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ESTIMATE OF COASTAL FLOOD STATISTICS FOR THE FAR SOUTH SAN FRANCISCO BAY

Lisa Andes[1], Frank Wu Ph.D[2], Jen-Men Lo Ph.D[3], Michael MacWilliams Ph.D[4], Chia-Chi Lu Ph.D[5],
Robert Dean Ph.D[6]

ABSTRACT

Flood stage frequency analysis is very important for the South San Francisco Bay Shoreline Study (SSFBSS). The physical processes of a coastal flood event in South San Francisco Bay (SSFB) are characterized by predicted (astronomical) tide and residual tide, including weather anomalies, El Nino effects and wind set-up. There are limited flood stage data available at SSFB; however, more than one hundred years of tide data have been measured at the National Oceanic and Atmospheric Administration (NOAA) San Francisco tide station. A sensitivity analysis of storm events measured at the San Francisco tide station was conducted to develop appropriate sampling criteria and establish probability distribution functions (PDFs) for the controlling parameters. A data transfer function was also developed through hydrodynamic modeling to transfer water surface elevation (WSE) data measured from San Francisco to the project site for flood stage frequency analysis. It was found that the predicted tide is amplified and the residual tide remains approximately unchanged as it propagates to the SSFB project site. Monte Carlo Simulation (MCS) analysis was adopted to carry out the statistical analysis. Extreme Probability Method (EPM) and Joint Probability Method (JPM) were also employed to analyze the data for comparisons. The statistical results of MCS compared well with those of EPM and JPM. It was concluded that the technical approaches developed provide a reasonable approach for the establishment of coastal flood stage frequency in the SSFB.

1. INTRODUCTION

The objective of this study is to develop flood stage frequency curves for the SSFBSS. The project study area is bounded by Alviso Slough and Coyote Creek. This area includes SSFB salt ponds A9 through A18 as shown in Figure 1. Two conceptual levee alignments are proposed and designed to protect the adjacent area landward of these ponds from flooding, as shown in Figure 2. The difference of the two alignments is in the center portion. One alignment is following along point 13 and does not include the triangular shaped New Chicago Marsh. The other alignment follows along

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[1] U.S. Army Corps of Engineers, San Francisco District, 1455 Market St., San Francisco, CA 94103

[2] U.S. Army Corps of Engineers, San Francisco District, 1455 Market St., San Francisco, CA 94103

[3] Santa Clara Valley Water District, 5750 Almaden Expressway, San Jose, CA 95118

[4] Delta Modeling Associates, Inc., 870 Market St., Suite 1074, San Francisco, CA 94102

[5] Noble Consultants Inc., 2201 Dupont Drive, Suite 830, Irvine, CA 92612

[6] University of Florida, Gainesville, FL 32611

point 18 through point 22 and includes a portion of New Chicago Marsh. The general approach and methods used to estimate flood stage frequency curves for both alignments are described in the following sections.

Limited data is available for use in the SSFB to estimate flood stage frequency. However, over one hundred years of tide data have been measured at the San Francisco tide station, located approximately 40 miles north of the project site. A methodology was developed to transfer the astronomical and residual tide from San Francisco to the project site for statistical analysis. Section 2 presents the data analysis and conditional sampling criteria. Section 3 presents the hydrodynamic modeling used to transfer WSE from the San Francisco tide station to the project site. Section 4 presents the statistical analysis using MCS.

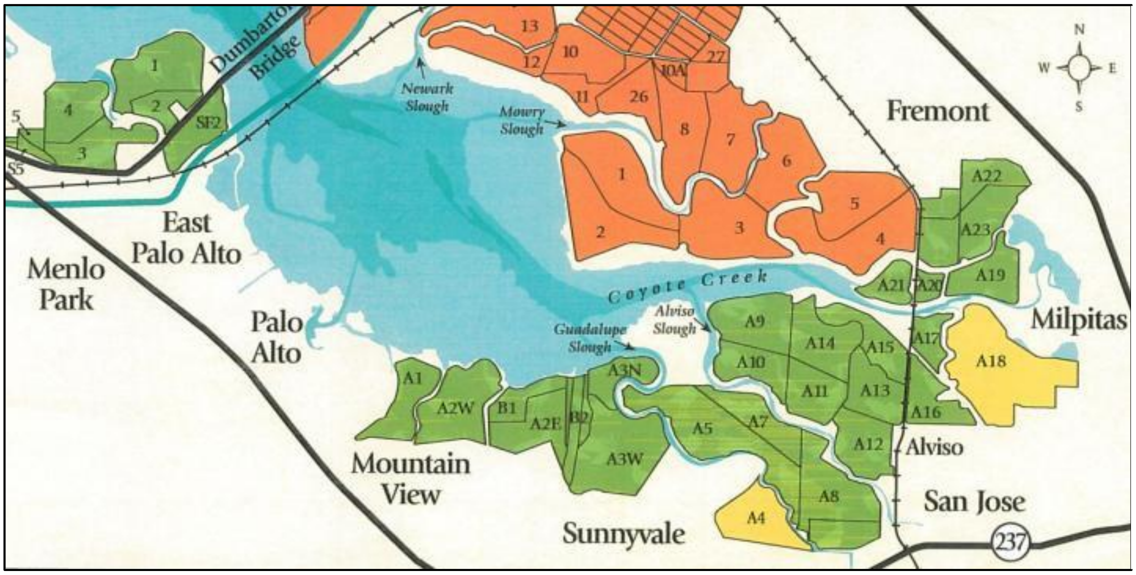

Figure 1 Project site map

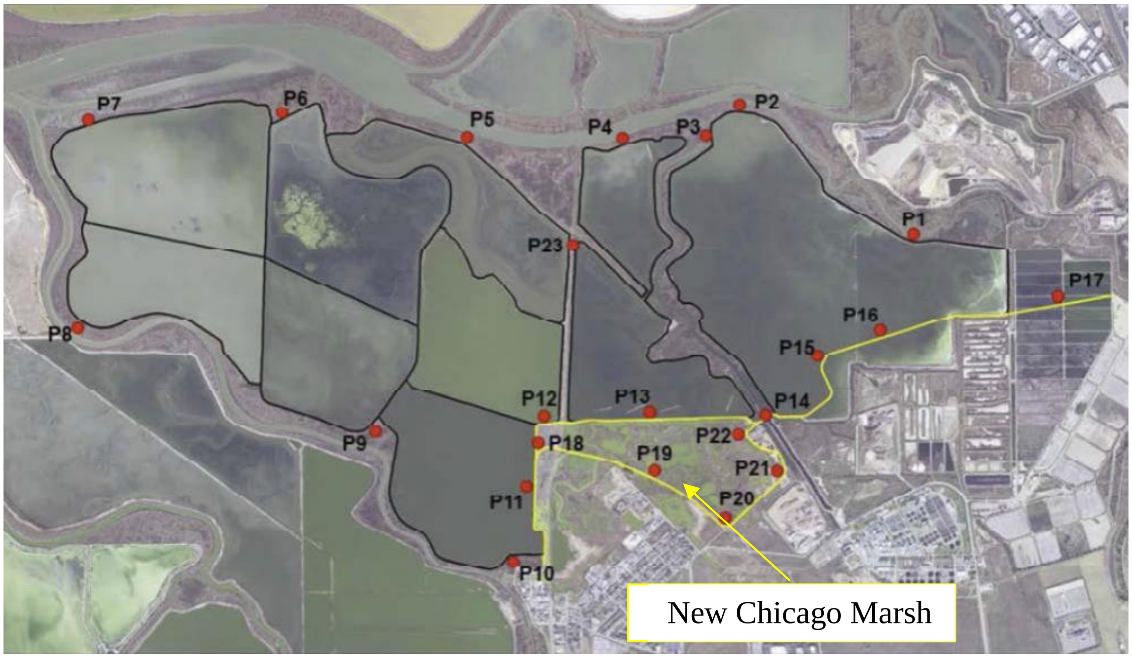

Figure 2 Hydrodynamic model simulation output location

2. DATA ANALYSIS

A conditional sampling (partial duration) approach was adopted for the SSFBSS to select representative samples of predicted and residual tide to be used in the MCS for the analysis of extreme coastal flood stage statistics described in Section 4. The controlling parameters of the MCS were identified as predicted tide, residual tide, in-bay wind direction and corresponding wind speed and levee failure.

2.1 San Francisco Tide Station Data

Tidal WSE was obtained from the NOAA tide station 9414290, located in San Francisco, California. Hourly tidal information was downloaded between 1901 and 2005 and used to establish a data record of predicted and measured tides spanning 105 years. Figure 3 presents time series of one month of representative tidal WSE that occurred in December 2002, including measured, predicted and residual tide. Residual tide was calculated by subtracting predicted tide from measured tide.

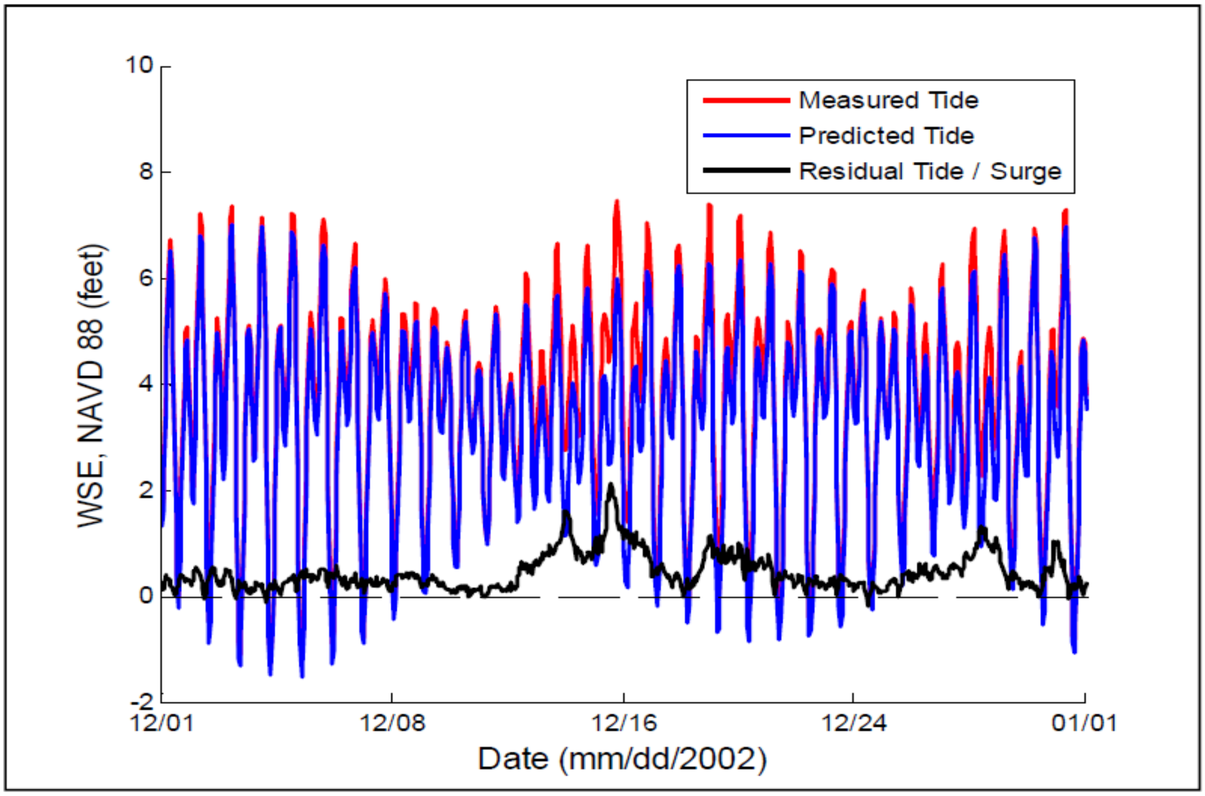

Figure 3 Time series of WSE at the San Francisco tide gauge

2.2 Sampling Criteria and Methods

Conditional sampling and annual maximum methods were adopted to analyze the tidal WSE obtained from the San Francisco tide station. The conditional sampling approach samples multiple events that satisfy the sampling criteria, while the annual maximum approach samples only one maximum WSE event per year. The events sampled form a database for statistical analysis of flood stage frequency at San Francisco. The event being defined as the highest WSE (measured tide) in a time series consisting of predicted and residual tides, shown in Figure 3, that satisfy the sampling criteria. The durations of the events typically ranged from 1-5 days, with the most frequent range being 2-3 days.

Four conditional sampling criteria were selected for this analysis (Table 1). The first three criteria include measured WSE (>= 6.9 feet above MLLW) and residual tide (>= 0.0, 0.5, and 1.0 feet) measured at the San Francisco tide station. The residual tide elevations selected reflect the contribution of residual tide to the total WSE sampled. The measured tide criterion (>= 6.9 feet above MLLW) was selected because it is the lowest annual peak predicted tide within the 105-year measured tide record, which justifies the selected events as significant events. The 0.5 foot residual tide criterion was selected because it is of a reasonable threshold beyond the noise level to identify a meaningful residual tide contribution. The 0.0 and 1.0 foot residual tide criteria selected are trying to provide upper and lower bounds of residual tide criteria. The fourth criterion adopted the annual maximum WSE (measured tide) approach for the 105-year record, which can serve as the basis for comparison. Table 1 summarizes sampling criteria, number of events sampled, and rate of occurrence of events for the four scenarios analyzed in the following sections.

Table 1 Conditional Sampling Criteria for Sensitivity Analysis

Scenario	Measured Tide >= MLLW (ft)	Residual Tide >= (ft)	Number of Events Sampled	Rate of Occurrence (Event #/yr)
1	6.9	0.0	522	4.97
2	6.9	0.5	276	2.63
3	6.9	1.0	93	0.89
4	Annual Maximum	--	105	1.0

The EPM and JPM were applied to develop the preliminary flood stage frequency curves for evaluation and comparison of each scenario.

EPM utilizes the Gumbel maximum distribution function to fit flood stage frequency curves for the four data sets sampled of measured WSE. Figure 4 presents the four flood stage frequency curves developed at San Francisco. In general, Scenarios 1, 2, 3 and 4 compare well. However, Scenario 3 and 4 seem to underestimate the WSE at the smaller range of return periods (=< 7-year return period) compared to the return periods developed from the Scenarios 1 and 2 curves. For the return period range from 100 to 500-year, it seems the Scenario 1 curve has lower estimated WSEs than those of other curves. The Scenario 2 curve shows the most reasonable estimate of WSEs over the whole range of interested recurrent frequencies. This implies that Scenario 2 sampling criteria captures the appropriate storm events representing adequate physical processes for statistical analysis. Based on the analyses and comparisons described above, the Scenario 2 dataset was selected as the most reasonable one to be used.

JPM uses Joint Probability Distribution (JPD) function derived from the PDFs of predicted and residual tide, measured coincidently, to calculate the flood stage frequency curve. The PDFs of predicted and residual tide for Scenario 2 are shown in Figure 5.

Figure 6 presents stage frequency curves of three scenarios compared with the annual maximum approach. As expected, the results of the JPM are slightly higher than that of annual maximum approach. In general, the JPM flood frequency curves comparison is similar to the EPM flood frequency curves. This comparison further supported the selection of Scenario 2 as the most reasonable curve to be used. It also implies that the de-coupling and re-coupling process of predicted and residual tide is applicable for this analysis of extreme flood statistics within acceptable uncertainty limits. If Scenario 2 and the annual maximum curves are considered as upper and lower bounds of flood stage frequency curves, respectively, then the uncertainty is very small as shown in Figure 7.

Although the wind contribution to peak WSE can exceed one foot for individual events when strong winds are aligned with the axis of San Francisco Bay, it was found that the wind contribution to the overall flood statistics was minor as a result of the rare occurrence of wind with the combination of large magnitudes and direction along the primary axis of San Francisco Bay.

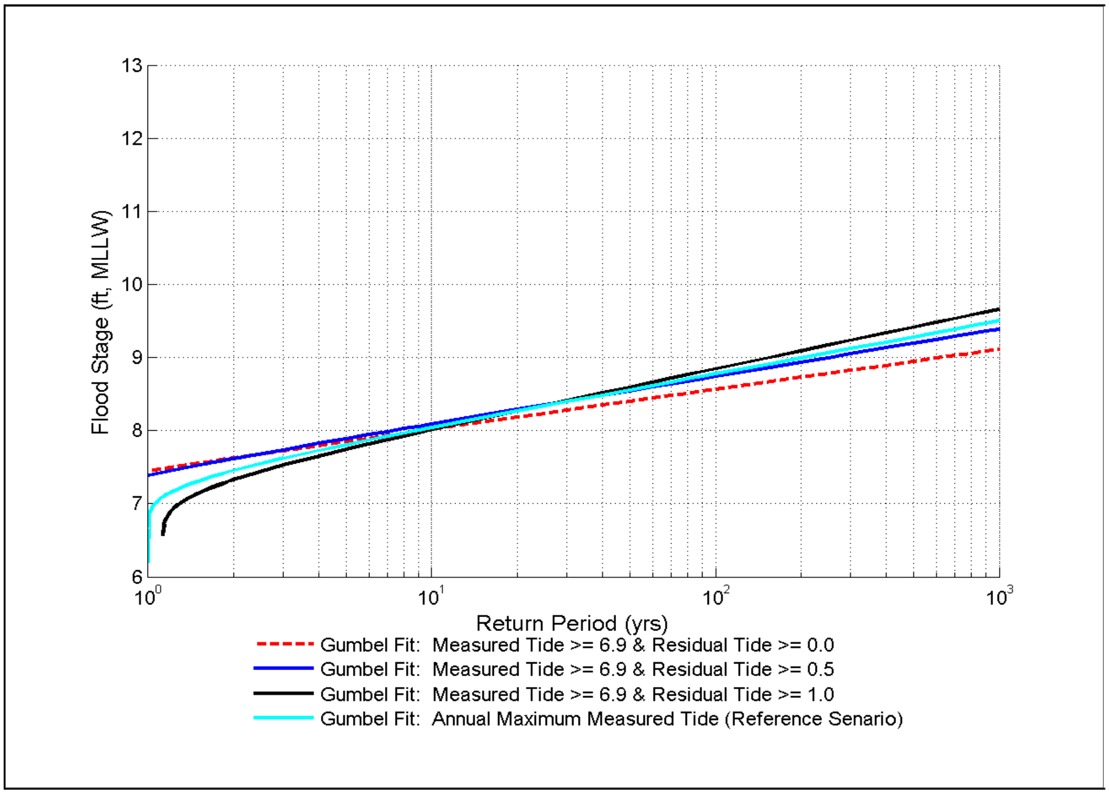

Figure 4 Flood stage frequencies of EPM comparisons for four scenarios

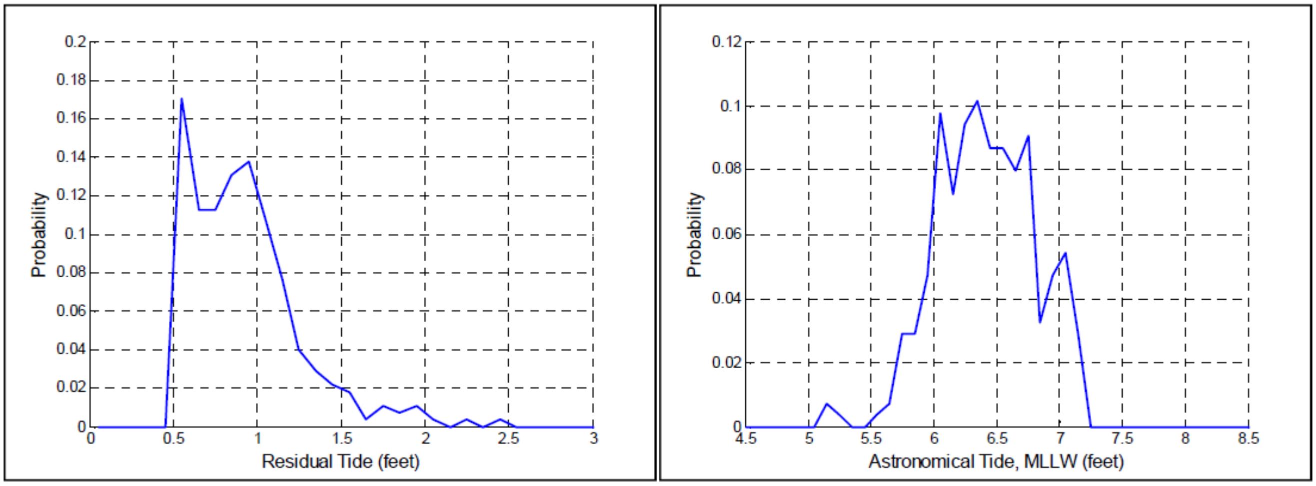

Figure 5 PDFs of residual (left) and predicted (right) tides from Scenario 2

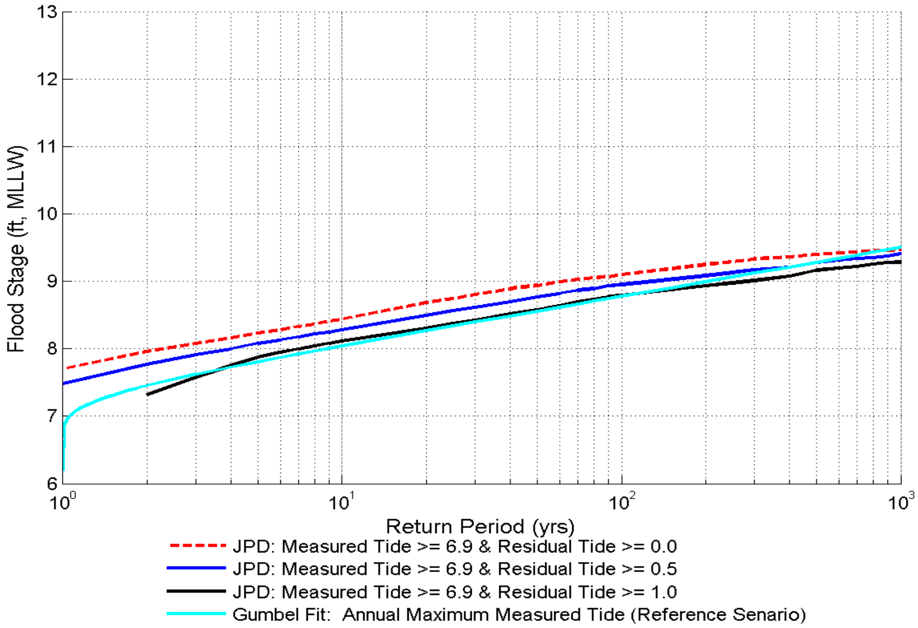

Figure 6 Flood stage frequency comparisons of JPD and annual maximum approach at San Francisco

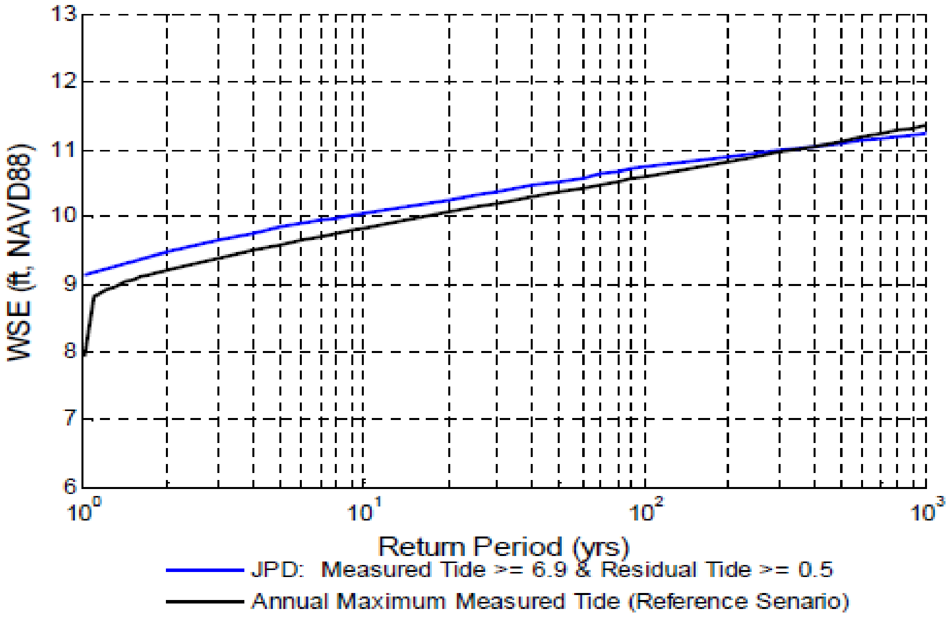

Figure 7 Flood stage frequency comparisons of JPM and annual maximum approach at the outer levee

2.3 Data Transfer to the Project Site

Each conditional sampling scenario was transferred to the project site using a direct transfer method to provide a preliminary estimate of flood stage frequency at the outer levees. The direct transfer method separates predicted tide and residual tide, amplifies predicted tide by an amplification factor of 1.4 to 1.9, adds the residual tide back to the amplified predicted tide and adjusts for the local tidal datum. Factors used to amplify the predicted tide at San Francisco were computed by comparing predicted tide at the San Francisco tide station and simulated predicted tide at the Coyote Creek tide station located near the project outer levees. The comparison indicated tidal amplification varied with amplitude of predicted tide WSE at the San Francisco tide station. Four amplification factors were established to account for the range of predicted tide used as boundary conditions in the hydrodynamic simulations, with a focus on the daily higher-high tide (Andes and Wu, 2012). The comparison of measured tide at Coyote and transferred tide from the San Francisco tide station shows good agreement of the transferred and measured daily higher-high tides as shown in Figure 8. Amplification factors were not developed for WSEs less than 4.94 feet above MLLW at the San Francisco tide station. These amplification factors are considered preliminary and additional numerical model simulations were conducted to transfer the WSE to the project site for input into the MCS as described in Section 3.

Numerical model simulations were conducted to evaluate how the residual tide recorded at the San Francisco tide station changes as it propagates into the far SSFB. The simulations indicated that residual tide varies minimally for the at five NOAA tides stations (Figure 9) between San Francisco and Coyote Creek as shown in Figure 10 (MacWilliams, et al., 2012).

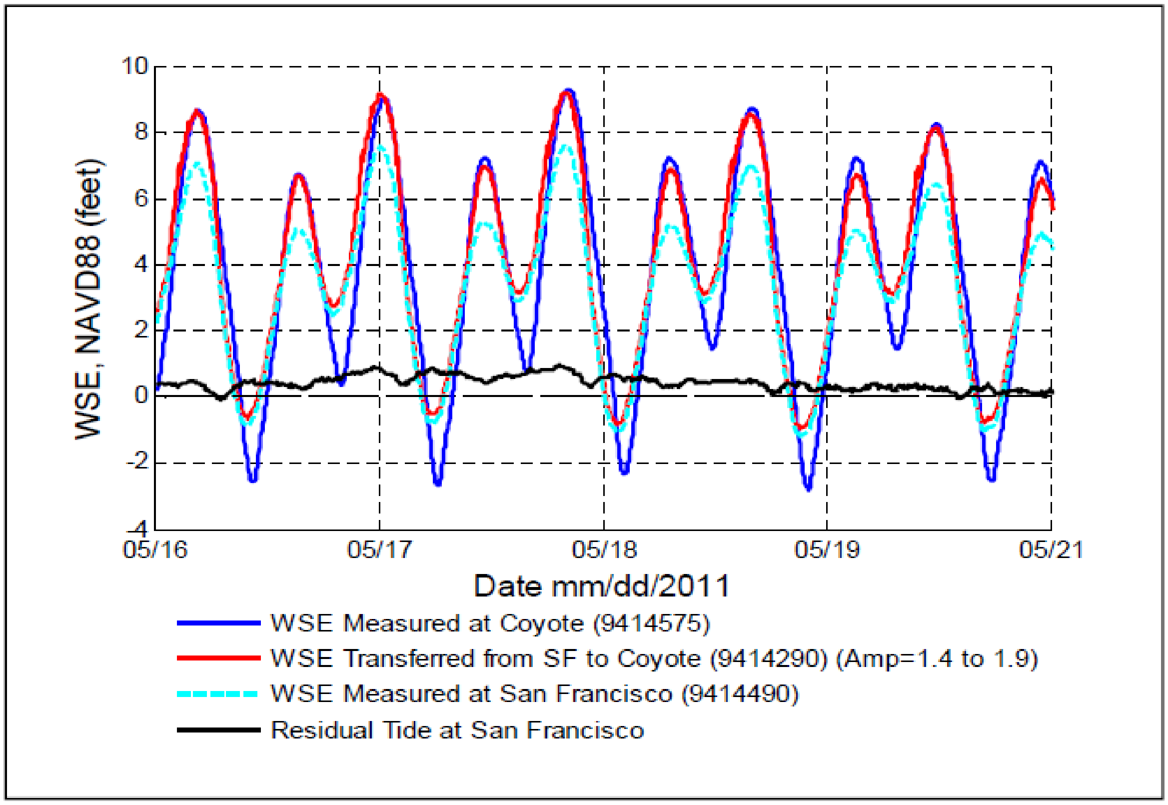

Figure 8 Comparison of amplified tide at San Francisco and measured tide at Coyote Creek.

Figure 9 NOAA tide stations in the SSFB

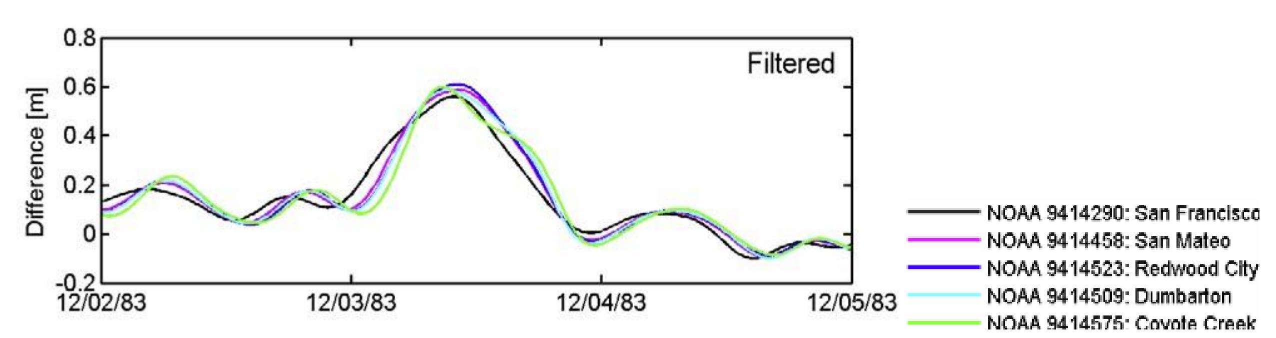

Figure 10 Comparison of tidal residual at NOAA tide stations in the SSFB (MacWilliams et al., 2012)

3. NUMERICAL MODELING – DATA TRANSFER TO THE PROJECT

Synthetic storm events were developed to cover the full range of predicted and residual tides from the selected conditional sampling scenario, Scenario 2 as described in Section 2. The purpose of the simulations is to transfer the WSE from the San Francisco tide station to the project site at 23 predefined locations, shown in Figure 2, for the calculation of flood stage frequency curves. Four predicted tide WSEs, 5.15, 5.85, 6.55 and 7.25 feet MLLW, and three residual tide WSEs, 0.50, 1.50 and 2.50 feet, were selected to generate a four by three matrix of simulations to cover the full range of predicted and residual tide WSEs. The WSE at the project site is used as input into the MCS for the interpretation of the response of the input parameters on the proposed levee alignments. Additional controlling parameters such as wind speed and direction, future sea level rise and levee failure were also included in the model simulations. The combinations of predicted and residual tide along with additional controlling parameters were simulated to generate a database in the form of look-up tables for the responses of WSE at the project site.

Hydrodynamic model simulations were conducted using the UnTRIM San Francisco Bay-Delta Model (MacWilliams et al., 2007; MacWilliams et al., 2008; MacWilliams et al., 2009). Four scenarios were simulated for each proposed levee alignment. The scenarios were without wind, with wind, without levee breaching and with levee breaching. The with and without wind scenarios are compared to estimate the wind set-up contribution to the overall flood statistics. Wind set-up contributions are negligible as a result of the small occurrence of wind speeds with large magnitudes and direction along the primary axis of the bay. The with and without levee breaching simulations are designed to evaluate the outer levee failure contribution to the overall flood statistics. Table 2 and Table 3 present the modeled predictions of peak WSE for the proposed levee alignments at representative output locations 3, 7, 13, 14, 16 and 20 with and without levee failure, respectively (MacWilliams, 2012). Output locations 3 and 7 present transferred WSE at the outer levees and output locations 13, 14, 16 and 20 present transferred WSE along the proposed levee alignments.

Table 2 Predicted peak WSE (ft, NAVD88) for the proposed levee alignments

	Tide at San Francisco		Evaluation Location					
Event	Astronomical (feet, MLLW)	Residual (feet)	3	7	13	14	16	20
1	5.15	0.5	7.49	7.28	4.89	7.52	4.25	-0.30
2	5.15	1.5	8.34	8.17	4.98	8.36	4.32	-0.30
3	5.15	2.5	9.27	9.16	5.08	9.31	4.39	-0.30
4	5.85	0.5	8.17	7.97	4.94	8.21	4.34	-0.30
5	5.85	1.5	9.04	8.92	5.03	9.09	4.41	-0.30
6	5.85	2.5	9.98	9.88	5.12	10.01	4.49	-0.30
7	6.55	0.5	8.95	8.80	5.02	9.00	4.38	-0.30
8	6.55	1.5	9.86	9.77	5.10	9.91	4.44	-0.30
9	6.55	2.5	10.82	10.76	5.18	10.86	4.51	-0.30
10	7.25	0.5	9.54	9.42	5.09	9.60	4.48	-0.30
11	7.25	1.5	10.47	10.39	5.18	10.50	4.55	-0.30
12	7.25	2.5	11.46	11.36	5.29	11.51	4.62	-0.30

Table 3 Predicted peak WSE (ft, NAVD88) for the proposed levee alignment with outer levee breaching contribution

	Tide at San Francisco		Evaluation Location					
Event	Astronomical (feet, MLLW)	Residual (feet)	3	7	13	14	16	20
1	5.15	0.5	6.09	7.03	5.65	6.11	5.74	-0.30
2	5.15	1.5	6.84	7.94	6.25	6.86	6.70	-0.30
3	5.15	2.5	7.84	8.91	6.96	7.87	7.76	0.84
4	5.85	0.5	6.54	7.70	5.98	6.57	6.36	-0.30
5	5.85	1.5	7.53	8.68	6.68	7.55	7.41	-0.30
6	5.85	2.5	8.57	9.63	7.56	8.59	8.50	2.38
7	6.55	0.5	7.04	8.53	6.51	7.06	6.88	-0.30
8	6.55	1.5	8.00	9.47	7.25	8.02	7.91	1.54
9	6.55	2.5	9.08	10.43	8.13	9.11	9.02	5.54
10	7.25	0.5	7.72	9.14	7.01	7.74	7.61	1.39
11	7.25	1.5	8.78	10.09	7.83	8.82	8.72	3.82
12	7.25	2.5	9.98	11.00	9.05	10.08	9.90	8.86

4. STATISTICAL ANALYSIS – MONTE CARLO SIMULATION (MCS)

The MCS statistical approach is used to predict an uncertain system by recreating a random process to solve a problem which cannot be easily evaluated by a standard numerical analysis. This technique allows for the random sampling of a pre-defined (known) occurrence distribution of each controlling parameter, physical processes, to statistically characterize the behavior of the uncertain system such as WSE (Nobel Consultants Inc., 2012).

MCS was used to estimate WSE, in terms of flood stage frequency, at 10 points along the outer levees and 13 points along of the two proposed levee alignments, as shown in Figure 2 and Table 4. The physical processes simulated in the MCS are predicted and residual tide, wind speed, wind direction and outer levee failure. Both static and dynamic failure modes were considered as levee failure mechanisms. The dynamic levee failure, resulting from wind wave generated overtopping, was found to provide nearly no contribution to the overall flood statistics due to the sheltered location of the projects site (Dean, 2010). Static levee failure considered seepage and stability failure modes to contribute to the overall flood statistics (Hubel, 2012).

A representative flood stage frequency result is presented at point 3 along the outer levee shown in Figure 11 and Table 5. Flood stage frequency results are also presented at point 16 along the proposed levee alignment (Figure 2) in Figure 12 and Table 6. All the statistical results presented include 5%, 50%, and 95% confidence levels. Figure 12 shows a step-like increase in flood stage elevation on the return period curves at approximately 5 to 8 years due to the levee failure contribution to flood stage inside the pond. The approximate 4.5 foot WSE for the return periods less than five years is the WSE inside the pond without levee failure conditions.

Figure 13 shows the comparison of the preliminary data transfer using the direct transfer method described in Section 0 and the MCS results at point 3 along the outer levee. The comparison shows good agreement between both approaches.

Table 4 Representative locations to estimate peak water level

	Points Selected
Outer Levee	1,2,3,4,5,6,7,8,9, and10
Inner Levee	11,12,13,14,15,16,17,18,19,20,21,22, and 23

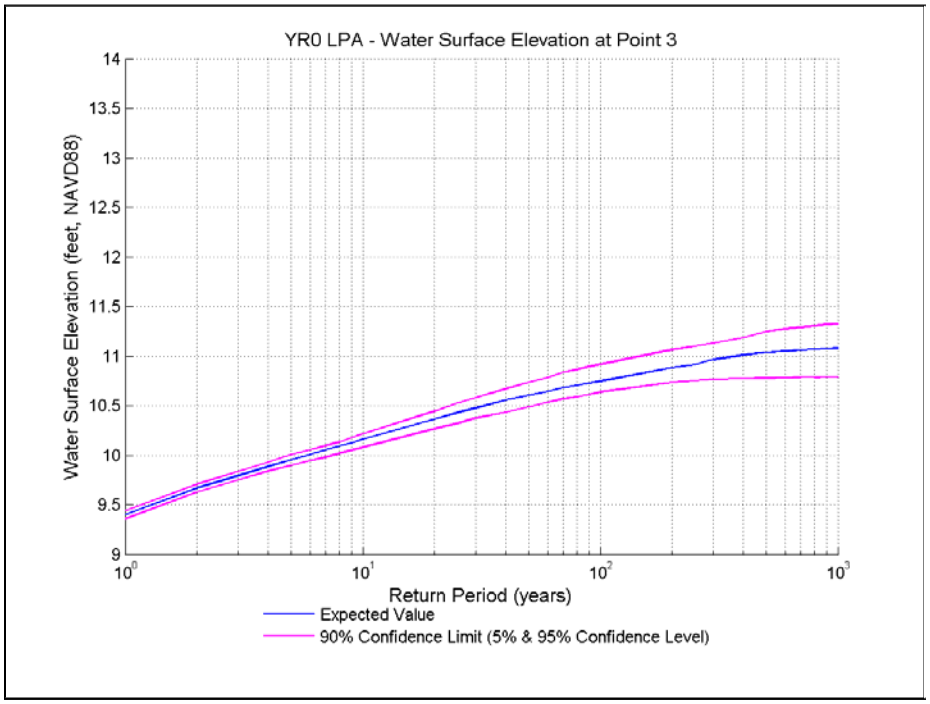

Figure 11 Flood stage frequency at Point 3 for the proposed alignment

Table 5 Flood stage frequency at point 3 for the proposed alignment

Return Period (yrs)	5% (feet, NAVD88)	50% (feet, NAVD88)	95% (feet, NAVD88)
1	9.36	9.40	9.44
10	10.08	10.16	10.22
100	10.64	10.75	10.91
1000	10.79	11.08	11.32

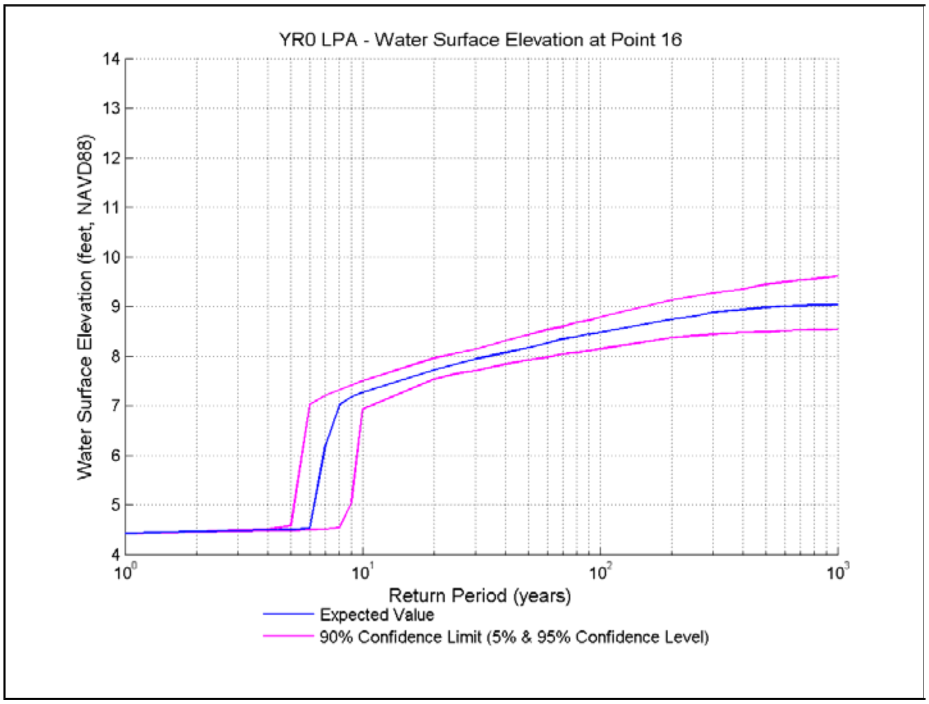

Figure 12 Flood stage frequency at Point 16 for the proposed alignment

Table 6 Flood stage frequency at point 16 for the proposed alignment

Return Period (yrs)	5% (feet, NAVD88)	50% (feet, NAVD88)	95% (feet, NAVD88)
1	4.42	4.42	4.43
10	6.93	7.26	7.50
100	8.14	8.48	8.79
1000	8.54	9.04	9.61

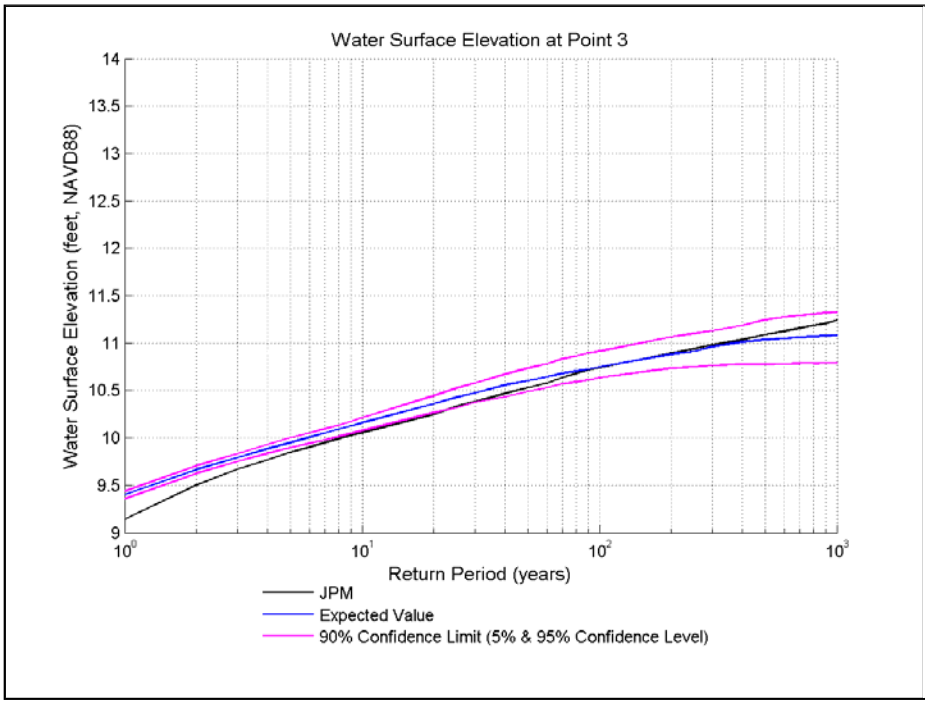

Figure 13 Flood stage frequency comparison at Point 3 for MCS and JPM

5. CONCLUSIONS

Based on the evaluation of three conditional sampling (partial duration) scenarios, the flood stage frequency curves developed from EPM and JPM compared well with that of the annual maximum curve at the San Francisco tide station. This also implies that the de-coupling and re-coupling process of predicted and residual tides is applicable for the analysis of extreme flood stage statistics and acceptable within reasonable uncertainty limits. If Scenario 2 and annual maximum curves are considered as upper and lower bounds of flood frequency curves, respectively, the uncertainty of extreme flood statistics estimated in this study is very small.

It was found that predicted tide was amplified by a factor of 1.4 to 1.9 between the NOAA San Francisco tide station and the project site, and the residual tide remains approximately unchanged. The wind set-up contribution to the total flood stage frequency curve is negligible due to the small occurrence of wind direction and speed along the primary axis of the bay. The dynamic failure mechanism associated with locally generated wind waves does not play an important role as the fetch is limited for the sheltered project site.

A set of synthesized events was developed to cover the range of all the controlling parameters, such as predicted tide, residual tide, wind speed and wind direction. Predicted peak water levels for each event were provided in lookup tables to allow for the interpretation of the responses of all the synthesized events randomly selected by the MCS process during statistical analysis. Static and dynamic levee failure mechanisms were included in the MCS process for the analysis of the flood stage inside the ponds.

Reasonable flood stage frequency curves with uncertainties were estimated by MCS method under each levee layout evaluated. We conclude that the technical approaches developed, using hydrodynamic model simulations and MCS, provided a reasonable way for the establishment of coastal flood stage frequency at the project site.

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