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Technical Memo - Jacobs Avenue Levee Bathymetric, Hydrologic and Hydraulic Study, Humboldt County, CA

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Engineering – Hydrology – Stream Restoration – Water Resources

TECHNICAL MEMORANDUM

Date: 21 March 2016

To: Hank Seemann
Deputy Director - Environmental Services
Humboldt County Public Works Dept.
1106 Second Street
Eureka, CA 95501

From: Jeffrey K. Anderson, P.E., C50713
Corin Pilkington

21 March 2016

Re: Jacobs Avenue Levee Bathymetric, Hydrologic and Hydraulic Study, Humboldt County, CA

INTRODUCTION AND BACKGROUND

This technical memorandum describes a Hydrologic and Hydraulic Study (H&H Study) for the Jacobs Avenue Levee, conducted by Northern Hydrology & Engineering (NHE) for Humboldt County Public Works (County). The Jacobs Avenue Levee Project Area consists of the entire length of the Jacobs Avenue Levee and a portion of the Murray Field Levee, both located within a slough complex draining to Humboldt Bay (Figure 1). The purpose of the H&H Study is to provide water surface elevations along the Levee within the Project Area for 1% annual chance (100-yr) flood conditions, in support of the geotechnical evaluation of the Levee system.

The work products were developed under an agreement with the County, and include:

1. Collect bathymetric data in Eureka Slough. This task was conducted by GMA Hydrology, Inc., a subconsultant to NHE.
2. Estimate the 1% annual change peak fluvial discharge for Eureka Slough.
3. Determine water surface elevations for the 1% annual chance flood at five designated geotechnical cross-section locations for the following conditions:
    a. Develop a HEC-RAS hydraulic model to characterize fluvial flood conditions within the Project Area.
    b. Use an existing EFDC hydrodynamic model developed for Humboldt Bay by NHE to determine tidally driving flood levels.
4. Perform a general analysis of locally-generated wind waves to semi-quantitatively assess the effects of wind on 1% chance flood levels, to assist with freeboard analysis.
5. Compare results to the most recent readily available work products from FEMA's Open Pacific Coast Study.

All water surface elevations are in feet or meters referenced to NAVD88, unless noted otherwise.

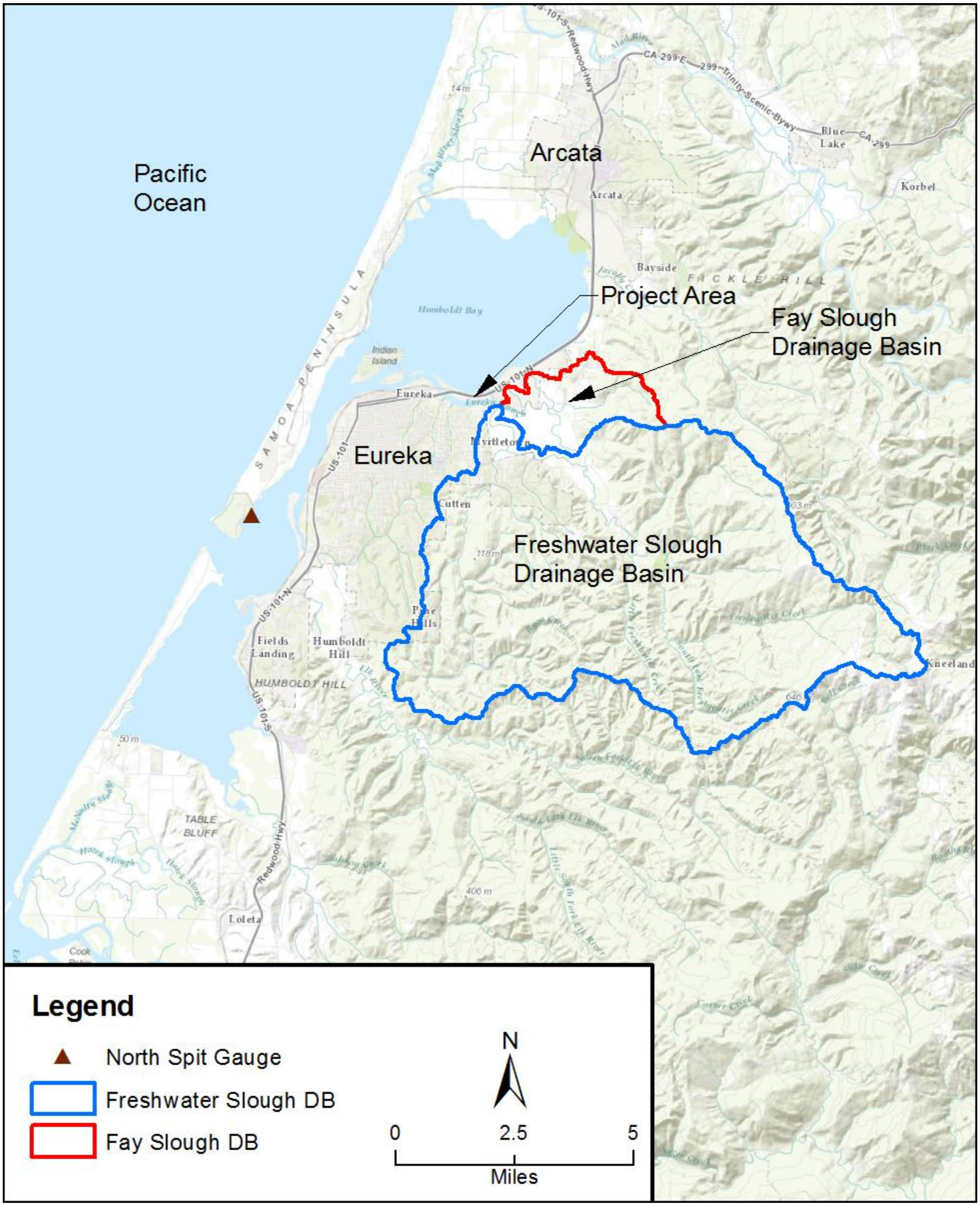


Figure 1. Location map of Jacobs Avenue Levee Project Area, and Freshwater Slough and Fay Slough drainage basin extents.

PROJECT AREA

The general Jacobs Avenue Levee Project Area (Project Area) is located within Eureka Slough, and consists of the Jacobs Avenue Levee Reach located along the northern edge of Eureka Slough, a portion of the Murray Field Levee, and the lower portions of Freshwater Slough and Fay Slough (Figure 2). Eureka Slough is a relatively short slough channel beginning at the confluence of Freshwater Slough and Fay Slough, and ending at its confluence with Humboldt Bay. Five geotechnical borings are located along the Levee as indicated on Figure 2. All cross-sections in the HEC-RAS model are located in Eureka Slough, and the lower portions of Freshwater and Fay Sloughs.

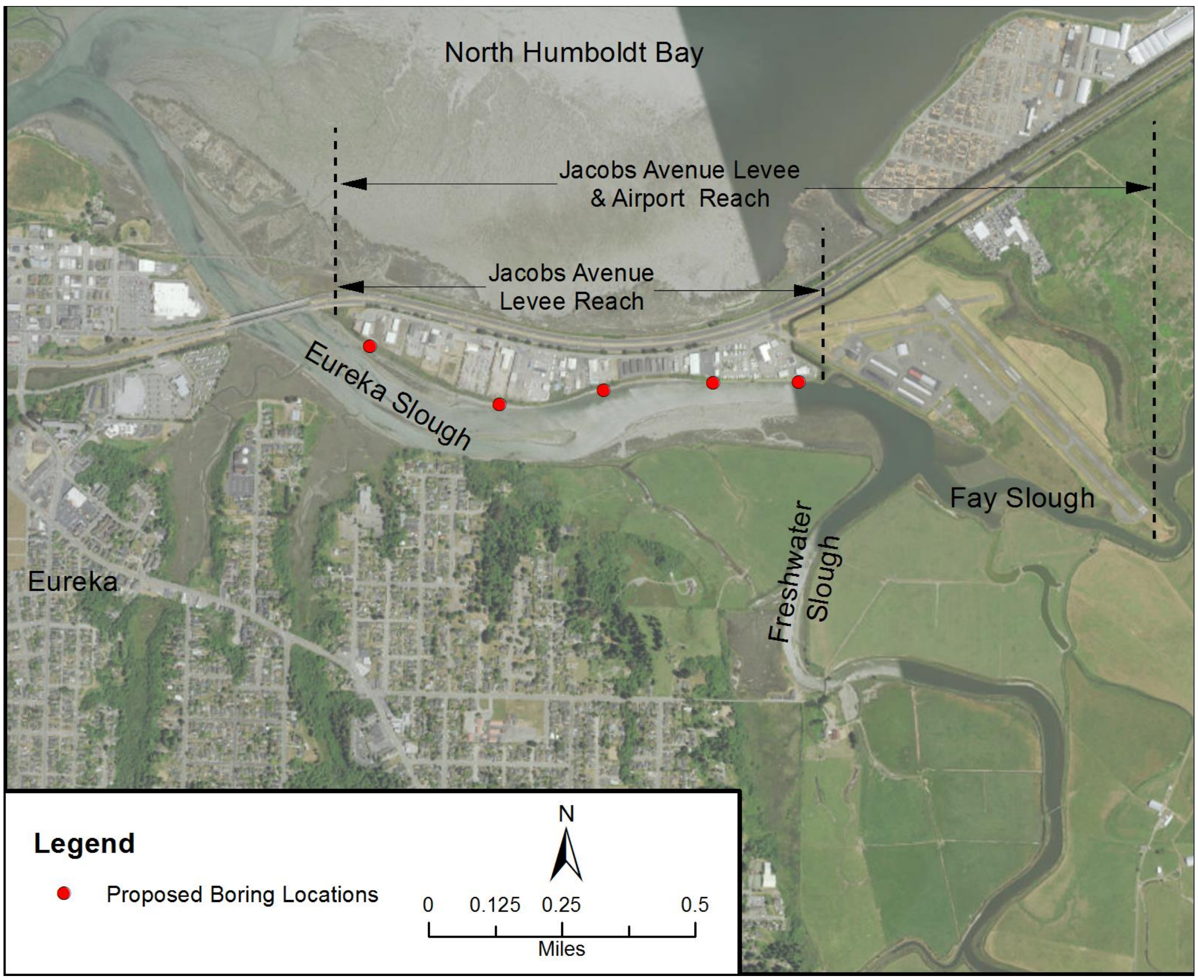


Figure 2. Map showing key features of Jacobs Avenue Levee Project Area.

DISCLAIMER

This study provides estimates of the 1% annual chance (100-yr) flood for both fluvial and coastal flood conditions for the Jacobs Avenue Levee Project Area. The 1% chance fluvial flood estimates were determined using methodologies such that the fluvial estimates are consistent with what FEMA defines as the 1% annual base flood elevation. However, the 1% chance coastal flood estimates do not represent what FEMA would define as the 1% annual base flood elevation for coastal flooding. FEMA's methodology (FEMA, 2004) includes analysis of wave setup and runup when determining the 1% annual base flood elevation for coastal flood conditions. In this study, the 1% chance coastal flood level was determined for both stillwater conditions (no wave effects) and conditions with locally generated wind waves (wave crest elevation). The wave crest elevation does not include the effects of wave setup and runup, which was beyond the available scope and budget for this study.

DATA SOURCES

This section summarizes the available existing data sources used for this study.

Topographic and Bathymetric data

Project Area topography consisted of four sources (Figure 3). In 2011, Humboldt County retained Sousa Land Surveys, Inc. to conduct a LiDAR based topographic survey of the general Jacobs Avenue Levee Project Area (Jacobs Avenue LiDAR), which was the primary upland topographic source. Humboldt County provided NHE a TIN surface of the Jacobs Avenue LiDAR topography. It was necessary to extend the aerial coverage of the Jacobs Avenue LiDAR with the 2009-2011 California Coastal Conservancy Coastal LiDAR project: Hydro-flattened Bare Earth Digital Elevation Model (Coastal LiDAR) downloaded from the NOAA Coastal Services Center Digital Coast website (http://csc.noaa.gov/digitalcoast/).

As part of this work, NHE subcontracted to GMA Hydrology, Inc. to conduct bathymetric surveys of Eureka, Freshwater and Fay Sloughs at approximately 30 cross-section locations. The bathymetric survey was conducted in December 2015 using a single beam sonar and utilizing the same geodetic control as the Jacobs Avenue LiDAR survey. Appendix A contains the GMA Hydrology, Inc. Bathymetric Survey Report.

To better define the crown elevation of the Jacobs Avenue and Murray Field Levees, the County conducted a topographic survey along the top of the Jacobs Avenue Levee and a portion of the Murray Field Levee in February 2016. The County survey used the same geodetic control as the Jacobs Avenue LiDAR survey.

The project topography and bathymetry are referenced to California State Plane Zone 1, NAD83 horizontal datum, and NAVD88 vertical datum.

Wind Data

To conduct the wind wave analysis, wind speed and direction data are required for the general Project Area. A focus for this assessment was to use wind data sources that better represented open water wind conditions, which minimized the need to adjust land-based wind data to open water conditions. Wind speed and direction data were obtained for two stations: (1) Buoy Station 46022 (Buoy 22), National Data Buoy Center, located approximately 20 miles west-southwest of Humboldt Bay; and (2) North Spit Tide Gauge (North Spit), National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS), located interior to Humboldt Bay just north of the inlet (Figure 1). Information summarizing both stations are in Table 1.

Buoy 22 has a 34-yr record of hourly wind observations, and represents offshore wind speed and direction. The North Spit wind data represents wind conditions interior to Humboldt Bay. However, the

North Spit wind data only has an 8-yr record length. The dominant wind direction for both stations is from the north and north-northwest direction, which is the typical direction of spring, summer and early fall winds (Figure 4). Winter storms are generally from the south, and typically associated with the maximum/peak wind velocities (Figure 4).

The selected wind speeds and directions for the wind wave analysis are described in the wind wave analysis section of this memo.

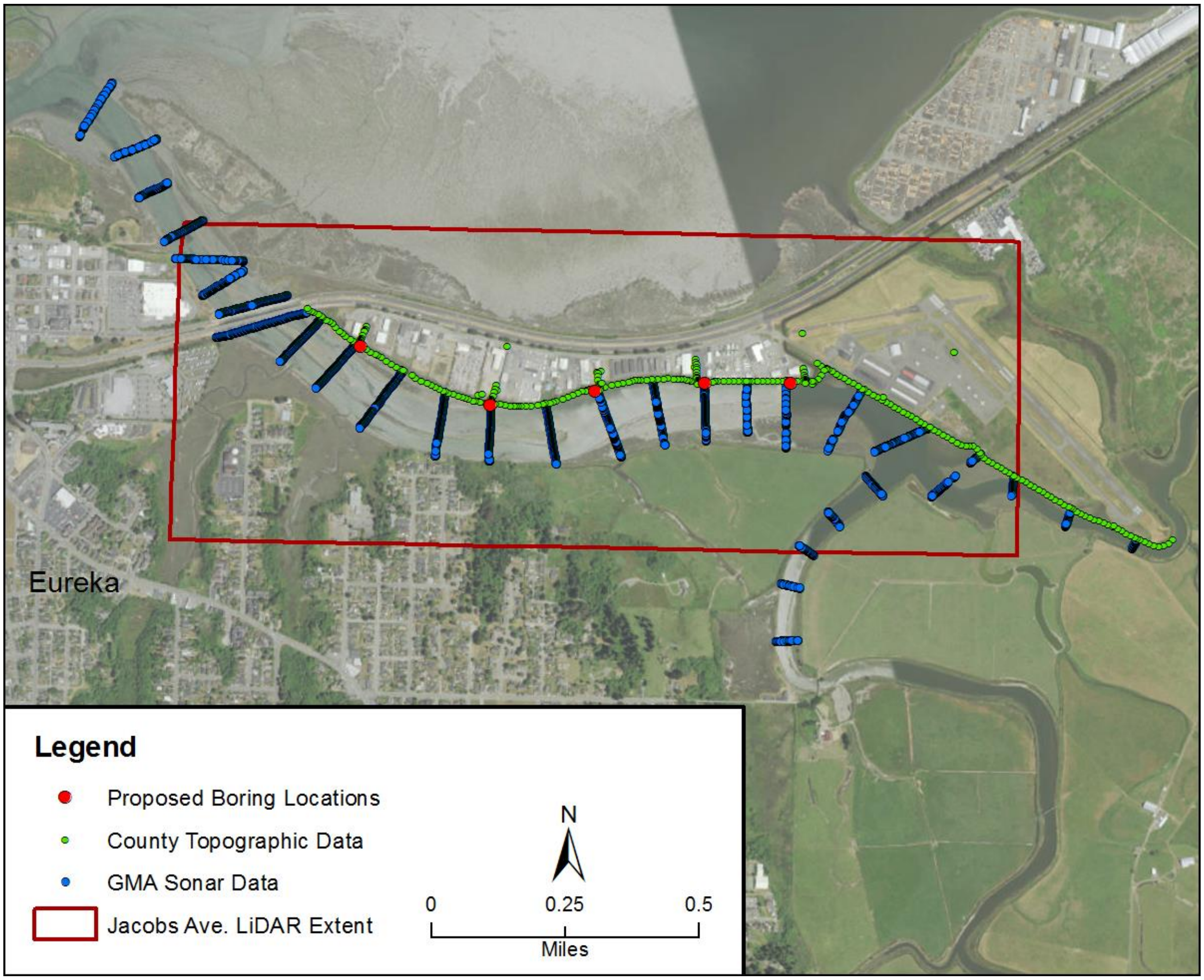


Figure 3. Extent of topographic and bathymetric data sources.

Table 1. Summary information for wind data sources.

Station	Period of Record Used	Anemometer height	Sampling Frequency Used	Data Source (Download Link)
Buoy 22	34-yrs; 1982 to 2015	16.4 ft (5 m)	1-hr	National Data Buoy Center (http://www.ndbc.noaa.gov)
North Spit	8-yrs; 2008 to 2015	44.6 ft (13.6 m)	1-hr	National Oceanic Atmospheric Administration (https://tidesandcurrents.noaa.gov)

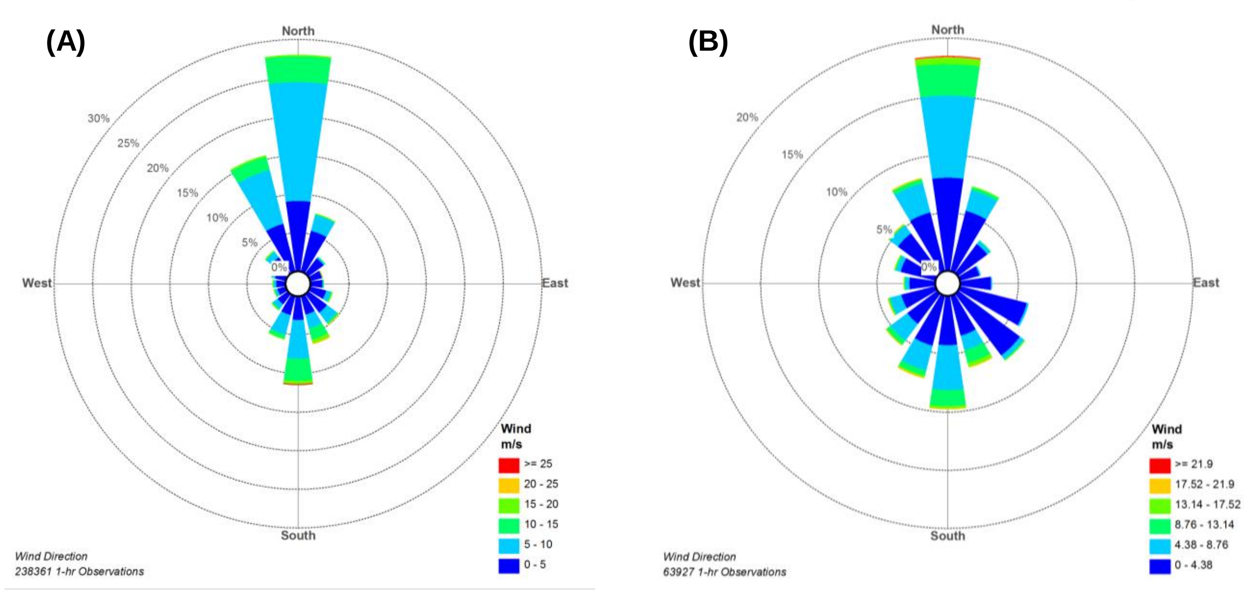


Figure 4. Wind rose plots for the Buoy 22 (A) and North Spit (B) wind data.

Humboldt Bay Coastal Stillwater Flood Elevations

The coastal stillwater flood elevations for the Project Area were taken from the recently completed Humboldt Bay sea level rise (SLR) modeling and inundation vulnerability mapping project conducted by NHE (NHE, 2015). As part of the NHE (2015) work, a two-dimensional hydrodynamic model (2D model) was developed and used to predict water levels within the existing shoreline of Humboldt Bay for five SLR scenarios: year 2012 existing sea levels and half-meter SLR increments of 0.5, 1.0, 1.5 and 2.0 m. The 2D model was forced by a 100-yr long stationary hourly sea level height series developed for the Crescent City tide gauge. The 100-yr hourly series accounts for astronomical tides, and varying effects including wind, sea level pressure, and El Niño variability, and represents ocean stillwater levels. The 100-yr series was incrementally adjusted for each half-meter SLR scenario. Each hydrodynamic model simulation produced 100 years of predicted water levels throughout the bay. Estimates of average high water levels and annual exceedance probabilities of extreme high water levels were determined bay-wide for each of the five SLR scenarios.

For this work, results for the Year 2012 existing sea level simulations were used to represent existing 1% chance coastal stillwater flood elevations at the project area. The 1% chance flood levels were extracted for the model grids adjacent to the Jacobs Avenue Levee and the Murray Field Levee.

The Humboldt Bay 2D model developed for the SLR modeling and mapping project was used for conducting the wind wave analysis in this work. Details of the wind wave analysis methods are provided in a later section of this memo. Reference to the NHE (2015) report can be made for a detailed discussion of the hydrodynamic model development, boundary conditions, and results of the SLR modeling and analysis for Humboldt Bay.

HYDROLOGIC ANALYSIS

This section describes the hydrologic analysis conducted for determining the fluvial flood-frequency estimates for the Project Area.

Methods

Streamflow data for Freshwater Creek above the Project Area are limited (primarily focused on supporting suspended sediment yield estimates) and were not used in this study. For this analysis, flood flow estimates for Eureka Slough at the Project Area were determined immediately downstream of the Freshwater Sough and Fay Slough confluence (Figure 2) using the regional flood-frequency equations for California (Gotvald et al., 2012).

These regional flood-frequency estimates were scaled for Freshwater Slough above the confluence with Eureka Slough using the methodology (Eq. 1) for scaling T-year peak discharge estimates from a gaged station to an ungaged site based on the flow per unit area of the gaged and ungaged stations:

$$Q_{T(U)} = Q_{T(G)} \left[\frac{A_u}{A_g}\right]^b \quad \text{(Eq. 1)}$$

where

$Q_{T(U)}$ is the T-year peak-flood estimate for the ungaged site based on the flow per unit area of the gaged stream,
$Q_{T(G)}$ is the T-year peak-flood estimate for the upstream or downstream gaged station,
A_u is the drainage area for the ungaged site,
A_g is the drainage area for the upstream or downstream gaged station, and
b is an exponent, which can be taken from the regional flood-frequency equations.

The Fay Slough flood frequency estimates were determined by differencing the Eureka Slough and scaled Freshwater Slough peak flows.

Results

Regional-equation parameters for Eureka Slough below the confluence with Freshwater Slough and Fay Slough (Table 2) were determined from the USGS online StreamStats program (http://water.usgs.gov/osw/streamstats/). Table 3 provides a summary of the flood-frequency estimates for the Jacobs Avenue Levee Project Area (Eureka Slough below the confluence with Freshwater Slough and Fay Slough).

Table 2. Regional flood-frequency equation parameters and watershed areas for the Jacobs Avenue Levee Project Area.

Parameter	Unit	Eureka Slough below the confluence with Freshwater Slough and Fay Slough
Basin area	mi^2	53.169
Annual Precipitation	in	52.3

Table 3. Summary of flood-frequency estimates for Eureka Slough below confluence with Freshwater Slough and Fay Slough (Eureka Slough at Project Area).

Return Interval (yr)	Chance Exceedance (%)	Peak Discharge Estimates Eureka Slough below the confluence with Freshwater Slough and Fay Slough (cfs)
2	50	3,230
5	20	5,840
10	10	7,680
25	4	10,100
50	2	11,800
100	1	13,700
500	0.2	17,700

Watershed areas for Freshwater Slough above the confluence with Eureka Slough were also determined using StreamStats. Table 4 lists the ratio between the drainage areas for Freshwater Slough and Fay Slough to Eureka Slough below the confluence. Table 5 summarizes results of the T-year flood flow estimates for Freshwater Slough and Fay Slough above the confluence with Eureka Slough. The exponent (b) used in Eq. 1 are the appropriate California regional flood-frequency equation area exponents (Gotvald et al., 2012).

Table 4. Drainage basin area and ratios for Freshwater Slough and Fay Slough above the confluence with Eureka Slough.

Location	Drainage Area (mi^2)	Ratio of A_u/A_g
Freshwater Slough above confluence with Eureka Slough		
Eureka Slough below the confluence with Freshwater Slough and Fay Slough (A_g)	53.169	0.922
Freshwater Slough above the confluence with Eureka Slough (A_u)	49.024	

Table 5. Scaled flood-frequency estimates for Freshwater Slough and Fay Slough above the confluence with Eureka Slough.

Return Interval (yr)	Eureka Slough below the confluence with Freshwater Slough and Fay Slough Annual-Peak Discharge (Q_g) (cfs)	Regional Eq. Area Exponent (b)	Freshwater Slough above the confluence with Eureka Slough Annual Peak Discharge (Q_u) (cfs)	Fay Slough above the confluence with Eureka Slough Annual Peak Discharge (Q_u) (cfs)
2	3,230	0.904	3,001	229
5	5,840	0.887	5,434	406
10	7,680	0.880	7,151	529
25	10,100	0.874	9,408	692
50	11,800	0.870	10,995	805
100	13,700	0.866	12,770	930
500	17,700	0.860	16,507	1,193

HYDRAULIC ANALYSIS

This section describes the hydraulic analysis conducting for determining water surface elevations for the 1% annual chance (100-yr) flood conditions within the Project Area. The hydraulic analysis consisted of three conditions: (1) fluvial flooding from upstream sources, (2) coastal flooding based on stillwater elevations, and (3) the potential increased coastal flooding from locally generated wind waves.

Fluvial Flooding

Methods

One-Dimensional Hydraulic Model

The U.S. Army Corps of Engineers (COE) HEC-RAS modeling system (COE, 2010) was used to develop a one-dimensional hydraulic model (1D model) of the Jacobs Avenue Levee Project Area. The HEC-RAS model calculates one-dimensional water surface profiles and average channel velocities for both steady gradually varied flow and unsteady flow through a channel. For this analysis, steady flow modeling was used to predict flood levels within the project reach for the Project Area. Reference can be made to the HEC-RAS manual (COE, 2010) for information specific to steady state modeling.

Model Extent and Setup

The 1D model reach includes Eureka Slough from Humboldt Bay to the confluence with Freshwater Slough and Fay Slough, and the lower portions of Freshwater and Fay Sloughs (Figure 2).

To generate the 1D model geometry, a geo-referenced HEC-RAS geometry file was created using ArcGIS. The centerline alignments were digitized from the LiDAR surface and ESRI imagery. The bathymetry points from the 30 surveyed cross-sections (Figure 3) were input into ArcGIS. Cross-section lines were drawn between the points perpendicular to the channel flow, and the surveyed ground elevations were snapped along a perpendicular line to the drawn cross-section line. The Jacobs Avenue LiDAR TIN surface data (Figure 3) within the channel were removed and replaced with the snapped cross-section data. Cross-section lines where extended into the floodplain, and dog-legged perpendicular to the expected flood flow direction based on floodplain contours and professional judgment. Similarly, overbank flow lines were generated based on floodplain contours and professional judgment, and bank lines were determined based on the ESRI imagery.

The HEC-GeoRAS extension was used to create the HEC-RAS geometry file from the surveyed cross-section bathymetric data, the Jacobs Avenue and Coastal LiDAR data, and the cross-section lines, centerline, bank lines, and overbank lines. The geometry file was imported into HEC-RAS and checked for consistency. Final model editing was conducted within HEC-RAS. Figure 5 shows the geometric layout of the developed HEC-RAS model.

A discrepancy was discovered between the LiDAR elevations and the County topography along the levee crown, presumably due to the presence of vegetation, with the LiDAR having elevations 1-foot or greater than the County elevations. To accommodate this difference, all elevations along the Jacobs Avenue Levee and Murray Field Levee above the County surveyed levee crown elevations were truncated within the HEC-RAS model to the crown elevation at each cross-section.

Levees were set at the top of all levee structures, and ineffective flow areas were set in obvious non-conveyance floodplain backwater areas.

For this analysis, the Highway 101 Bridge and Railroad Bridge were not incorporated into the 1D model. Due to the wide, slow velocity nature of Eureka Slough it was assumed that the bridge structures would not have a significant effect on predicted water surface elevations. Furthermore, the skewed bathymetric cross-sections at the Highway 101 Bridge and Railroad Bridge were also not incorporated into the 1D model. A sensitivity analysis showed that water surface elevations varied by only 0.01 ft when the skewed cross-sections were included into the 1D model.

Model Parameters

Manning's roughness coefficients (*n* values) were determined based on prior modeling experience, professional judgment and field observations. Model *n* values were 0.03 for the slough channels, and 0.05 for the tidal wetland, levee and pasture surfaces. Contraction and expansion energy loss coefficients were set at 0.1 and 0.3, respectively, for all cross-sections.

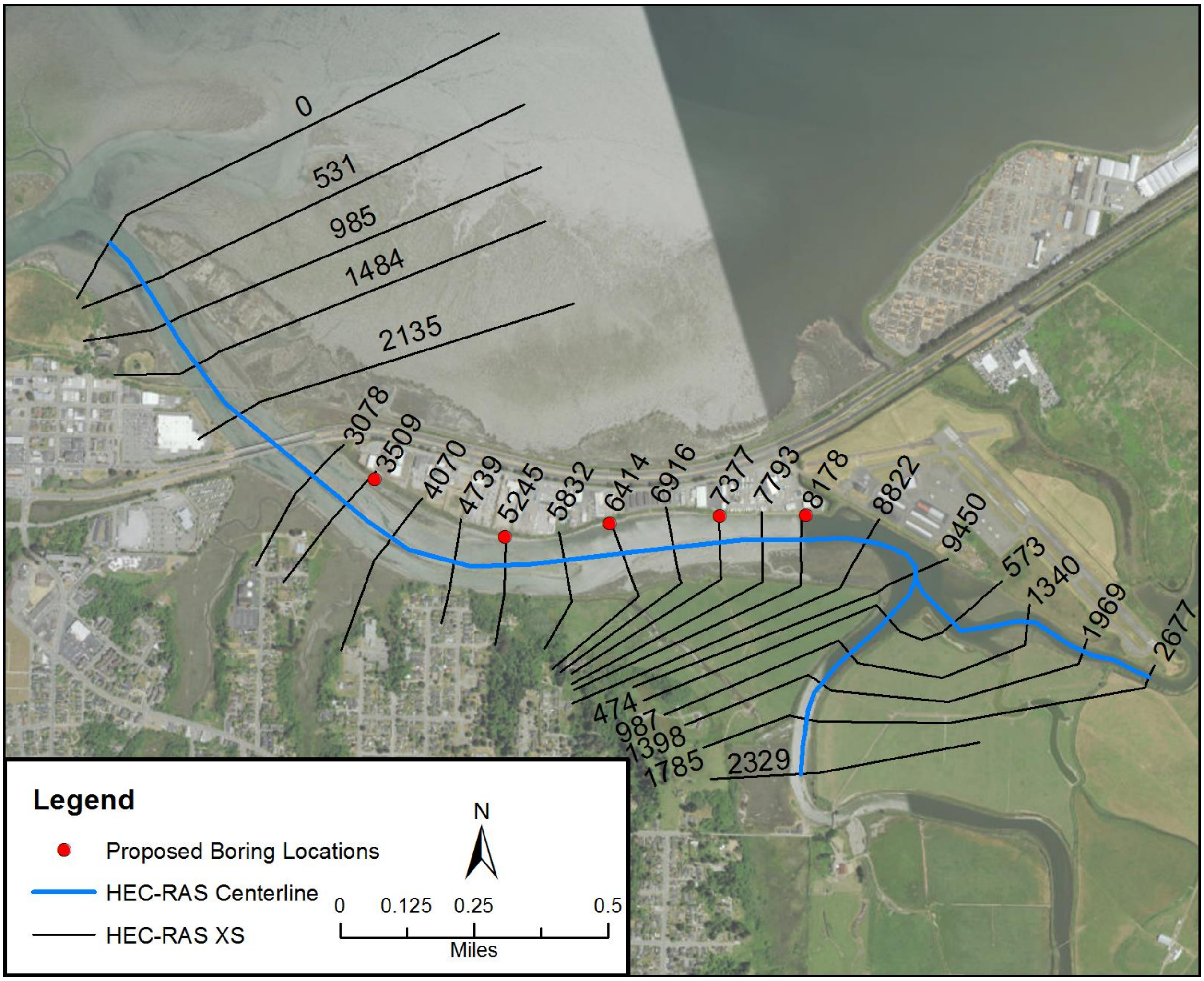


Figure 5. Geometric configuration of 1D model for the Jacobs Avenue Levee Project Area.

Boundary Conditions

The upstream boundary conditions were the 1% chance flood estimates for Freshwater Slough and Fay Slough (Table 5).

The downstream boundary condition consisted of known or estimated water surface elevations at the downstream cross-section (Station 0) of the 1D model (Figure 5). Initially it was assumed that the downstream boundary conditions would be the mean higher high water (MHHW) tide level. However, an evaluation of coincident annual peak flood flows to maximum daily tide levels showed that the likely tidal elevation during a peak flood ranged from MHHW to the 2-yr annual extreme high stillwater level (Figure 6). This evaluation used the Little River annual peak discharge data, and the maximum daily tide level that occurred on the same day as the peak discharge for North Spit and Crescent City tide gauges on station datum (STND).

Based on this evaluation, and discussions with County staff (Hank Seemann, personal communication), it was decided to use mean high water (MHW), MHHW, and the 2-yr annual extreme high stillwater level as downstream boundary conditions for the 1% chance fluvial flood estimate. The MHHW and 2-yr extreme stillwater level downstream boundary conditions were extracted from the HBSLR 2D model results for the Year 2012 simulation (NHE, 2015) at the grid cell coinciding with the downstream cross-section (Station 0) of the 1D model. The MHW estimate was determined by subtracting the average difference of 0.71 ft (0.217 m) between MHHW and MHW for all NOAA tide gauges in Humboldt Bay (NHE, 2015), from the MHHW estimate. Table 6 summarizes the downstream boundary conditions used for the 1% chance fluvial flood estimate.

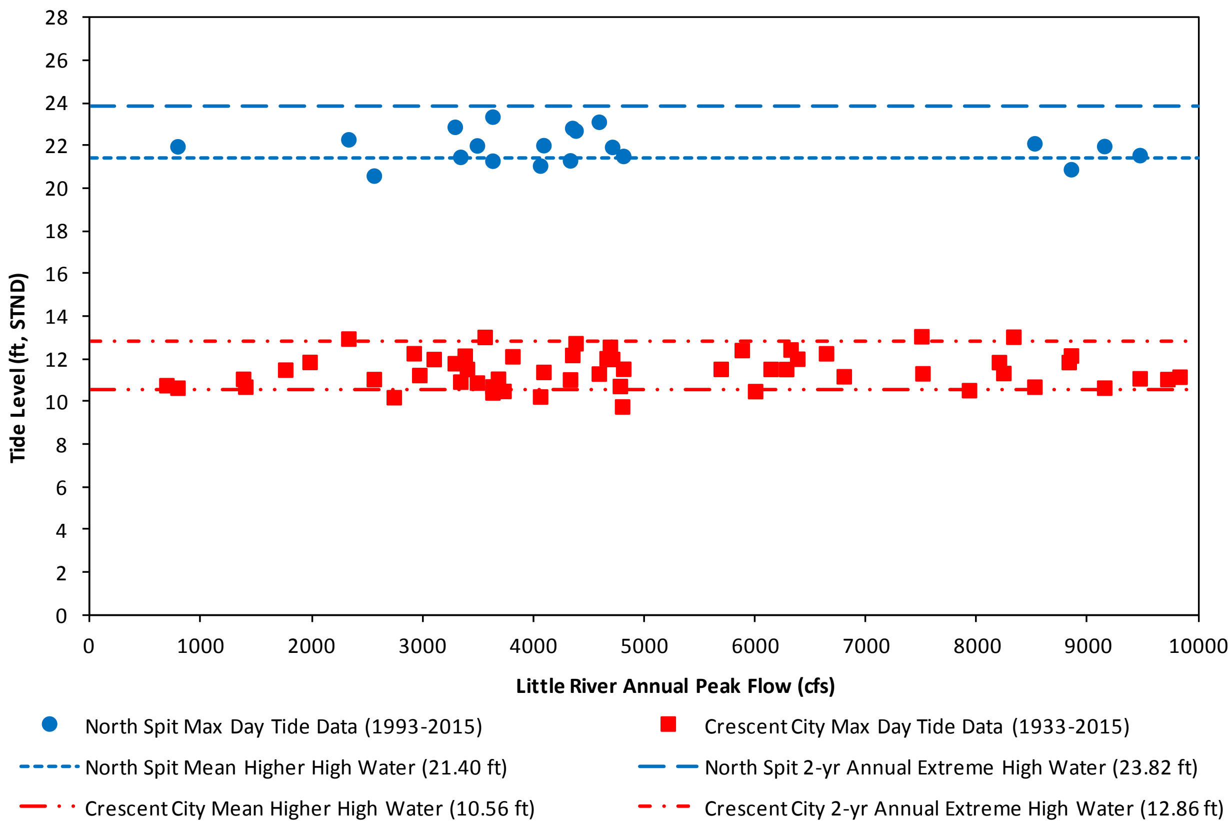


Figure 6. Comparison of Little River near Trinidad (USGS 11481200) annual peak flows and coincident maximum daily tide levels for the North Spit (NOAA 9418767) and Crescent City (NOAA 94119750) tide gauges. Tide gauge data reported on station datum (STND).

Table 6. One-dimensional model (HECRAS) downstream boundary conditions extracted from Humboldt Bay Sea Level Rise 2D model results for Year 2012 (NHE, 2015).

1D model downstream boundary condition	Water surface elevation (EFDC Grid (L) = 1031)	
	(ft, NAVD88)	(m, NAVD88)
Mean High Water	6.29	1.916
Mean Higher High Water	7.00	2.133
2-yr annual extreme water level	9.30	2.836

Results

The developed 1D model (HEC-RAS) for the Project Area was used to predict 1% chance flood water surface elevations from upstream fluvial flooding for three downstream boundary conditions of MHW, MHHW and 2-yr annual extreme high water (Figure 7). Results indicate that the downstream boundary condition has a significant backwater effect on predicted 1% chance fluvial flood water surface elevations along the Jacobs Avenue Levee and Murray Field Levee Reaches. Due to the backwater effects, results for all three boundary conditions were used to represent a range of 1% chance fluvial flood levels for this study.

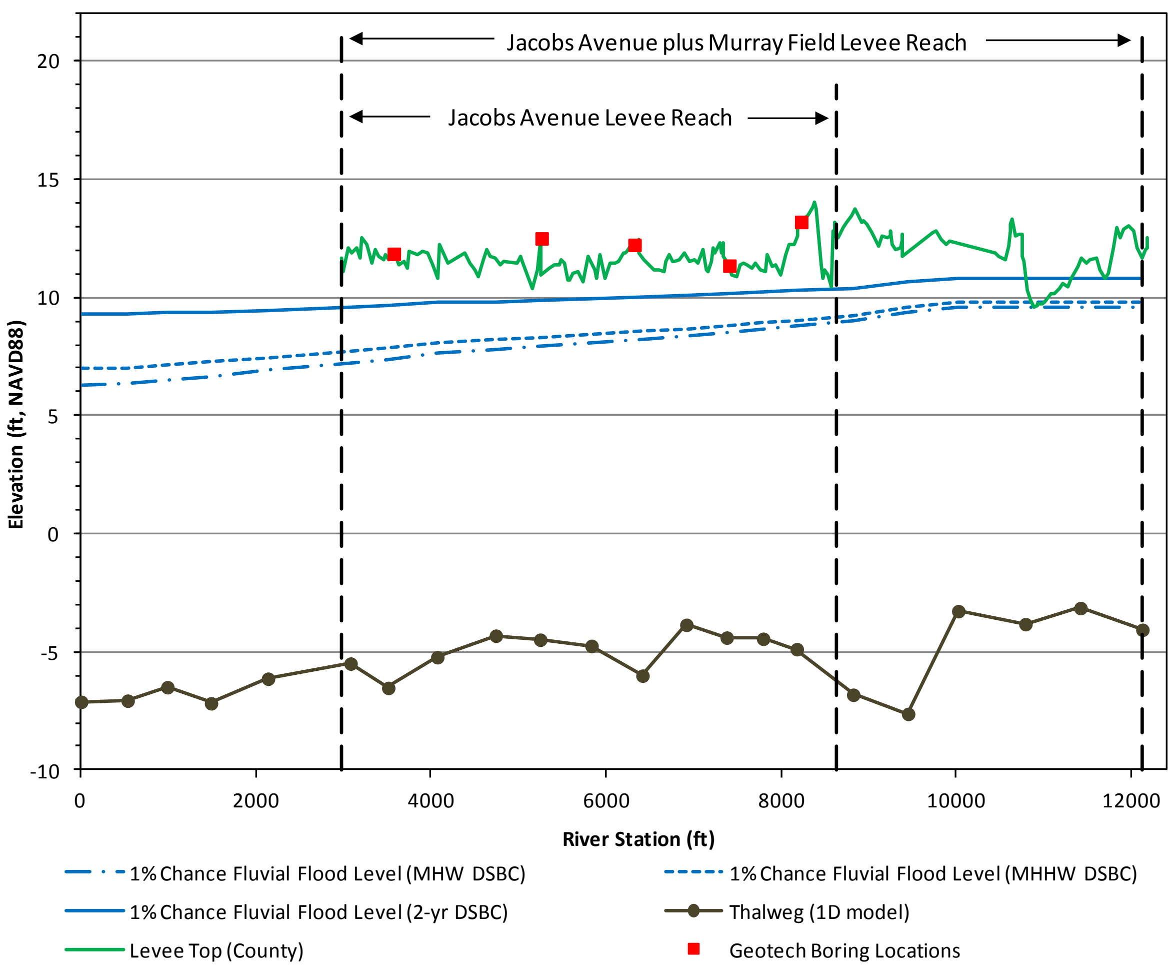


Figure 7. 1% chance fluvial flood profiles for Jacobs Avenue Levee Project Area. Flood profiles are for the 1% chance flood with a mean high water (MHW DSBC), mean higher high water downstream boundary condition (MHHW DSBC), and for the 1% chance flood with a 2-yr annual extreme high water downstream boundary condition (2-yr DSBC).

Coastal Stillwater Level Flooding

Methods

Model results from the Humboldt Bay SLR modeling and mapping project (NHE, 2015) for Year 2012 were used to represent 1% chance coastal stillwater flood levels within the Project Area. The 100-yr annual extreme high water predictions were extracted from approximately sixteen grid cells along the Jacobs Avenue Levee and Murray Field Levee Reaches.

Results

Figure 8 shows the 1% chance coastal stillwater flood elevations within the Project Area. As mentioned earlier, the coastal stillwater flood levels are water surface elevations from open ocean conditions, which include astronomical tides and nontidal sea levels, but exclude the effects of riverine flooding and locally generated wind waves. Figure 8 also shows the estimated 1% chance coastal wave crest flood elevation, which is the combined 1% chance stillwater elevation and the estimated total wave crest height change. The estimated 1% chance coastal wave crest flood level is discussed in more detail below.

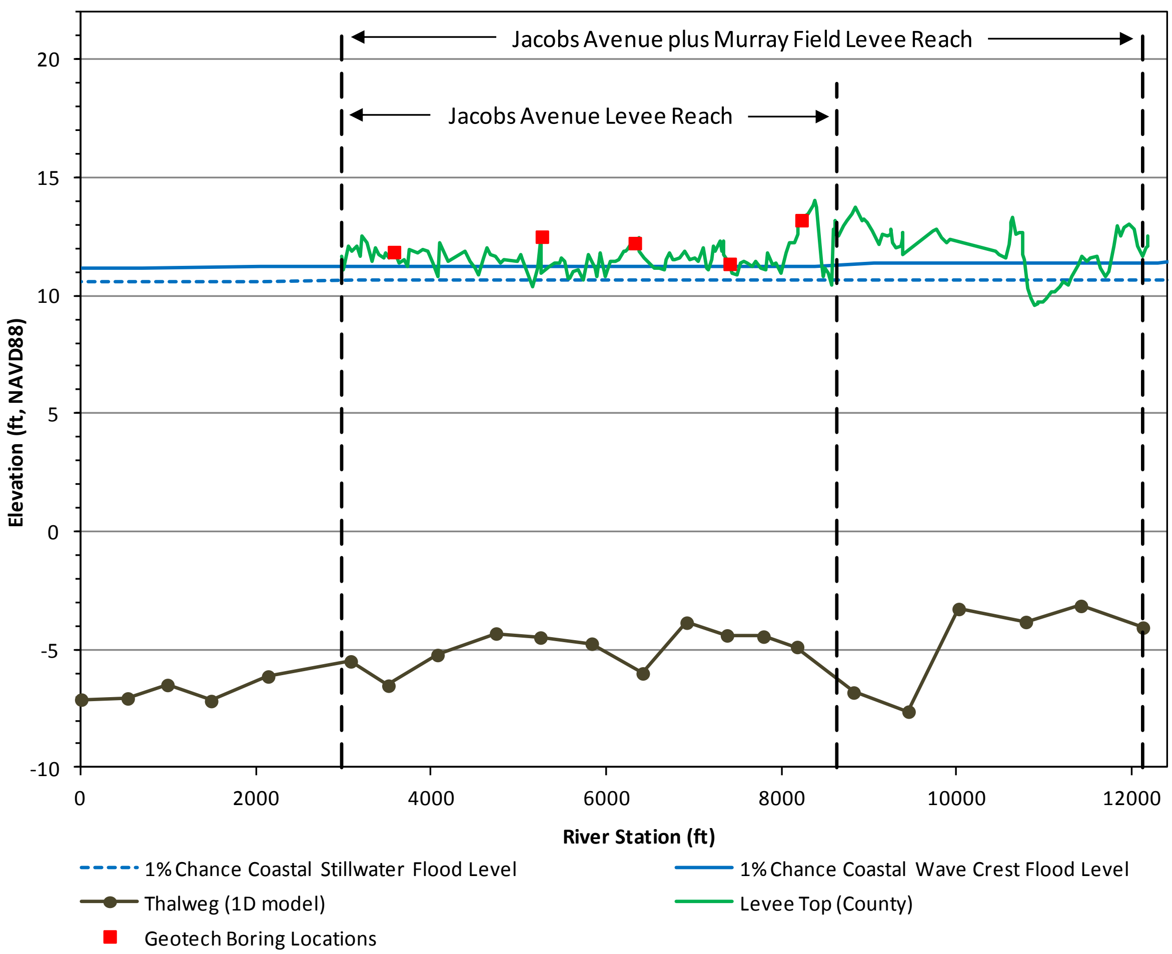


Figure 8. 1% chance coastal flood profiles for Jacobs Avenue Levee Project Area. Flood profiles are for the 1% chance coastal stillwater flood with no wind wave effects, and the 1% chance coastal wave crest flood level, which is the stillwater level plus estimated total wave crest height change.

Coastal Wave Crest Flood Level

Methods

Two-Dimensional Hydrodynamic Model

A general wind wave analysis was conducted for the Project area using the existing 2D model developed in the SLR modeling and mapping project (NHE, 2015), and a basic wind wave sub-model. The 2D model was developed using the Environmental Fluids Dynamics Code (EFDC) modeling platform (Hamrick, 1992), which is a public domain model supported by the U.S. Environmental Protection Agency. EFDC is a multifunctional surface water modeling system for simulating three-dimensional or two-dimensional flow, transport and biogeochemical processes in surface waters including rivers, lakes, wetlands, estuaries and coastal regions. The full documentation of the EFDC model can be found in Hamrick (1992) and Tetra Tech (2007a, 2007b and 2007c).

Dynamic Solutions-International, LLC (DSI) has made a number of enhancements to the EFDC code, and has its own open source version of EFDC (EFDC_DSI). The primary enhancements of EFDC_DSI include (1) dynamic memory allocation, (2) enhanced heat exchange modeling options, (3) Lagrangian particle tracking sub-model, (4) internal wind wave generation sub-model, and (5) the development of a multi-threaded version of EFDC (EFDC_DSI_OMP) that significantly decreases computational time. DSI has also developed EFDC_Explorer7.3 (EE7.3), a windows-based GUI for pre- and post-processing of the various EFDC models (Craig, 2015). EE7.3, EFDC_DSI_OMP, and the DSI wind wave sub-model were used in this study.

The DSI wind wave sub-model (Chung and Craig (2011) is dynamically linked to EFDC_DSI_OMP, and estimates wind wave parameters at each model grid using the Sverdrup, Munk and Bretschneider empirical equations (SMP model) for shallow waters. The SMP model determines wave height, direction and period using wind speed, average water depth over the entire model domain, and wind fetch length from the model boundary to each grid cell over 16 directions. A key assumption of the SMP model is that the wave direction is the same as the wind direction. Consequently, the DSI wind wave sub-model does not account for the effects of wave refraction, diffraction and reflection. A full description of DSI wind wave model and formulation can be found in Chung and Craig (2011).

Besides providing estimates of wind wave height and period over the entire model domain, another advantage of using the 2D hydrodynamic model linked to a wind wave model is that the effects of wind stress on the water levels (wind setup) are directly accounted for in the simulation.

Model Extent and Setup

The same general 2D model grid used in the SLR modeling project was used for the general wind wave analysis work (Figure 9). The original 2D model was coarsely gridded in the general Jacobs Avenue Levee Project Area. To support the wind wave modeling and provide more resolution in the Project Area, the model grid was refined in Eureka Slough and lower Fay Slough (Figure 10). To preserve the original 2D model grid formulation and results, the original model grid elevations were interpolated to the refined model grid elevations.

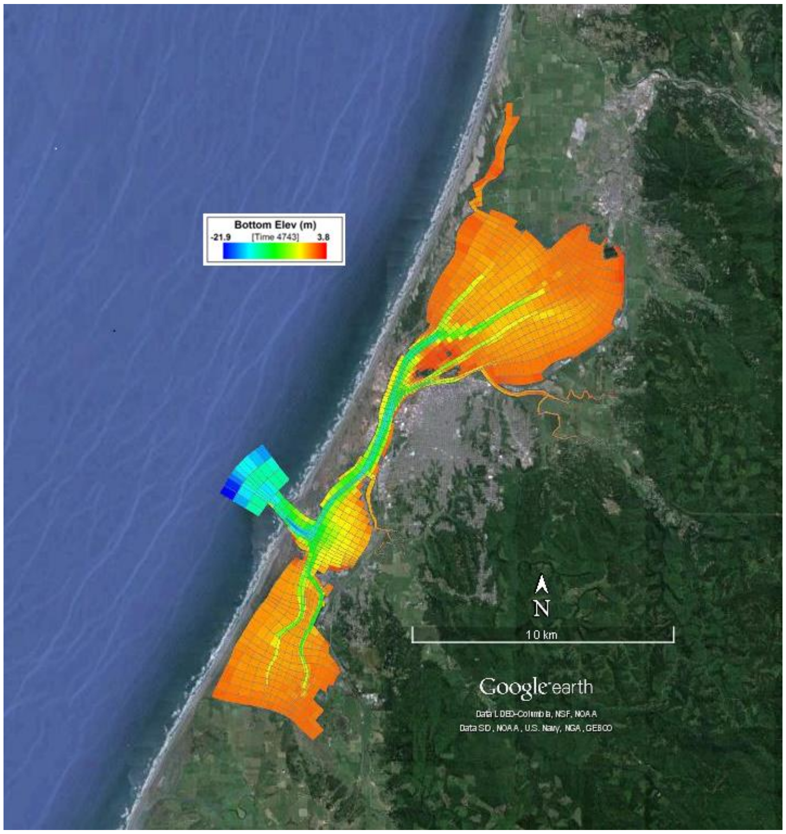


Figure 9. Humboldt Bay sea level rise modeling and mapping project 2D hydrodynamic model grid and bottom elevations (m) referenced to NAVD88 (NHE, 2015).

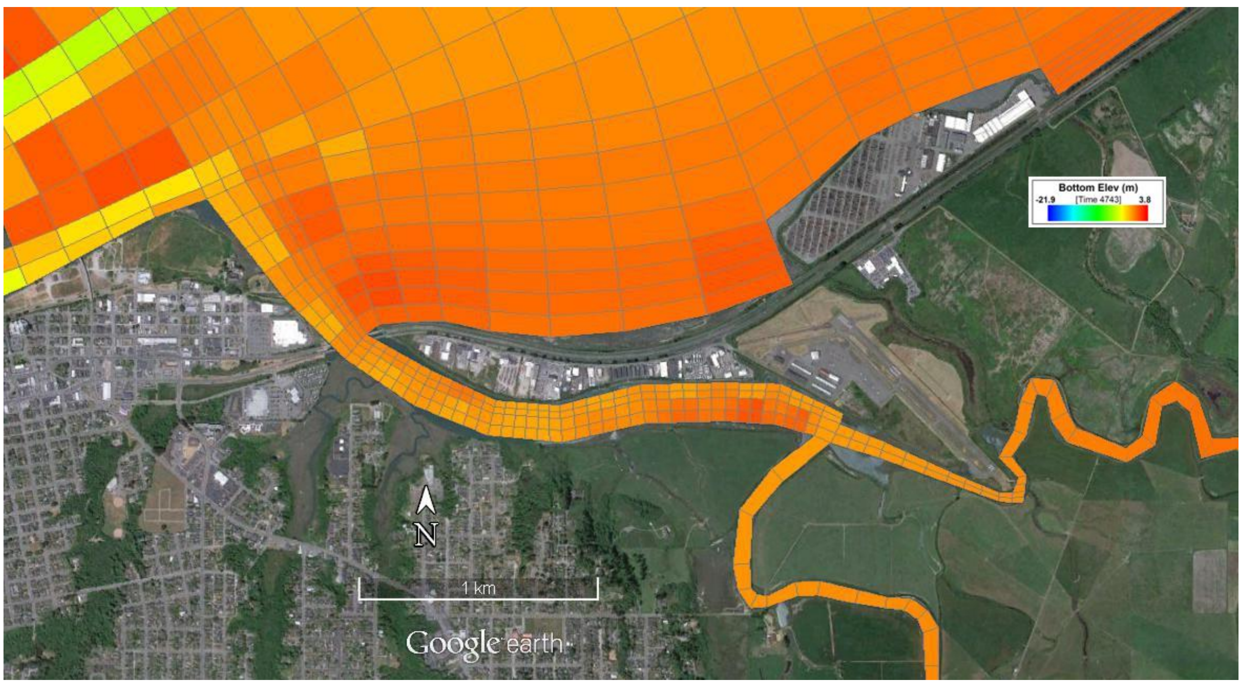


Figure 10. Refined 2D model grid in the Jacobs Avenue Levee Project Area.

Model Parameters

The same 2D model parameters used in the SLR modeling project (NHE, 2015) were used for the wind wave analysis, with the total effective roughness height (Z_0) set to 0.005 m. Since wave data were not available to calibrate the wind wave sub-model, the simpler wave model option that does not account for radiation stresses was used. The only wave parameter required for the simpler option was the Nikuradse sand roughness height (K_s). Assuming the Project Area consists of fine-grained bed materials, a conservative K_s value of 2.5E-5 was used for all wind wave simulations.

Boundary Conditions

Boundary conditions for the wind wave analysis consisted of open ocean water levels, wind speed and wind direction. The purpose of the wind wave analysis was to understand how wind and wave conditions could affect extreme coastal stillwater flood levels. This was accomplished by running the modified 2D model over a range of wind conditions and directions for a 7-day period that had produced the highest stillwater levels.

Ocean Water Levels

The ocean boundary condition for the wind wave analysis consisted of a 7-day period from the 100-yr hourly sea level height series that contained the maximum observed water level for the Crescent City tide station. The 7-day period spanned 19 to 26 January 1983, which was during the 1982-83 El Niño. During this 7-day period a large El Niño driven storm coincided with higher than normal astronomical high tides producing the highest water level of record at the Crescent City tide gauge on 29 January 1983 that exceeded the 100-yr extreme exceedance probability event (NHE, 2015). The highest predicted stillwater levels in Humboldt Bay for the SLR modeling project were also generated on 29 January 1983 (NHE, 2015).

Wind Speed

To better understand the likelihood that peak water levels and maximum wind events occur simultaneously, the Buoy 22 hourly wind speeds greater than or equal to 33.6 mph (15 m/s) were compared to the hourly tide levels for North Spit and Crescent City occurring at the same time (Figure 11). A similar comparison was not conducted for the North Spit wind data due to the short 8-yr period of record.

Results of this assessment show that North Spit water levels do not exceed the 2-yr annual extreme water level (50% chance) for wind speeds at Buoy 22 greater than or equal to 33.6 mph. However, the North Spit tide gauge hourly water level record only begins in 1993, and does not cover the 1982-83 El Niño. Results for Crescent City water levels and Buoy 22 winds (Figure 11), which covers the 1982-83 El Niño period, show that a number of extreme water levels greater than the 2-yr (50% chance) event occurred during periods when the wind was greater than or equal to 33.6 mph. In fact, the 29 January 1983 extreme water level event occurred when winds exceeded 33.6 mph. Based on this assessment, extreme coastal water levels can and do occur during peak wind events.

The maximum hourly wind speed for the 34-yr Buoy 22 wind record was 55.9 mph (25.0 m/s) and was from the south. The shorter 8-yr North Spit wind record had a maximum hourly wind speed of 49.0 mph (21.9 m/s) which blew from the north.

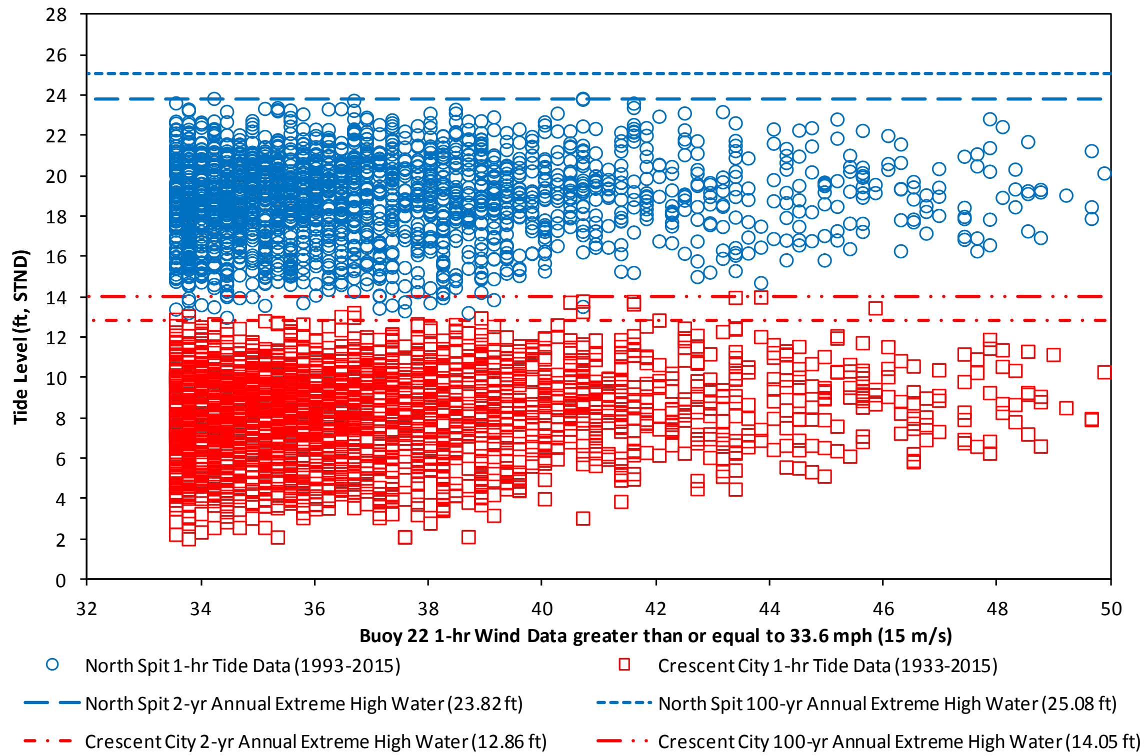


Figure 11. Comparison of Buoy 22 hourly wind data greater than or equal to 33.6 mph (15 m/s) and coincident hourly tide levels for the North Spit (NOAA 9418767) and Crescent City (NOAA 94119750) tide gauges. Tide gauge data reported on station datum (STND).

Maximum Fetch Lengths

At a given location and wind speed, the SMP wind model generally produces maximum wind wave heights and periods for the wind direction with the maximum fetch length. The 2D model and wind wave sub-model automatically determines fetch lengths for each model grid cell for 16 wind directions at 22.5° increments. Within the Project Area, maximum fetch lengths are for winds blowing from westerly and easterly directions, due to the configuration of Eureka Slough. However, maximum wind speeds in the Project Area are generally from northerly and southerly directions, with much lower maximum wind speeds for winds from easterly and westerly directions (Figure 4). The Buoy 22 and North Spit wind records indicate that no wind greater than or equal to 44.7 mph (20.0 m/s) has come from a westerly or easterly direction, and only a few hourly records are greater than equal to 33.6 mph (15 m/s).

Wind Analysis Approach

For the wind analysis conducted in this study, the 2D model was run over a range of constant wind speeds and directions for the 7-day period of 19 to 26 January 1983, to see how wind and wave conditions could affect maximum predicted stillwater levels. The wind speed ranged from 11.2 to 55.9 mph (5 to 25 m/s) at 11.2 mph (5 m/s) increments, and was applied over 16 wind directions at 22.5° increments.

Results

The 2D model and wind wave sub-model was used to estimate how wind and waves could increase extreme stillwater elevations at the Jacobs Avenue Levee Project Area for a range of wind speeds and directions. Since five wind speeds were simulated over 16 directions, the wind analysis produced a large amount of data and results. Only summary results of the wind analysis are provided below.

Results were evaluated at each grid cell adjacent to the Jacobs Avenue and Murray Field Levee Reach for the following:

1. Water level change compared to the stillwater results (no wind condition), which represents the wind setup effect.
2. Wind wave height, which is the total wave height from wave trough to crest.
3. Total wave crest height change, which is the sum of the water level change and one-half the wind wave height.

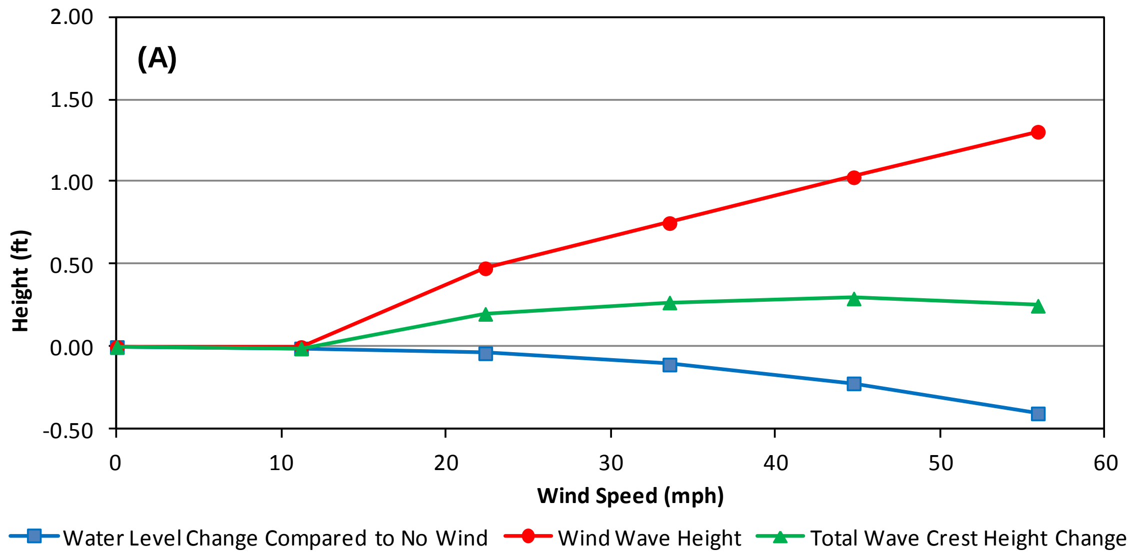
Table 7 presents results for the grid cell that produced the largest wind wave height and total wave crest height change along the Jacobs Avenue Levee Reach compared to the stillwater condition for three wind directions; east-southeast (ESE), west (w), and west-northwest (wnw). For comparison purposes, results are also provided for the maximum grid cell along the entire Jacobs Avenue and Murray Field Levee Reach for a west wind.

Results indicate that maximum wind wave heights along the Jacobs Avenue Levee Reach occur for winds from the east-southeast direction. However, the dynamics of an east-southeast wind reduces the water level along Jacobs Avenue Levee compared to the no wind condition, which results in the lowest total wave crest height change for the wind directions reported in Table 7 (Figure 12(A)). The maximum total wave crest height change along the Jacobs Avenue Levee occurs for a west-northwest wind direction (Figure 12(B)). These results demonstrate the advantage, and perhaps need, of using a coupled 2D hydrodynamic model and wind wave model when extreme water levels occur during maximum or peak wind events.

Wind wave results for a 44.7 mph (20 m/s) wind from the west-northwest direction were used to represent the total wave crest height change (0.72 ft) for the Jacobs Avenue Levee Project Reach. The 0.72 ft total wave crest height change was added to the stillwater levels along the entire Jacobs Avenue and Murray Field Levee Reach. (Figure 8).

Table 7. Wind wave analysis summary results for wind directions producing maximum wave heights and water level changes for the Jacobs Avenue Levee Project Area. Water level change compared to no wind column is the difference between predicted water level with wind and predicted water level without wind, and represents wind setup. Wind wave height column is the total wave height from trough to crest. Total wave crest height change column is the sum of water level change and one-half wind wave height.

Wind Speed	Wind Direction From	Levee Reach	Water Level Change Compared to No Wind (ft)	Wind Wave Height (ft)	Total Wave Crest Height Change (ft)
11.2 mph (5 m/s)	ESE	Jacobs Ave	-0.01	0.00	-0.01
	W	Jacobs Ave	0.01	0.00	0.01
	WNW	Jacobs Ave	0.01	0.00	0.01
	W	Jacobs Ave and Murray	0.01	0.00	0.01
22.4 mph (10 m/s)	ESE	Jacobs Ave	-0.04	0.48	0.20
	W	Jacobs Ave	0.06	0.35	0.24
	WNW	Jacobs Ave	0.05	0.40	0.25
	W	Jacobs Ave and Murray	0.07	0.52	0.33
33.6 mph (15 m/s)	ESE	Jacobs Ave	-0.11	0.75	0.27
	W	Jacobs Ave	0.16	0.56	0.44
	WNW	Jacobs Ave	0.14	0.63	0.46
	W	Jacobs Ave and Murray	0.17	0.82	0.58
44.7 mph (20 m/s)	ESE	Jacobs Ave	-0.22	1.03	0.29
	W	Jacobs Ave	0.32	0.77	0.70
	WNW	Jacobs Ave	0.28	0.87	0.72
	W	Jacobs Ave and Murray	0.34	1.12	0.90
55.9 mph (25 m/s)	ESE	Jacobs Ave	-0.40	1.30	0.25
	W	Jacobs Ave	0.53	0.99	1.02
	WNW	Jacobs Ave	0.48	1.12	1.04
	W	Jacobs Ave and Murray	0.57	1.42	1.28



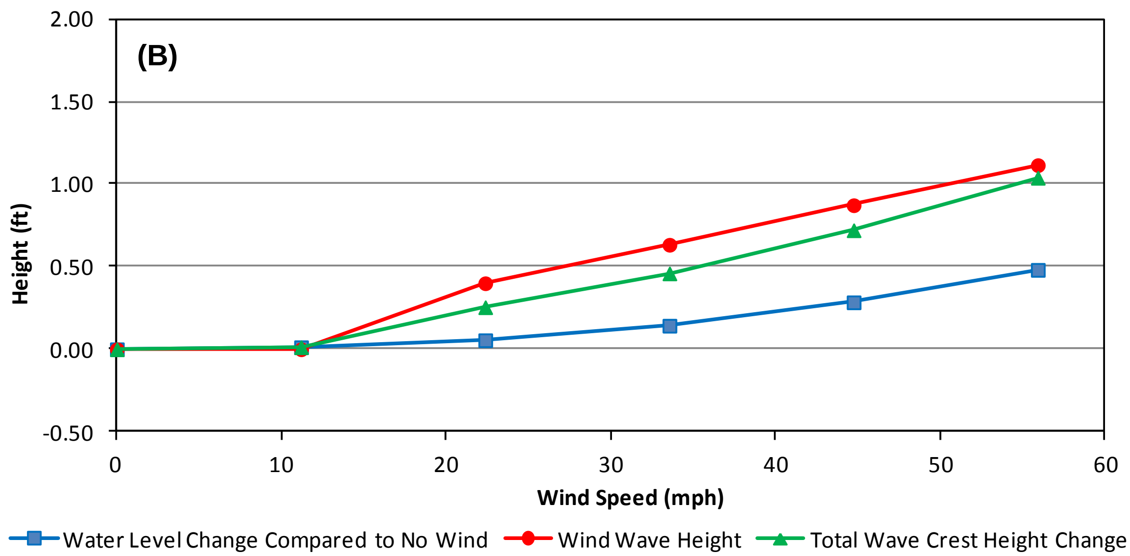


Figure 12. Wind wave results for wind from the east-southeast direction (A), and west-northwest direction (B).

1% Chance Flood Elevations

This section summarizes the final 1% chance flood elevations for the Jacobs Avenue Levee, and at the five geotechnical boring locations.

Jacobs Avenue Levee Reach

Figure 13 shows the final estimated 1% chance flood elevations along the Jacobs Avenue Levee Project Area for a fluvial flood, coastal stillwater flood, and coastal wave crest flood (stillwater plus wave crest height change), and the Levee crown elevations from the County survey. Coastal flood elevations are greater in the Jacobs Avenue Levee Reach than fluvial flooding, with the effects of wind waves increasing coastal stillwater levels. Results indicate that the 1% chance flood for both coastal stillwater and coastal wave crest flood conditions can produce water levels that overtop the Jacobs Avenue Levee. Table 8 summarizes the difference between 1% chance flood levels and the Levee crown elevation for the Jacobs Avenue Levee Reach. Positive numbers indicate available freeboard, and negative numbers indicate no freeboard is available.

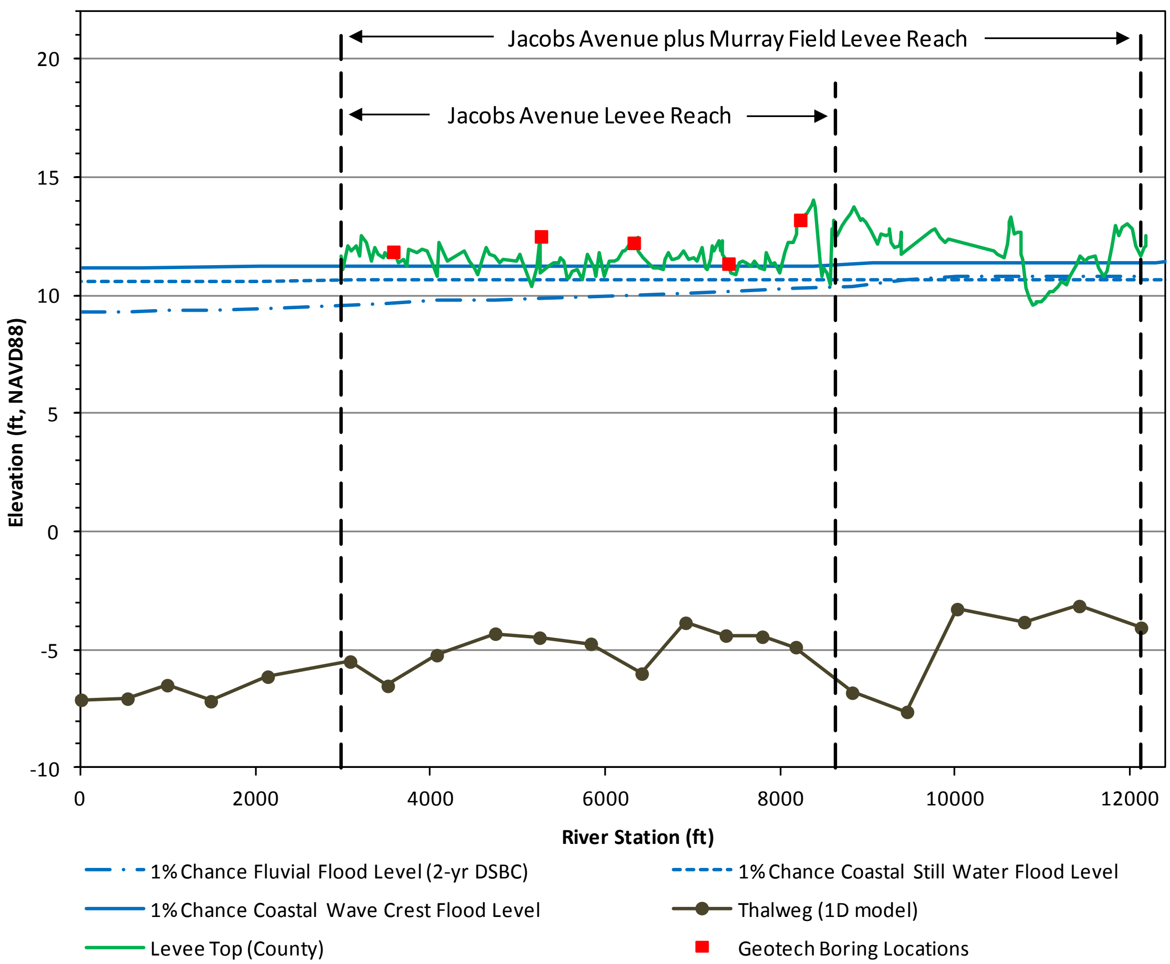


Figure 13. Final 1% chance flood profiles for Jacobs Avenue Levee Project Area. Flood profiles are for the 1% chance fluvial flood, 1% chance coastal stillwater flood with no wind wave effects, and the 1% chance coastal wave crest flood (stillwater plus wave crest height change).

Table 8. Summary of levee freeboard for 1% chance flood levels along the Jacobs Avenue Levee (positive numbers indicate levee freeboard, negative numbers indicate no freeboard).

Statistic	Difference between crown elevation and 1% Chance Flood Water Surface Elevation (ft)		
	Fluvial Flood	Coastal Stillwater Flood	Coastal Wave Crest Flood
Average	1.70	1.02	0.44
Minimum	0.52	-0.24	-0.81
Maximum	3.66	3.34	2.76

Geotechnical Boring Locations

Table 9 summarizes the 1% chance flood levels at the five geotechnical boring locations. Based on conversations with County staff (Hank Seemann, personal communication), water surface elevations are only provided for the 1% chance fluvial flood, and 1% chance coastal stillwater flood. For the 1% chance fluvial flood, results are provided for the MHW, MHHW, and 2-yr extreme stillwater level downstream boundary conditions. For the coastal stillwater flood condition, results are provided for the 50-, 20-, 10-, 2-, and 1% chance levels.

Table 9. Summary of fluvial and coastal stillwater flood elevations (ft, NAVD88) at the five geotechnical boring locations within the Jacobs Avenue Levee Project Area.

Geotech Boring Number	1% Chance Fluvial Flood (Downstream boundary condition)			Coastal Stillwater Flood (% Chance Level)				
	MHW	MHHW	2-yr	50	20	10	2	1
1	7.41	7.86	9.66	9.34	9.73	9.97	10.45	10.63
2	7.92	8.29	9.88	9.34	9.74	9.98	10.46	10.63
3	8.22	8.54	10.03	9.35	9.74	9.99	10.46	10.64
4	8.48	8.78	10.15	9.36	9.75	9.99	10.47	10.65
5	8.80	9.04	10.31	9.36	9.76	10.00	10.47	10.65

COMPARISON WITH RESULTS FROM FEMA'S OPEN PACIFIC COAST STUDY

In 2015, BakerAECOM completed a coastal engineering study of the Open Pacific Coast (OPC) along northern and central California on behalf of FEMA Region IX as part of the California Coastal Analysis and Mapping Project. The results of the OPC study were used by FEMA to prepare preliminary Flood Insurance Rate Map (FIRM) panels. The preliminary FIRM panels were released on October 27, 2015, and are expected to become effective in 2017. The OPC study used different data sets, methodologies, and models compared to NHE (2015) and this Jacobs Avenue Levee study. This section is intended only to present the OPC study results and mapping information on the associated preliminary FIRM panel relevant for the Project Area, and does not discuss the different approaches in detail.

The 1% chance stillwater elevation at the North Spit gauge site was calculated to be 10.2 feet (NAVD88) (BakerAECOM, 2012). BakerAECOM elected to apply a uniform stillwater elevation throughout the bay. BakerAECOM evaluated locally generated wind waves at 20 transects within Humboldt Bay (BakerAECOM, 2014); however, the wind wave analysis was only conducted for Arcata Bay and did not extend into Eureka Slough.

On the preliminary FIRM panel (Map No. 06023C0845G) depicting the Project Area (Figure 14), Eureka Slough and the land behind the Jacobs Avenue Levee are mapped as a special flood hazard zone without a designated base flood elevation (i.e., an unnumbered Zone A). Highway 101 and the North Coast Railroad Authority railroad corridor serve as a boundary between flood zones on the preliminary FIRM panel. The area within Arcata Bay near the Project Area on the north side of the highway and railroad corridor is mapped with a base flood elevation of 11 feet (i.e., Zone AE 11). This base flood elevation reflects a total water level of 10.73 feet (10.16 feet stillwater elevation plus 0.57 feet wave runup), rounded to the nearest foot.

For comparison, this study calculated a 1% annual chance stillwater elevation of 10.63 to 10.65 feet, and a coastal wave crest flood level of 11.35 to 11.37 feet, along the Jacobs Avenue Levee.

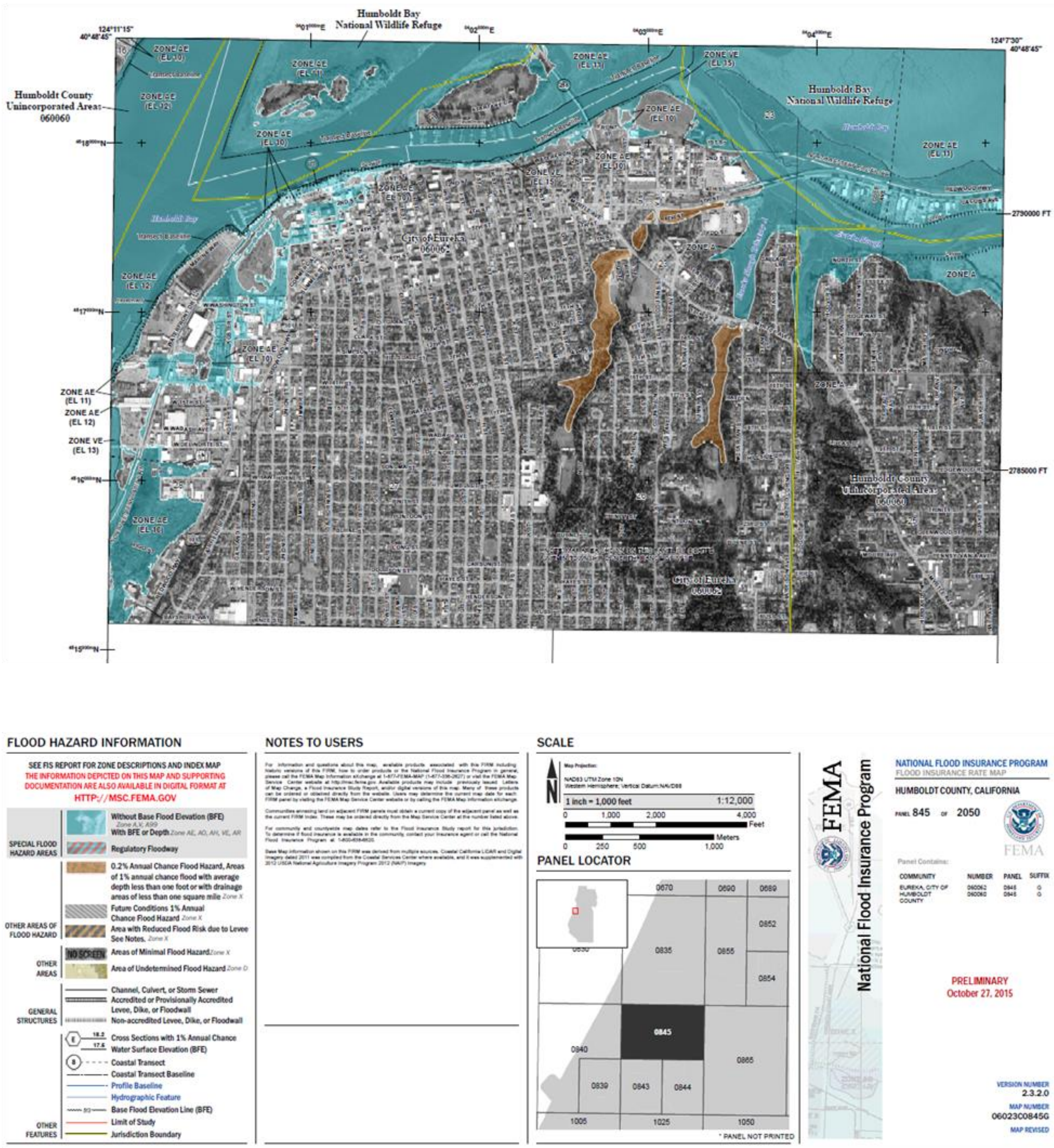


Figure 14. **Portion of the preliminary FIRM panel (Map No. 06023C0845G) and legend information for the Jacobs Avenue Levee Project Area.**

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APPENDIX A

Bathymetric Survey Report

BATHYMETRIC SURVEY REPORT

JACOBS AVENUE LEVEE EVALUATION
EUREKA, CA

County of Humboldt Service Agreement 251059

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December 2015

Hydrology – Geomorphology – Stream Restoration
Land and Hydrographic Surveys

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INTRODUCTION

In November 2015, GMA Hydrology, Inc. (GMA) was contracted by Northern Hydrology and Engineering (NHE) to collect bathymetric cross sectional data on Eureka Slough within the vicinity of Jacobs Avenue in Eureka, CA. The project is located on the north side of Eureka, CA, extending up and downstream of the Highway 101 bridge over Eureka Slough. Cross sections for data collection are located within an area 1.7 miles upstream of the Highway 101 bridge, into Freshwater Slough and Fay Slough, and half a mile downstream of the Highway 101 bridge (Figure 1). NHE requested that the survey be consistent with the datum and projection used by Sousa Land Surveying Inc. during the Humboldt County LiDAR Survey Project

Figure 1: Project Location Map

GEODETIC CONTROL

GMA requested the survey control coordinates for the Humboldt County LiDAR Survey Project from NHE so that the sonar data could be tied directly to the LiDAR datum. Review of data indicated that the horizontal datum is based on NAD83 (2007.00) and the vertical datum is based on NAVD88, Geoid 09. Data are projected in California State Plane Zone 1 and units are US Survey Feet (us ft).

METHODOLOGY

GNSS Reference Station

GMA established a Trimble R8 Model 3 Real Time Kinematic (RTK) Global Navigation Satellite System (GNSS) base receiver on LV1180. LV1180 is located at Murray Field and is a standard survey disk that is set in the top of a 10-inch concrete post. The NAD83 (2007.00) coordinates were held by Brian L. Sousa (CAPLS#7917) as part of the Humboldt County LiDAR Survey Project. In addition to monument LV1180, GMA utilized two other monuments, points 102 and 1045, in order to verify antenna heights and to check the relative stability of the control provided.

Single Beam Sonar Survey

NHE provided cross section data collection locations in shapefile format (Figure 1). The bathymetric sonar survey was performed using a SonarMite MILSpec Single Beam Echosounder and a Trimble R8 Model 3 GNSS receiver deployed from an inflatable kayak. Sonar data and RTK GNSS data were recorded in a Trimble TSC 3 Data Collector. Data were collected at the 30 designated cross sections, at one second intervals, on December 11, 2015, during an 8.0 foot, high tide event at the Eureka Slough Bridge. In addition to the sonar data, sound velocity measurements were collected in the project reach using a Sontek CastAway-CTD.

Post-Processing

RTK observations collected over known control points 102 and 1045 were reviewed in Trimble Business Center v3.61 and enabled as checks against the provided coordinates.

Sonar data were edited in CARIS Hips and Sips v8.1.13 and in ArcMap v10.1 using the LP360 v2014.1.51.1 extension. Processing in CARIS included: defining vessel configurations, converting raw ASCII data files to HIPS format, applying sound velocity corrections, reviewing and correcting attitude and navigation data, review and editing of raw sounding data, manual and automated filtering as well as merging the attitude, navigation and raw sounding data. Due to the limitations of the instrumentation and the draft of the sensor (0.40 feet), data collected in areas with depths less than 1.50 feet or in areas with thick vegetation were removed. Final inspection and visualization of data occurred in ArcMap using the LP360 extension.

Generally, points with a position dilution of precision (PDOP) value greater than 3.0 are filtered from the dataset. This dataset did not have any PDOP values greater than 3.0 with exception of points collected at the railroad trestle cross section; downstream of the highway 101 bridge. Due to the large number of points with PDOPs greater than 3.0 at the railroad cross section, points were not filtered using PDOP values.

Results

Table 1 displays the control points and the check shots performed by GMA.

Table 2 presents the statistics associated with the check shots made. Point 102, being a rebar with a cap, should be considered a more reliable check than point 1045, which is a spike set in an area that is subject to disturbance.

With the exceptions of areas that were too shallow to survey or that contained vegetation, sonar survey density was adequate to define cross section geometry. The number of sonar points per cross section ranged from 34 to 251 points depending on cross section width and surveyable area.

As expected, sound velocity profiles indicated increases in the speed of sound as temperature and conductivity increased. The lowest sound velocities were observed in Freshwater and Fay Slough, the locations with the most freshwater influence, and in general increased in the downstream direction.

GMA's professional land surveyor, David Edson (CAPLS#4974) provided professional oversight for all field and office tasks conducted during the course of this project.

Table 1: Eureka Slough Control Coordinates Check Shots

Point ID	Northing	Easting	Elevation	Description
1045	2184338.62	5968377.87	9.08	Set by CAPLS7917
1045 (V6765)	2184338.61	5968377.90	9.13	Measured by GMA
Δ Values	**0.01**	**-0.03**	**-0.05**	
1045 (V6766)	2184338.61	5968377.90	9.13	Measured by GMA
Δ Values	**0.01**	**-0.03**	**-0.05**	
102	2183422.40	5974686.24	10.83	Set by CAPLS7917
102 (V6767)	2183422.40	5974686.26	10.82	Measured by GMA
Δ Values	**0.00**	**-0.02**	**0.01**	
102 (V6768)	2183422.40	5974686.26	10.83	Measured by GMA
Δ Values	**0.00**	**-0.02**	**0.00**	

Horizontal Datum: **NAD83 (2007.00)**
Vertical Datum: **NAVD88, Geoid 09**
Projection: **California State Plane Zone 1**
Units: **US Survey Feet**

Table 2: Eureka Slough Check Shot Statistics

Point ID	Vector	Max PDOP	RMS	H Prec (95%)	V Prec (95%)
1045	V6765	1.26	0.01	0.03	0.04
1045	V6766	1.08	0.01	0.03	0.03
102	V6767	1.07	0.01	0.03	0.02
102	V6768	0.86	0.01	0.02	0.02