COAST & HARBOR ENGINEERING
A Division of Hatch Mott MacDonald

Technical Memorandum

Kersh-Wishkah Flood Wall Project
Flood Modeling and Statistical Analysis

1. Introduction

This technical report was prepared by Coast & Harbor Engineering (CHE) and summarizes engineering analysis and numerical modeling performed to assist AMEC Environment & Infrastructure (AMEC) in developing the flood wall design for the Kersh-Wishkah Flood Wall Project (project).

In the previous phase of work, CHE developed and validated the two dimensional (2-D) hydrodynamic model for the project (CHE, 2013) using MORPHO (Kivva, 2006); a snap shot of the model domain is shown in Figure 1. In the previous phase, CHE performed numerical modeling using the combination of extreme tidal elevation (10-year) and river flow return period (50-year) documented in FEMA Flood Insurance Study for Aberdeen, Washington (FEMA 1984). CHE simulated the FEMA conditions with time dependent dynamic inputs (river hydrograph and tide time series) for both the existing conditions and with the conceptual flood wall in place. CHE performed additional statistical analysis and numerical modeling to refine the water surface elevations at the project site for the one percent annual probability event (100-year return period event) considering a combination of tidal and river flow inputs using the existing site conditions without the proposed floodwall. Evaluation of sea level rise is also included. Analysis and modeling herein presumes that the intended lifespan of the project could be as long as 100 years.

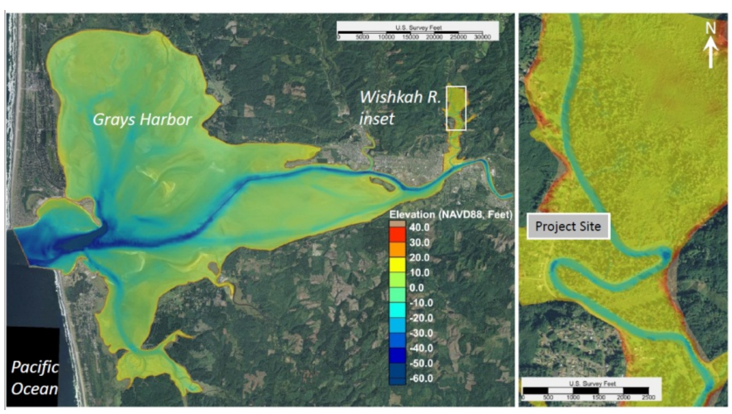

Figure 1. Grays Harbor (left) and Wishkah River (right) elevation model. Blue colors indicate lower elevations (deeper water) and yellow and red colors indicate higher elevations (shallower water and low-lying land).

2. Statistical Analysis and Numerical Modeling

Two factors control the water level elevation at the project site: tide level at Aberdeen and river flow volume (discharge) in the Wishkah River. To determine the one percent annual probability event resulting from the joint occurrence of high tide levels and high river flow volumes, CHE analyzed available data and selected tide and flow combinations for numerical modeling runs. Recommended design water surface elevations (WSEL) at the site are then provided based on the results of the model runs. The model results, and thus the recommended WSEL, are subject to the quality and reliability of the input data.

2.1. Available Data

Hydraulic data reviewed included existing hydraulic studies and water level records. Aberdeen Flood Insurance Study (FIS) by FEMA (1984) identifies 10-, 50- and 100-year return period tide levels at Aberdeen, Washington and discharge in the Wishkah River. The joint-probability tide and river flow of the FEMA-provided events is not documented. Additionally, AMEC provided discharge volume and hydrograph shape in the Wishkah River at the upper end of the project area for 2-, 5-, 10-, 25-, 50-, 100-, and 500-year discharge events, by scaling available data for the Nisson gauge to the larger drainage area at the project site. The AMEC-provided discharges were slightly higher than FEMA, and were adopted and applied by CHE.

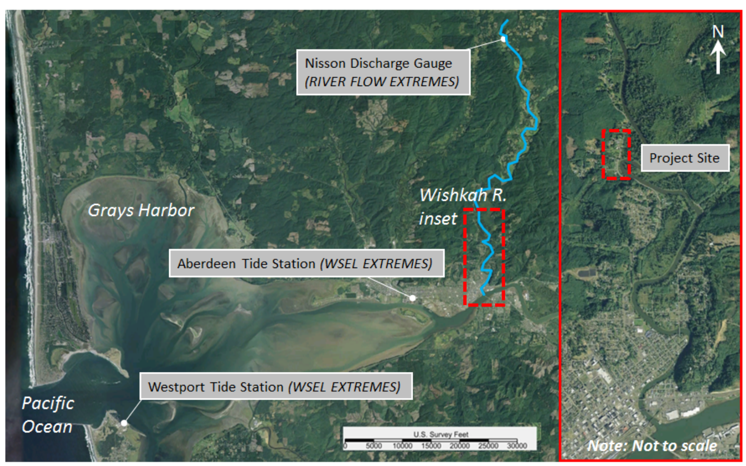

Figure 2. Available measured data sites

Measured data are available in time-series format from sites around Grays Harbor (see Figure 2). Hydraulic data from these sites was analyzed to determine if data quality and record length were sufficient to develop extreme events and/or determine correlations between high tides and river flow events.

Ten years (2003-2013) of river flow records were evaluated at the Nisson River gauge on the Wishkah River, located approximately eleven miles upstream of the site (as shown in Figure 2). Review of the available data indicates the stream gauge is only able to record river flows up to a maximum of approximately 3,700 cubic feet per second (cfs). Based upon review of the data, peak flows frequently exceed the gauge reporting limit. Therefore, discharge measurements cannot be used for generating joint-probability statistics between flow and tide level because peak flow during extreme events are not accurately reported. Readily available tide data is summarized in Table 1. The short length (7 years) of tidal data at Westport does not allow for confident extremal event analysis beyond a 25-year return period event. Lacking a long-term record of tide measurements at Aberdeen (less than two years), a tidal time series hindcast was generated by adding the measured tidal anomaly at Westport (difference between predicted and measured tide) to the predicted tide at Aberdeen. Analysis showed the anomaly at Aberdeen was equal to anomaly at Westport during overlapping periods of tide records in 1999; therefore the measured anomaly at Westport can be added to Aberdeen predicted tide to obtain a reasonable tidal hindcast. These data were analyzed and used to determine the elevation of lower but more frequent high water events than what was provided by FEMA (1984).

Table 1. Available Tidal Data

Source	Date	Description
NOAA, Station 9441102	3/23/2006 - 03/28/2013	Predicted and Measured @ Westport, WA
CHE Hindcast	3/23/2006 - 03/28/2013	Hindcast at Aberdeen, WA. Based on anomaly to Westport
NOAA	12/19/1999 - 11/20/2009	Predicted @ Westport, WA
USACE	9/13/1999 -11/17/1999	Measured @ U.S. Coast Guard Station Westport, WA
NOAA Station 9441187	2/20/2004 - 12/14/2005	Predicted and Measured Tides @ Aberdeen, WA
NOAA	12/19/1999 - 12/14/2009	Predicted Tide @ Aberdeen
USACE	9/12/1999 - 11/17/1999	Measured @ Aberdeen, WA

The joint occurrence of high tide and high discharge events was qualitatively evaluated. Based upon review of the data, large low pressure storms causing elevated tide levels also are sometimes associated with higher river flow events. However, the exact phasing of high tide and peak flow cannot be reliably determined from the available data. Also, given the stream gauge reporting limitations at Nisson, a statistically reliable joint-probability analysis of extreme tides and river flow cannot be performed with the available data.

2.2. Modeled Extremal Events

In the absence of sufficient data for reliable joint-probability analysis, extreme tide and river flow events were treated as statistically independent. Probability of the simultaneous occurrence of a specific recurrence interval high tide and high river discharge was computed by multiplying the individual event probabilities. Since we wanted to determine combinations of tide and river events that together had a one percent annual probability of occurrence, we chose combinations where the product of tide probability and flow probability equaled to 0.01 (1 percent). For example, considering a combined event where the tide level and river flow each had an annual probability of 10 percent (0.10), the combined event probability is 1 percent (0.10 x 0.10 = 0.01).

Table 2 below shows the seven (7) modeled event tide/flow (T/F) combinations that were generated, each with a 1 percent chance of occurring annually. In Table 2, the model scenario column refers to which tide and flow events are being modeled; for example, the "T-100, F-1" row indicates the 100-year tide, and the 1.01-year river flow. Flow volume and tide elevation values came from multiple sources. Some values were interpolated between values found in the available studies; these are indicated in the source column with "Interp."

Table 2. Modeled 1 Percent Annual Probability Event Combinations used for Numerical Modeling

	Tide			*Flow*		
Model Scenario	**Return Period (yr)**	**WSEL Height (feet, NAVD88)**	**Source**	**Return Period (yr)**	**Volume (cfs)**	**Source**
T-100, F-1	100	13.5	FEMA	1.01	6,262	Interp.
T-50, F-2	50	13.2	FEMA	2	8,260	AMEC
T-20, F-5	20	12.6	Interp.	5	10,400	Interp.
T-10, F-10	10	12.3	FEMA	10	12,900	AMEC
T-5, F-20	5	12.04	CHE	20	14,500	Interp.
T-2, F-50	2	11.59	CHE	50	17,100	AMEC
T-1, F-100	1.01	11.3	CHE	100	19,200	AMEC

The events shown in the rows of Table 2 were represented by a pair of time series data (tide levels and river flows) which were put into the model as dynamic boundary conditions to simulate each of the seven (7) selected 100-year event combinations. The peak WSEL modeled for each of these scenarios was recorded. This is shown conceptually in Figure 3 for the combination of the annual tide and 100-year flood. This figure also shows the numerical modeling mesh, which is used to compute the hydrodynamic parameters.

2.3. Model Results

The model provides WSEL and flow velocity throughout the entire domain for all time steps. Model results at two locations within the site are shown in Figure 4, which are Baretich Road (blue diagonal hatching) and the upstream extent of the project area (red solid fill). Locations of these extraction points are shown in Figure 6. The two highest modeled WSEL values at the project site occur when either the

100-year river flow or 100-year tide level occurs. The highest combination of tide and flow (highest WSEL) occurs for the 100-year river flow and 1-year tide scenario.

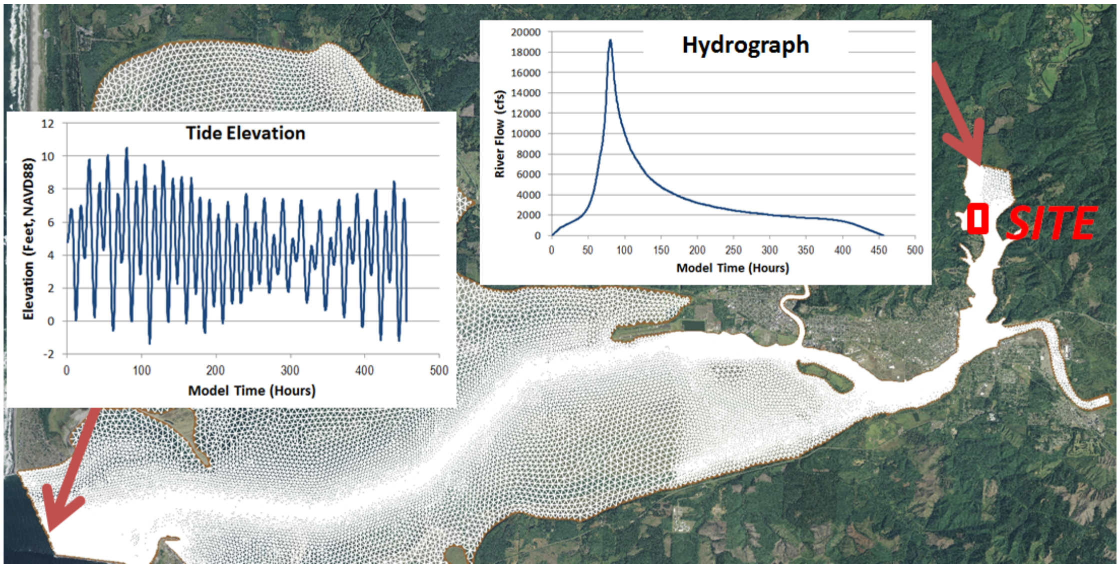

Figure 3. Model mesh and boundary conditions for case T-1, F-100

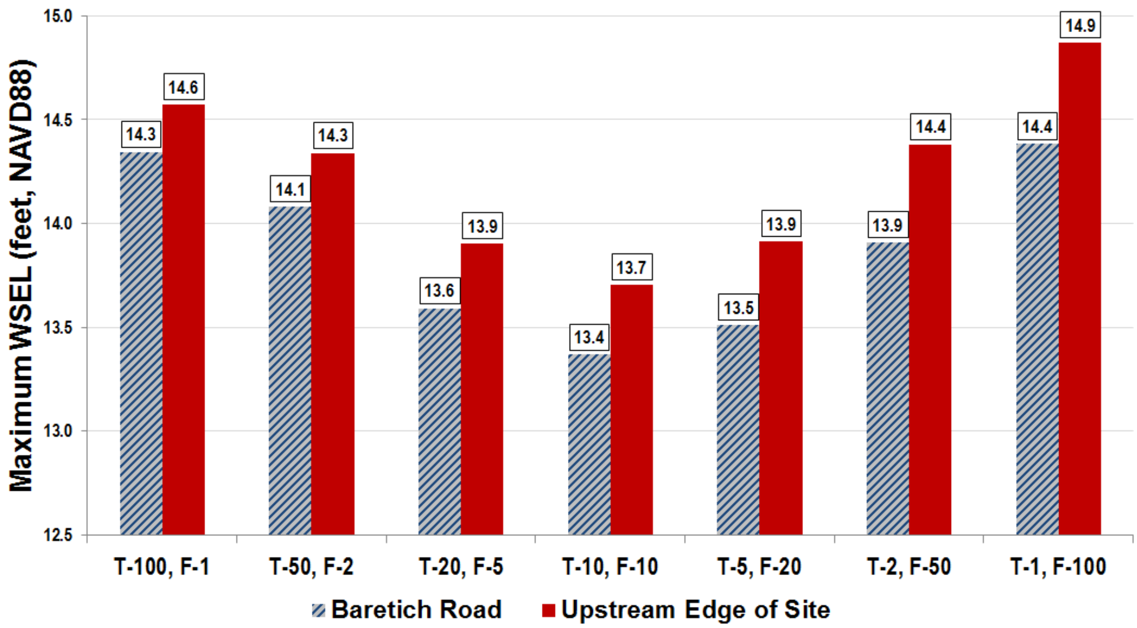

Figure 4. Simulation results for seven (7) 1 percent annual probability events

From Figure 4, it is observed that WSEL varies between the two locations; this is because the WSEL profile slopes from upstream to downstream. Figure 5 shows the slope of the WSEL profile along the preliminary floodwall alignment, with stationing beginning at the southern end of the floodwall. Also shown is the ground elevation based upon LIDAR data. The WSEL profile slope is greater during the 100-year flow event than the 100-year tide event because a larger portion of the flood-water propagation is due to water coming from upstream in the T-1, F-100 case than the T-100, F-1 case.

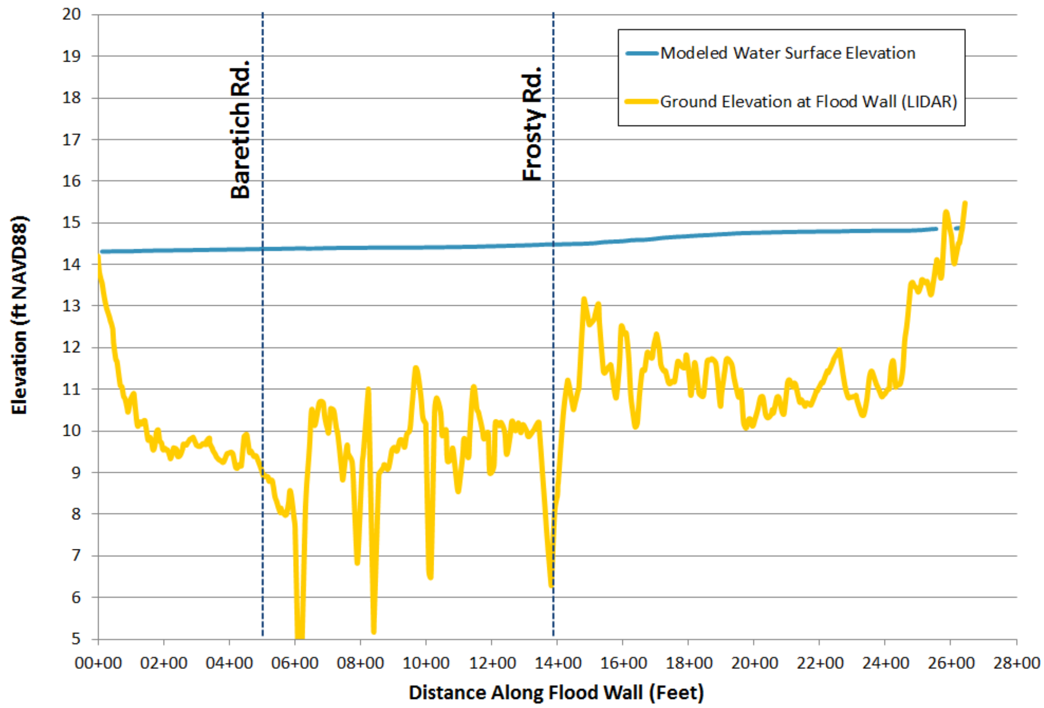

Figure 5. Water surface elevation profile for T-1, F-100 case

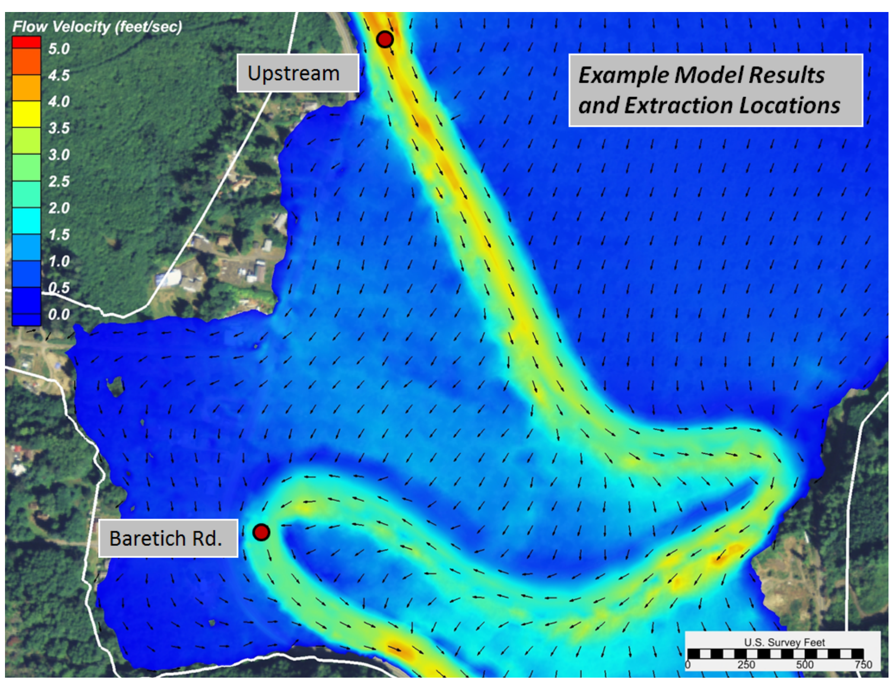

Figure 6. Simulation result from the previous study at the project site, and WSEL extraction locations

The maximum WSEL results are similar to our results from the previous phase of work (CHE, 2013). Table 3 compares WSEL results from this phase of work with that reported in the previous phase. Results from this phase generated slightly higher WSEL than the previous analysis using FEMA inputs. This demonstrates the value of the approach taken to simulate a variety of combinations of tide and flow events to determine the controlling (worst case) combination.

Table 3. Model Result Comparison to Previous Phase Work

Annual Probability	Flow Return Period (Yr)	Tide Return Period (Yr)	Baretich WSEL (ft NAVD88)	Upstream WSEL (ft NAVD88)
Phase 1				
1/500 (0.2%)	50	10	14.3’	14.8’
Phase 2				
1/100 (1%)	1.01	100	14.3’	14.6’
1/100 (1%)	10	10	13.4’	13.7’
1/100 (1%)	100	1.01	14.4’	14.9’

3. Sea Level Rise

The project site is affected by the tide and therefore also rising sea levels. When considering the design height of a flood control structure with a long lifespan, possible effects from sea level rise (SLR) should be considered. CHE evaluated and compared the range of expected SLR estimates for the next 100-years based upon available data and various literature. Future SLR estimates are essentially predictions based on different assumptions about future climate conditions. Unlike tide and river flow data, future SLR estimates do not come with statistical probabilities. Therefore, designing for SLR requires use of engineering judgment to balance project risk versus cost, considering the undefined uncertainty inherent in future predictions.

3.1. Available SLR Trends and Models

Three available approaches to sea level rise were evaluated: Local tide gauge data for SLR trends; Available sea level rise studies, and United States Army Corps of Engineers (USACE) engineering guidance.

Local tide gauge data came from and the National Oceanic and Atmospheric Administration (NOAA). The climate sea level rise studies used were the Intergovernmental Panel on Climate Change (IPCC) studies, and Mote *et al.* (2006). The USACE engineering guidance for SLR design is applicable to projects that are subject to tidal influence (USACE 2011)..

3.1.1. Recorded Tide Gauge Data

Tide records in Grays Harbor do not provide sufficient data to reliably establish a trend for sea level. The nearest site with sufficient long-term tide gauge records is located in Willapa Bay at Toke Point. At this site, mean sea level varies from year to year with an overall trend of rising sea levels, as shown by the red line in Figure 7. From 1973-2006 the mean SLR rate was measured at 1.6 mm/year, with a 95 percent confidence of +/- 1.4 mm/year. If long-term trends were to continue, SLR could range from 0 inches (lower end of confidence interval) to 12 inches (upper end of confidence interval) in 100 years, with a mean rise of 6 inches in 100 years. It is noted that after 2006 the SLR rate has decelerated to a mean rate of 0.26 mm/year (1" in 100 years); such a low SLR rate may not account for variability in sea levels depicted in Figure 7, and is not recommended for design.

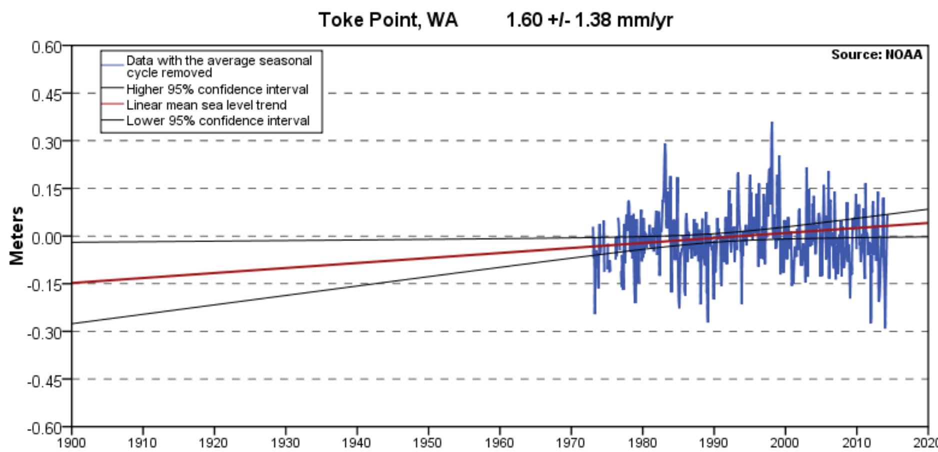

Figure 7. Long-term (1973-2006) mean sea-level variation and rise at Toke Point, WA (figure by NOAA)

3.1.2. Sea Level Rise Studies

Mote *et al.* (2006) presents SLR estimates specific to the Washington Coast and Olympic Peninsula, and accounts for vertical uplift caused by glacial rebound and tectonic movements, as well as atmospheric effects. Global sea level rise rates are based on the 2006 IPCC estimates, with adjustments made for local effects. For this work, CHE has updated Mote's methods to include the more recent 2013 IPCC estimates, while keeping local effects the same as in Mote et al. (2006).

The IPCC document presents low, medium, and high estimates based on different greenhouse gas emission scenarios. These scenarios are called Representative Concentration Pathways (RPCs), and have variable radiative forcing values (watts/meter) relative to pre-industrial values, such as +2.6 (low), +6 (medium), and +8 (high). Historically, the high estimates of SLR from earlier reports have not been realized.

SLR from Mote's work was updated with 2013 IPCC values and extrapolated to 2114 for this project. In each scenario, the Global SLR is based on IPCC estimates for low, medium, and high RPCs, local atmospheric dynamics that relate to RPCs, and different scenarios for vertical land movement. Unless otherwise noted, the elevations presented in Table 4 are in inches.

Table 4. Estimates of SLR from 2014 to 2114 using Mote *et al.* updated with 2013 IPCC Estimates

Scenario	**SLR (Inches)**
Lowest of Low Estimate	9
Medium Estimate	24
Highest of High Estimate	52

3.1.1. USACE Engineering Guidance

Guidance on design considerations for sea level rise is provided by USACE (2011). USACE recommends that a range of SLR predictions be computed for each site. The low SLR rate is based on a nearby tide gauge with similar physical conditions to the project site and a sufficient length of record. The Toke Point tide gauge meets the USACE criteria. Therefore, the Toke Point station is a reasonable source for the low estimate of SLR at the site (0 inches). USACE also accounts for vertical land movement by comparing the site to a vertically stable location within the region. This guidance then develops higher estimates by considering future SLR acceleration based on a 1987 report by the National Research Council "Responding to Changes in Sea Level: Engineering Implications," and the 2007 IPCC report, which Mote *et al.* references. These predictions for 2100 give an intermediate value of 19.7 inches and a high value of 59 inches relative to 1992 SL, before accounting for vertical land movement, which compare well to the Mote estimates.

3.2. SLR Recommendations

CHE recommends the design account for a minimum SLR estimate of 6 inches by 2114 (0.06 inches per year). . If sea level rise rates are measured to exceed this rate in the future, additional rise can be adaptively managed on a long-term basis by providing a design that can accommodate additional height in the future.

Table 5. Source and Corresponding Average Rate and Yearly SLR from 2014 to 2114

Source	**Average Rate (in/yr)**	**SLR, Year 2014 to 2114 (inches)**
Mote *et al.* High	0.52	52
Mote *et al.* Medium	0.24	24
Toke Point Highest	0.12	12
Mote *et al.* Low	0.09	9
Toke Point Mid	0.06	6
Toke Point Low	0.00	0
Recommended Range	-	6 inches (min.)

4. Conclusions

Considering the numerical modeling results and analysis presented herein, the design water levels for combined tidal and river flooding should range from 14.4 ft to 14.9 ft NAVD88, depending upon the location within the project area. We recommend that the design process accommodate a minimum of 6 inches of future potential sea level rise over the presumed 100-year life of the project (0.06 inches per year). The wall should be designed and constructed as to allow adaptive management increase of the wall elevation up to at least another 6 inches. Ultimate selection of the design elevation of the flood wall must also account for other factors such as geotechnical and topographic conditions which are being addressed by AMEC, and are not included herein.

5. References

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