 2012 and 2100 are included in the Table. The water surface elevations in year 2100 take into consideration 55-inches of SLR. The water surface elevations upstream of the bridges are higher than those at the bridge crossings, as shown in the preceding profile Figures. The 100-year water surface elevation touches the east-end soffit of the East Carlsbad Boulevard Bridge as shown in Figure 5-4 in year 2100, but it does not create pressurized flow. Existing Carlsbad Boulevard Bridge has approximately 1.5 feet of freeboard above the 100-year maximum water levels under current conditions. Sufficient freeboard exists above the maximum flood elevations for the I-5 and RR Bridges under both current and future SLR scenarios.

Table 9-1: Summary of Bridge Soffit and 100-Year Surface Water Elevations

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	Inlet (ft, NGVD)		RR (ft, NGVD)		I-5 (ft, NGVD)	
			Year-2012	Year-2100	Year-2012	Year-2100	Year-2012	Year-2100
1	Shoaled	Existing Shoaled	7.1	9.3	7.9	10	8.9	10.7
2	Dredged	Existing Dredged	7.5	9.6	8.1	10.1	8.8	10.6
3	Dredged	Optimized Dredged	7.6	9.7	8.3	10.2	8.6	10.5
4	Shoaled	Optimized Dredged	7.6	9.7	8.4	10.3	8.7	10.5
Bridge Soffit Elevation (ft, NGVD)			9.2		17.3		16.1	

Table 9-2 summarizes 100-year peak flood velocities at bridge crossings under both current and future SLR scenarios. The velocities will be slightly lower under the future SLR scenario than under current conditions because the tidal inlet cross-sectional area is larger under the SLR condition than under existing conditions.

Table 9-2: 100-Year Peak Flood Velocity (fps) at Bridge Crossings

Modeling Scenario	Lagoon Bathymetry	Bridge Condition	Inlet		RR		I-5	
			Year-2012	Year-2100	Year-2012	Year-2100	Year-2012	Year-2100
1	Shoaled	Existing shoaled	9.2	8.5	5.9	5.5	7.1	6.5
2	Dredged	Existing dredged	7.6	7.2	5.0	4.9	6.6	6.3
3	Dredged	Optimized dredged	8.0	7.5	4.5	4.4	4.8	4.5
4	Shoaled	Optimized dredged	7.9	7.4	4.2	4.1	4.7	4.4

10.0 FINDINGS AND RECOMMENDATIONS

Channel dimensions (width and depth) under the I-5 and RR Bridges were optimized to achieve the optimal tidal range and flood conveyance in Batiquitos Lagoon in order to support optimal ecosystem, lagoon circulation and sediment transport conditions. The tidal inlet at Carlsbad Boulevard Bridges has been performing well since construction in 1995, so no further optimization is required for that channel. A summary of findings and recommendations is below.

1. Dredging of the lagoon and channels under the bridges is an effective way to increase the tidal range and reduce tidal velocities under the bridges. Simply dredging the lagoon to its design condition will increase the tidal range by 0.4 feet in the Central Basin and by 0.7 feet in the East Basin, and will reduce the tidal velocity by more than 0.5 fps.
2. The current channel invert elevation of -7 feet NGVD for both the RR and I-5 Bridges is appropriate and is the optimal channel invert elevation.
3. The recommended optimal channel bottom width under the I-5 Bridge is 134 feet, which is 68 feet wider than its current channel width.
4. The recommended optimal channel bottom width under the RR Bridge is 202 feet, which is 40 feet wider than the existing channel width.
5. The tidal range will increase by 0.2 feet in both the Central and East Basins with the optimized channel dimensions under both the I-5 and RR Bridges, compared to those under the existing dredged condition.
6. The flood water surface elevation with the optimized channel dimensions will be lowered in the East Basin, but will be raised in the Central and West Basins compared to those under the existing condition.
7. Tidal flow velocities at the bridge crossings with the optimized channel dimensions will be lowered, especially at the I-5 Bridge, compared to those under the existing condition. This should significantly reduce the scour depth on both sides of the I-5 Bridge. The storm flood velocities will also be lowered.
8. Fluvial sediment transport in the East Basin under the optimized condition should be slightly improved than under existing conditions due to reduced backwater effects and the shortened flood travel time through the East Basin.
9. Residence time, a measure of tidal circulation, is relatively short for Batiquitos Lagoon. In the West Basin the residence time is approximately one half of a day. It gradually increases to approximately 1.5 days in the Central Basin and to about 5.5 days in the East Basin. A residence time of less than one week is considered good for an estuary wetland system. The tidal circulation in Batiquitos Lagoon is good, but can be further enhanced with maintenance dredging.
10. Under the optimized channel dimensions condition the tidal inundation frequency curve is very similar to that under existing conditions. The vertical range of the intertidal habitats would increase slightly under the optimized channel dimensions condition. The

study shows that dredging would increase the vertical tidal range (therefore, the intertidal habitat) by approximately 0.5 feet in the Central Basin and approximately 0.7 feet in the East Basin.

11. In year 2100 with projected SLR, channels under both the existing and optimized I-5 and RR Bridges would pass the 100-year flood with a more than 3 feet of freeboard. However, the east-end soffit of the East Carlsbad Boulevard Bridge will be just below the 100-year flood water level. Flood velocities under the SLR scenario at all three bridge crossings will be lower than those under the current time horizon.

11.0 REFERENCES

California Coastal Records Project. 2012. http://www.large.images.californiacoastline.org /images/2002/large/8/9138.JPG.

California State Coastal Conservancy. 1987. Batiquitos Lagoon Watershed Sediment Control Plan.

California State Coastal Conservancy. 2012. http://scc.ca.gov/2009/01/21/coastal-conservancy-climate-change-policy-and-project-selection-criteria/.

Caltrans. 2011. Guidance on Incorporating Sea-level Rise. Prepared by the Caltrans Climate Change Workgroup and the HQ Divisions of Transportation Planning, Design, and Environmental Analysis. May 16, 2011.

Caltrans. 2012. Proposed Batiquitos Lagoon I-5 Bridge Section. Caltrans, District 11.

Chaudhry, M. Hanif. 1993. Open-Channel Flow. Prentice-Hall, Englewood Cliffs, New Jersey.

Fischer, H.B., List, E.J., et. al., 1979. "Mixing in Inland and Coastal Waters", Academic Press, Inc., 1979.

McAnally, W.H. and Thomas, W.A. 1985. User's Manual for the Generalized Computer Program System, Open Channel Flow and Sedimentation, TABS-2 Main Text. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Merkel & Associates. 2009. Batiquitos Lagoon Long-Term Biological Monitoring Program. Final Report. 2009.

Moffatt & Nichol. 1990. Batiquitos Lagoon Enhancement Plan, Phase I, Preliminary Study Summary Report.

Moffatt & Nichol. 1993. Batiquitos Lagoon Enhancement Plan Set, prepared for City of Carlsbad and Port of Los Angeles.

Moffatt & Nichol. 1997. Batiquitos Lagoon As-Built Plans, prepared for City of Carlsbad and Port of Los Angeles.

Moffatt & Nichol. 2012. San Elijo Lagoon Bridge Optimization Study, Final Report.April 2012.

National Oceanic and Atmospheric Administration. 2005. Oceanic and Atmospheric Research Pacific Marine Environmental Laboratory, Center for Tsunami Inundation Mapping Efforts, http://nctr.pmel.noaa.gov/index.html.

National Oceanic and Atmospheric Administration. 2011. Center for Operational Oceanographic Products and Services, website: http://tidesandcurrents.noaa.gov/.

U.S. Army Corps of Engineers, Los Angeles District. 1971. Flood Plain Information: San Marcos Creek, vicinity of San Marcos, San Diego County, California.

U.S. Army Corps of Engineers. 2009. Users Guide To RMA-2 WES Version 4.5. Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulics Laboratory.

WRA, Inc. 2010. Topographic and Vegetation Analysis of Batiquitos Lagoon and Agua Hedionda Lagoon, I-5 North Coast Corridor Project, San Diego County, California. Prepared for Caltrans, District 11 and San Diego Association of Governments. August 2010.