



Joint Occurrence and Probabilities of Tides and Rainfall

City of Virginia Beach, Virginia

CIP 7-030, PWCN-15-0014, Work Orders 2 and 5A

Final Report

Date: October 9, 2017

Submitted to: City of Virginia Beach

Department of Public Works



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NOTE TO READER

This document combines previous report deliverables for PWCN-15-0014 Work Orders 2 (Rainfall Correlated Tailwaters for the Lynnhaven Watershed – completed December 2015) and 5A (Design Coastal Tailwater Conditions in Virginia Beach and Norfolk Based on Rainfall and Tide Joint Probability Analysis – completed December 2016). The reports were merged to provide the information from the two successive studies in a single document.

Results of the joint probability analysis supersede the correlated tailwaters. As such, recommendations for use of the correlated tailwaters and data lookup tables for the values across the Lynnhaven and Elizabeth River watersheds were not included here. Otherwise, the original text from both documents is presented herein with minimal changes. Exceptions include revision of the executive summary to encompass both documents, and slight revisions to references of the correlation study and Work Order tasks.

EXECUTIVE SUMMARY

This report summarizes analyses to assess the joint occurrence and probabilities of elevated coastal water levels with stormwater design rainfall. The effort addresses concerns raised by City of Virginia Beach Public Works who observed that many instances of flooding from many rainfall events appeared to coincide with elevated coastal water levels. Such observations led to reservations on existing design guidance. To address these concerns, two sequential studies were commissioned by the City. These include a correlation analysis, summarized in Chapter 1; and a joint probability analysis, summarized in Chapter 2.

The correlation analysis was a first step in evaluating the relationship between two variables. The analysis used observed rainfall depths for durations of up to 3 days for the period 1948-2015, along with corresponding maximum tide levels and concluded that a general relationship existed between the tide and inland rainfall. Rainfall data were obtained from Norfolk airport, and coastal water level data were obtained from stations at Sewell's Point and the Chesapeake Bay Bridge Tunnel. Results showed that more than 50 percent of the rainfall events occurred while the water level was higher than average daily high tide. Given this, it is very likely that tailwater elevations will be elevated when the City is experiencing a rainfall event. This result led to a recommendation that the City undertake a more robust statistical foundation for the adjustment of tailwater design guidance.

Subsequently, Dewberry was tasked to conduct a more robust joint probability analysis to support design guidelines, summarized in Chapter 2 of this report. The objective of the joint probability analysis is to develop a set design coastal tailwater elevations, which are tide elevations representing outlet blockage in conjunction with 24-hour design rainfall of 1-, 2-, 5-, 10-, 25-, 50-, and 100- year return period. The results are summarized in Tables 1, 2, and 3. These provide tailwater tidal elevations represented by the mean and maximum daily average tidal conditions in ft, NAVD 88, for each overall design level in conjunction with the use of selected 24-hour design storms, as well as the joint probability at each design level. Because of the location of tidal and rainfall stations used, the results from the joint probability study are primarily applicable to Norfolk coastal area but may also be used as design guidance for Virginia Beach coastal areas including the Elizabeth River and Lynnhaven watersheds.

A data assessment conducted to assess the viability of repeating this analysis for the Southern watershed did not reveal any tide/ rain gauges with sufficiently long record to facilitate study.

Design Tables

Note: It is general design practice to select the larger rainfalls in conjunction with lower tide elevations. Please note that the correlation between the 24-hour rainfall depth and the mean daily tide impacts the tide values in the tables for large storm events that exceeding the 10-year rainfall level. In these such cases, the tidal elevation that is shown in bold or underlined font (Tables 1 and 2), is likely to be elevated in comparison to the result shown where an assumption of independence of tide to rainfall is used. All other tide values in the table were evaluated, assuming the two variables are independent from each other. This table can be used for engineering design that involves tidal streams in the following manner:

The first step is for the designer to pick an overall design level, for example: 25-year for a culvert. Accordingly, the designer needs to go to the section of the table that highlights “25-year Design” and try the combination of the tide, representing the culvert tailwater elevation or outlet blockage, and the 24-hour rainfall depth, representing the recurrence interval of inland flooding, at each of the rows under this section. The combination which produces the most critical result, normally represented by the highest Water Surface Elevation upstream of the culvert should be used in conservative design. The design rainfall depths in the table are based on NOAA Atlas 14 values for Norfolk Airport, and the tide values are based on the mean daily tide (in NAVD 88 in feet) for NOAA coastal station Sewell’s Point, VA. To use the design table for nearby locations with slightly different tide or rainfall values, the designer may use Table 3. Table 3 features the recurrence intervals for both the tide and the rainfall for which the designer may replace the numbers given in Table 1 using local studies. The results reflected in Tables 1, 2 and 3 only apply to local tidal streams and waterways where the flood elevations are impacted by both inland flooding and coastal water elevations.

Table 1. Design table for rainfall-tide (tailwater elevation representing outlet blockage) based on mean daily tide, applicable to Norfolk and northern Virginia Beach coastal areas.

Tailwater Elevations for given Design Levels and Rainfall Recurrence Intervals																				
All Elevations are in NAVD 88 vertical datum and all rainfall values are inches per 24-hours																				
Values represent joint probabilities of rainfall to mean daily tides																				
1-year Design			2-year Design			5-year Design			10-year Design			25-year Design			50-year Design			100-year Design		
Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall	
2.92	0.00	No Rain	3.91	0.00	No Rain	4.75	0.00	No Rain	5.12	0.00	No Rain	5.93	0.00	No Rain	6.46	0.00	No Rain	7.12	0.00	No Rain
1.25	2.93	1-Yr P	2.04	2.93	1-Yr P	2.72	2.93	1-Yr P	3.01	2.93	1-Yr P	3.67	2.93	1-Yr P	4.09	2.93	1-Yr P	4.62	2.93	1-Yr P
			1.25	3.57	2-yr P	2.30	3.57	2-yr P	2.72	3.57	2-yr P	3.30	3.57	2-yr P	3.67	3.57	2-yr P	4.15	3.57	2-yr P
						1.25	4.62	5-yr P	2.04	4.62	5-yr P	2.87	4.62	5-yr P	3.22	4.62	5-yr P	4.00	4.62	5-yr P
									1.25	5.50	10-yr P	2.49	5.50	10-yr P	3.08	5.50	10-yr P	3.83	5.50	10-yr P
												<u>1.92</u>	6.82	25-yr P	2.61	6.82	25-yr P	3.45	6.82	25-yr P
															<u>1.96</u>	7.95	50-yr P	3.01	7.95	50-yr P
																		<u>2.42</u>	9.20	100-yr P

Notes:
 The tide value for No Rain entries were set based on High Tide not Mean Daily Tide to capture the critical tailwater elevations.
 Tide values in bold font (only for the 25-year design and higher) are correlated to rainfall so the two parameters are treated as interdependent using joint probability of the two variables.
 Results for inter-dependent entries are based Bumbel-Hourgaard Copula using de-trended mean daily tide data for days with maximum annual 24-hr rainfall.
 The underlined tide values are adjusted using curve-fitting to values from joint probability.

Table 2. Design table for rainfall-tide (tailwater elevation representing outlet blockage), based on **maximum daily tide** applicable to Norfolk and northern Virginia Beach coastal areas. Note: tidal values in this table were scaled using a linear relationship from mean daily to maximum daily tide on request. These values are not an explicit product of the joint probability analysis.

Tailwater Elevations for given Design Levels and Rainfall Recurrence Intervals																				
All Elevations are in NAVD 88 vertical datum and all rainfall values are inches per 24-hours																				
Values scaled from mean daily, to maximum daily tides using established linear relationship																				
1-year Design			2-year Design			5-year Design			10-year Design			25-year Design			50-year Design			100-year Design		
Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall		Tide	Rainfall	
2.92	0.00	No Rain	3.91	0.00	No Rain	4.75	0.00	No Rain	5.12	0.00	No Rain	5.93	0.00	No Rain	6.46	0.00	No Rain	7.12	0.00	No Rain
2.93	2.93	1-Yr P	3.91	2.93	1-Yr P	4.75	2.93	1-Yr P	5.12	2.93	1-Yr P	5.94	2.93	1-Yr P	6.46	2.93	1-Yr P	7.12	2.93	1-Yr P
			2.93	3.57	2-yr P	4.23	3.57	2-yr P	4.75	3.57	2-yr P	5.48	3.57	2-yr P	5.94	3.57	2-yr P	6.53	3.57	2-yr P
						2.93	4.62	5-yr P	3.91	4.62	5-yr P	4.94	4.62	5-yr P	5.38	4.62	5-yr P	6.35	4.62	5-yr P
									2.93	5.50	10-yr P	4.47	5.50	10-yr P	5.20	5.50	10-yr P	6.14	5.50	10-yr P
												3.76	6.82	25-yr P	4.62	6.82	25-yr P	5.66	6.82	25-yr P
															3.81	7.95	50-yr P	5.12	7.95	50-yr P
																		4.38	9.20	100-yr P

Notes:
 Values for maximum daily tide derived using established relationship between mean and maximum daily values (see High Tide vs. Mean Daily Tide Section).
 All notes for Mean Daily Tide also apply to these values.

Table 3. Design table based on rainfall and tide recurrence intervals.

Tailwater Recurrence Intervals (rounded to zero decimals) for given Design Levels and Rainfall Recurrence Intervals.													
1-year Design		2-year Design		5-year Design		10-year Design		25-year Design		50-year Design		100-year Design	
Tide	Rain	Tide	Rain	Tide	Rain	Tide	Rain	Tide	Rain	Tide	Rain	Tide	Rain
1-yr High Tide	No Rain	2-yr High Tide	No Rain	5-yr High Tide	No Rain	10-yr High Tide	No Rain	25-yr High Tide	No Rain	50-yr High Tide	No Rain	100-yr High Tide	No Rain
1-yr Tide	1-yr P	2-yr Tide	1-yr P	5-yr Tide	1-yr P	10-yr Tide	1-yr P	25-yr Tide	1-yr P	50-yr Tide	1-yr P	100-yr Tide	1-yr P
		1-yr Tide	2-yr P	2.5-yr Tide	2-yr P	5-yr Tide	2-yr P	12.5-yr Tide	2-yr P	25-yr Tide	2-yr P	56-yr Tide	2-yr P
				1-yr Tide	5-yr p	2-yr Tide	5-yr p	6-yr Tide	5-yr p	11-yr Tide	5-yr p	42-yr Tide	5-yr p
						1-yr Tide	10-yr P	3-yr Tide	10-yr P	9-yr Tide	10-yr P	31-yr Tide	10-yr P
								<u>2-yr Tide</u>	25-yr P	4-yr Tide	25-yr P	16-yr Tide	25-yr P
										<u>2-yr Tide</u>	50-yr P	8-yr Tide	50-yr P
												<u>3-yr Tide</u>	100-yr P

Notes:

The tide value for No Rain entries were set based on High Tide not Mean Daily Tide to capture the critical tailwater conditions.

Tide values in bold font (only for 25-year design and higher) are correlated to rainfall so the two parameters are treated as inter-dependent using joint probability of the two variables.

Results for inter-dependent entries are based on GH (Gumbel-Hougaard) Copula using de-trended mean daily tide data for days with maximum annual 24-hr rainfall.

The underlined tide values are adjusted using curve-fitting to values from joint probability.

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CHAPTER 1: RAINFALL CORRELATED TAILWATER ANALYSIS

Introduction

Current Virginia Department of Transportation (VDOT) tailwater elevation guidance does not consider the potential for storm surge to elevate water levels during conditions of peak runoff. The City of Virginia Beach (CVB) had observed that many rainfall events resulting in minor flooding corresponded with elevated coastal water levels due to wind and wave-driven storm surge. Multiple instances of these events have led to reservations about existing tailwater elevation design guidance. In response to this concern, the CVB undertook a study to assess co-occurrence between storm surge and rainfall events, documented by this report.

Correlation between elevated coastal water levels and precipitation was investigated using long-term water level records from both the Chesapeake Bay Bridge Tunnel (CBBT) and Sewell's Point (SWP) water level stations in conjunction with rainfall records from Norfolk International Airport. The analysis found a trend of elevated water levels co-occurring with rainfall events. An empirical relationship developed between the observed rainfall totals and maximum water levels observed during the duration of the precipitation events formed the basis to estimate tailwater elevations at SWP water level station. The effort provides rainfall-correlated tailwater elevations corresponding with 24-hour duration storm events at the 1-, 2-, 5-, 10-, 50-, and 100-yr return periods. Coastal water level stage-frequency relationships were leveraged from a recent Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) to relate the tailwater elevations from SWP across the CVB Lynnhaven River watersheds 1, 2, 3, 4, 5, 6, 7, 30, and 31 (Figure 1).

Literature Review

We conducted a literature review to inventory past work that may be relevant to this effort. Table 4 summarizes specific materials and is discussed further in the following text.

The Norfolk District U.S. Army Corps of Engineers (USACE) for City of Norfolk (USACE 1976) conducted one past water level-rainfall correlation study in the region. The VDOT Drainage Manual summarizes the final recommendations from this effort. The USACE analyzed past storm events and corresponding water levels to generate three graphs that relate rainfall frequencies for three different water levels: 2.5, 4.2, and 5.4 feet. This study recommended that, assuming tailwater elevations to be at 2.5, 4.2, or 5.4 feet, different design storm totals should be used. The study does not relate the design rainfall to the national

standards provided by the National Weather Service’s (NWS) currently effective Atlas 14 or the superseded TP-40.

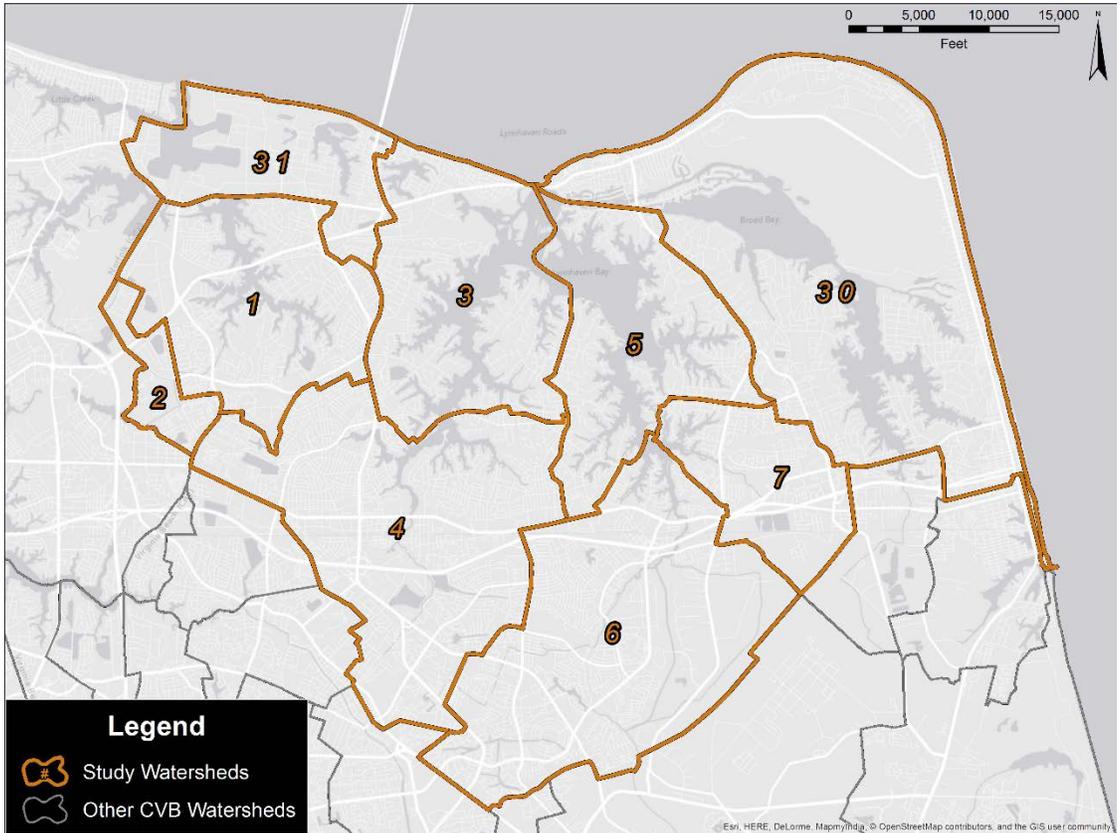


Figure 1. Watersheds identified for development of tailwater elevations.

A study by Parsons Brinckerhoff (2010) conducted for the CVB summarized the rainfall and water level observations during a November 2009 event. The study identified areas experiencing flooding during this event and concluded that the flooding was the result of strong sustained northeast winds in combination with heavy rains. The study plotted rainfall events recorded at Norfolk Airport and Oceana Naval Air Station on November 12, 2009, against the corresponding water level recorded at the CBBT. This effort illustrated that the water level remained above 3 feet mean sea level (MSL) during the 24-hour period the City’s watersheds experienced rainfall.

A 2003 University of Florida study conducted for the Florida Department of Transportation recommended design storm surge hyetographs associated with 50-, 100-, and 500-year storm surge events. This study analyzed past coastal events to come up with the hyetographs to be applied in the design of coastal bridges and roadways. Hyetographs of 40-hour duration were

developed for selected locations along the Florida coast based on observed water levels in combination with water levels simulated for hypothetical storms. The hyetographs developed by this study are purely based on coastal models and records; no attempts were made to correlate the surge hyetograph with inland storm frequencies. The study methodology was not found to be applicable to the current effort.

Table 4. Summary of reviewed materials and relevance to this effort.

Title	Relevance
Virginia Drainage Manual, chapter 6, Appendix 61-2 http://www.virginiadot.org/business/locdes/hydra-drainage-manual.asp)	Presents 1974 study results on storm-tide coincidence, conducted by Norfolk District USACE.
Tidal and Rainfall Flooding Evaluation, 9/7/2010, by Parsons Brinckerhoff for City of Virginia Beach	Summarizes storm rainfall/water levels recorded for November 2009 northeaster.
Design Storm Surge Hydrographs for the Florida Coast, submitted to the Florida Department of Transportation by the University of Florida, September 2003	This study recommends 50-, 100-, and 500-year storm surge hyetographs for coastal roads and bridges.
FEMA Flood Insurance Study for the City of Virginia Beach, 515531V000B, Revised January 16, 2015	This study provides updated 10-, 50-, 100-, and 500-yr storm surge return period elevations across the CVB. Existing elevations will be used to scale surge heights from the CBBT water level station across the study area.
Virginia Beach Streams, Canal Number Two, Virginia Beach, Virginia, USACE, September 29, 1976	USACE’s storm-tide coincidence analysis mentioned in Virginia Drainage Manual (reference 1).

Data Retrieval and Processing

Rainfall observations and hourly water level records were collected to evaluate the correlation between inland rainfall events and coastal water elevations. Hourly rainfall records were assessed to identify all precipitation events exceeding threshold values. The water level record was examined to identify the highest level experienced for each identified precipitation event. Correlation between the datasets was evaluated by plotting the total rainfall volume of the storm event and corresponding highest water level using Microsoft Excel. We developed an empirical relationship that relates the storm rainfall total to maximum water level. Atlas 14 1-, 2-, 5-, 10-, 50-, and 100-year 24-hour duration design rainfall were obtained and an empirical relationship was used to compute the corresponding water level. FEMA coastal return period elevation relationships were leveraged to transfer the tailwater elevation from water level station across the Lynnhaven River watersheds.

Rainfall Data Evaluation

Hourly precipitation data recorded at Norfolk International Airport weather station were downloaded for the period 1948-2015 from the National Oceanographic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC, http://www.ncdc.noaa.gov/cdo-web/search?datasetid=PRECIP_HLY#). The download used Eastern Standard Time as the reference time zone. The retrieved data were analyzed to identify storm events that had the potential to create runoff. Event durations of 1-hour (0.25 inches), 3-hour (0.50 inches), and 6-hour (0.75 inches) rainfall exceedance criteria to capture both short- and long-duration runoff events. We used a period of 3 hours or more without any measured rainfall as the criterion to distinguish one storm event from another. We extracted the start time, end time, and the total observed rainfall (in inches) for each identified storm using the R statistical software computing package.

Based on the rainfall record between the period of 1948 and 2015, 93 storms had a total precipitation of 2 inches or more. The duration of the rainfall varied between 1 hour and 60 hours. We only considered one rain gauge record in this study. No attempt was made to categorize the rainfall events based on their duration since the data is insufficient.

Corresponding Maximum Water Levels

Hourly recorded water levels at CBBT (1975-2015) and SWP (1938-2015) water level gauges were downloaded from NOAA's Tides and Currents website (http://tidesandcurrents.noaa.gov/tide_predictions.html). The data were retrieved relative to Local Standard Time (with daylight savings adjustment, same as EST/EDT). Locations of the water level stations at CBBT, SWP, and the precipitation gauge at Norfolk Airport are shown in Figure 2.

Water level measurements were collected relative to MSL and adjusted to bring water levels prior to 1992 to the current MSL (relative to the present National Tidal Datum Epoch of 1983-2001) using the historical rate of sea level rise available from NOAA for each water level station. The SWP water level station was also evaluated with measurements available starting in 1938, as the CBBT water level station was established in 1975 and rainfall records are available since 1948. The start/end times of each storm were used to query the CBBT and SWP water level records to find the maximum elevation attained during the storm. Appendix A summarizes the rainfall events and corresponding highest water elevation recorded. Table 5 summarizes the named hurricanes that brought more than 2 inches of precipitation at Norfolk Airport.

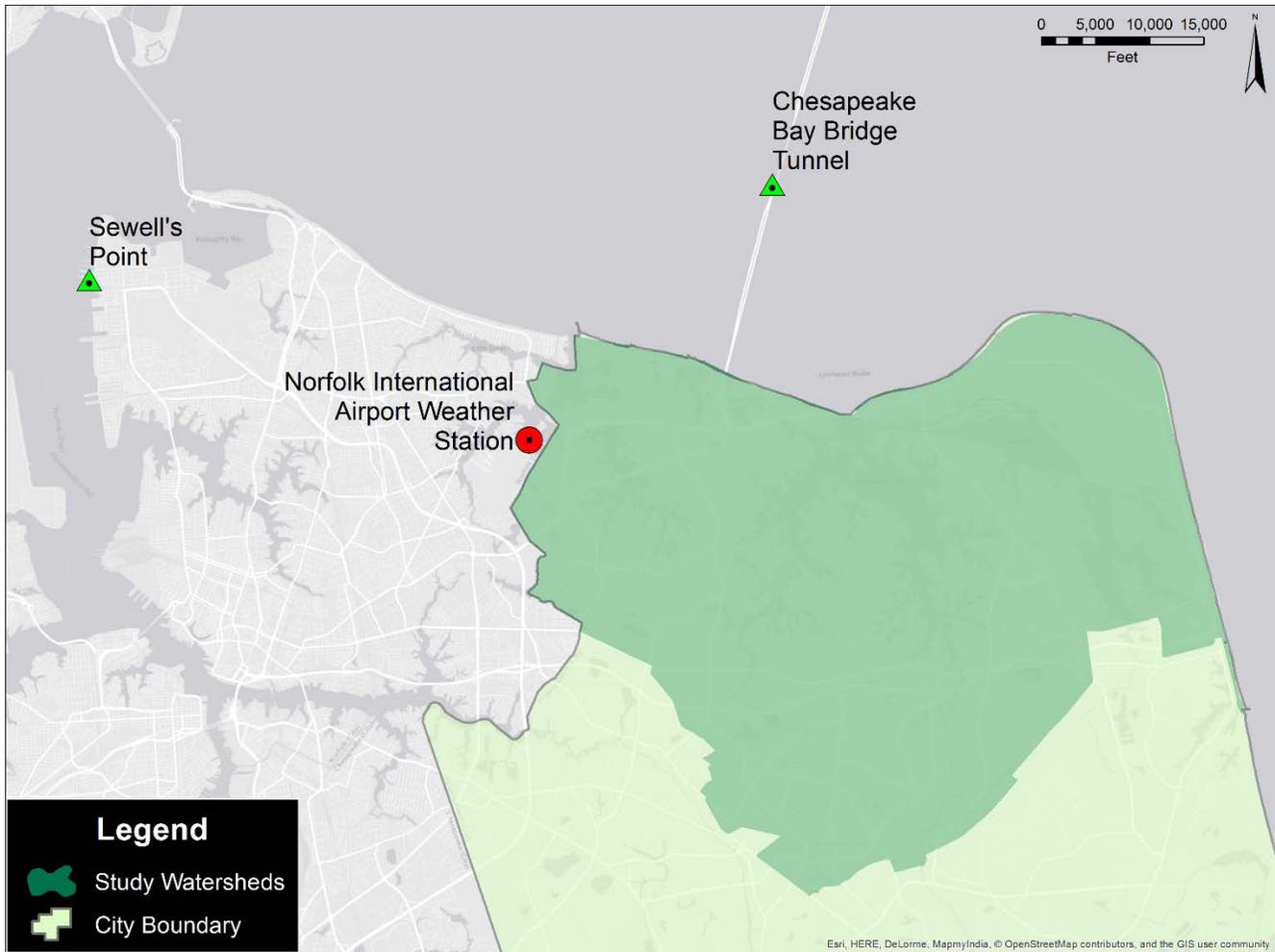


Figure 2. Locations of the SWP and CBBT water level gauges and Norfolk International Airport weather station in relation to the study area.

Table 5. Named hurricanes with larger than 2 inches of precipitation totals observed between 1948 and 2015.

Hurricane Name	Duration, hours	Precipitation Total, inches	Maximum Water Level, MSL	Time of Maximum Water Level, Date-hour
Connie	27	4.59	3.71	8/13/1955 0:00
Flossy	21	2.58	5.09	9/27/1956 11:00
Cleo	24	11.4	2.07	9/1/1964 12:00
Dora	30	4.8	4.57	9/14/1964 0:00
David	26	4.57	1.96	9/6/1979 3:00
Gloria	18	5.65	3.77	9/27/1985 7:00
Bonnie	14	3.65	3.97	8/27/1998 23:00
Floyd	27	5.65	3.45	9/16/1999 3:00
Irene	27	8.17	5.88	8/28/2011 3:00
Sandy	60	5.91	5.08	10/30/2012 1:00

Correlation of Precipitation and Water Elevations

Storm rainfall totals (in inches) and corresponding maximum water levels were analyzed for correlation using a Microsoft Excel function. Use of Excel facilitates client and any end-user access to the algorithm for repeatability, update, and review. At the conclusion of this effort, we extracted tailwater elevations (at CBBT and SWP water level station locations) that corresponded to 24-hour 1-, 2-, 5-, 10-, 50-, and 100-year design storms.

Atlas 14 24-Hour Duration Design Rainfall Totals

We obtained the design storm depths from the precipitation frequency data server of the NWS Hydro-Meteorological Center’s Atlas 14 (<http://hdsc.nws.noaa.gov/hdsc/pfds>). These values were obtained at the rain gauge at Norfolk International Airport (Station ID-44-6139) located at latitude 36.9033° and longitude -76.1922°. Table 6 shows the precipitation totals for 1-, 2-, 5-, 10-, 50-, and 100-year storms of 24-hour duration hypothetical storm.

Table 6. Precipitation frequency estimates for Norfolk International Airport.*

Return Period by Duration	1-yr, inches	2-yr, inches	5-yr, inches	10-yr, inches	25-yr, inches	50-yr, inches	100-yr, inches	200-yr, inches	500-yr, inches	1000-yr, inches
5-min:	0.41	0.48	0.55	0.63	0.71	0.78	0.84	0.9	0.98	1.05
10-min:	0.65	0.77	0.88	1	1.13	1.24	1.33	1.43	1.55	1.66
15-min:	0.82	0.97	1.12	1.27	1.43	1.57	1.69	1.8	1.95	2.08
30-min:	1.12	1.34	1.59	1.84	2.12	2.36	2.58	2.81	3.1	3.37
60-min:	1.4	1.68	2.04	2.4	2.82	3.19	3.56	3.94	4.46	4.91
2-hr:	1.66	1.99	2.47	2.96	3.55	4.09	4.64	5.22	6.01	6.73
3-hr:	1.78	2.15	2.67	3.21	3.9	4.54	5.2	5.92	6.92	7.84
6-hr:	2.17	2.6	3.24	3.9	4.77	5.57	6.4	7.32	8.61	9.82
12-hr:	2.57	3.08	3.85	4.66	5.74	6.75	7.83	9.02	10.72	12.33
24-hr:	2.93	3.57	4.62	5.5	6.82	7.95	9.2	10.58	12.64	14.4
2-day:	3.39	4.1	5.28	6.29	7.81	9.13	10.6	12.25	14.72	16.86
3-day:	3.58	4.34	5.55	6.58	8.1	9.41	10.84	12.42	14.78	16.9
4-day:	3.77	4.57	5.82	6.86	8.39	9.68	11.07	12.59	14.84	16.95
7-day:	4.39	5.3	6.66	7.79	9.43	10.79	12.27	13.86	16.14	18.04
10-day:	4.97	5.97	7.4	8.58	10.28	11.69	13.19	14.8	17.1	19.01
20-day:	6.71	8	9.71	11.12	13.11	14.73	16.43	18.22	20.73	22.74
30-day:	8.3	9.87	11.84	13.43	15.6	17.34	19.11	20.93	23.42	25.36
45-day:	10.27	12.15	14.48	16.38	19.02	21.15	23.34	25.62	28.76	31.24
60-day:	12.24	14.45	17.01	19.04	21.79	23.94	26.1	28.29	31.21	33.44

*Accessed on date/time (GMT): Wed May 27 14:18:09 2015

Correlation and Empirical Relationship

Data

The water level records coincident with the identified rainfall events were queried to determine the maximum elevation of each event at both the CBBT and SWP stations. The SWP water level data spanned the length of the entire precipitation data record (1948-2015), whereas the CBBT record had a more limited record, spanning from 1975 to 2015. All water level data were adjusted to present MSL to correct for historic sea level rise trends. Further review of the data records at SWP identified a data gap for July 1975, which affected three rainfall events occurring on the 5th, 12th, and 16th. The 67-year record at the SWP station provided the best dataset of rainfall and water level events with 90 coincident rainfall-water level data points. The shorter 40-year record at CBBT provided for 59 events.

Data Analysis

Storm rainfall totals and corresponding maximum water levels recorded at SWP and CBBT were organized in a Microsoft Excel spreadsheet. Data were plotted for the full length of record at each station and the concurrent record for both stations (1975-2015). The function “CORREL” was used to assess correlation between the rainfall and water level records.

Results of the correlation analysis at both stations showed a weak, but positive correlation trend between the total storm precipitation and the measured water elevations during the storms. Having established this positive relationship between the two datasets, we used the trend line as an empirical relationship to make predictions for the tailwater elevations corresponding to 24-hour storm depths defined in Atlas 14 for the Norfolk Airport rain gauge location for return periods: 1-, 2-, 5-, 10-, 50-, and 100-year. Data and trends are shown for the full length of record at SWP in Figure 3, and for the concurrent period of record between the CBBT and SWP stations in Figure 4 and Figure 5, respectively.

Comparison of predicted tailwater values for both SWP (Table 7, row 1) and CBBT (Table 7, row 2) indicated that the empirical relationships based on the data distributions at both stations had negligible differences. Consequently, it can be concluded that despite the proximity to the CVB, the CBBT location does not provide any benefit over the SWP station. The SWP data have the advantage over CBBT due to additional 27 years of record and was, therefore, used to provide the best data source for the final predictions. The Significance of F value for the SWP data was 1.35E-06, meaning that there is a less than 1% chance that the regression output was a chance occurrence. Significance of F values less than 0.05 indicate statistical significance.

Table 7. SWP and CBBT water level analysis results for the period 1975-2015.

No.	Return Period (yr)	1	2	5	10	25	50	100
	24-hr rainfall (in)	2.93	3.57	4.62	5.50	6.82	7.95	9.20
1	SWP 1975-2015 Peak Water Level (ft, MSL)	1.6	1.9	2.4	2.8	3.4	3.9	4.5
2	CBBT 1975-2015 Peak Water Level (ft, MSL)	1.6	1.9	2.3	2.7	3.2	3.7	4.2

MHHW [mean higher high water] (ft, MSL) = 1.4

The empirical correlation relationship established in Figure 3 provides an estimate for tailwater elevations. These values are based on the full record of SWP water level data from 1948 to 2015 covering all 90 storms previously identified for use in this study. The final tailwater elevation recommendations for the various return periods are shown in Table 8.

Table 8. Summary of correlation analysis estimates for tailwater elevations.

Return Period (yr)	1	2	5	10	25	50	100
24-hr rainfall (in)	2.93	3.57	4.62	5.5	6.82	7.95	9.2
Recommended Tailwater Elevations (ft, MSL)	1.65	1.89	2.27	2.59	3.08	3.49	3.95
Recommended Tailwater Elevations (ft, NAVD88)	1.40	1.64	2.02	2.34	2.83	3.24	3.70

MHHW (ft, MSL) = 1.4, MHHW (ft, NAVD88) = 1.15

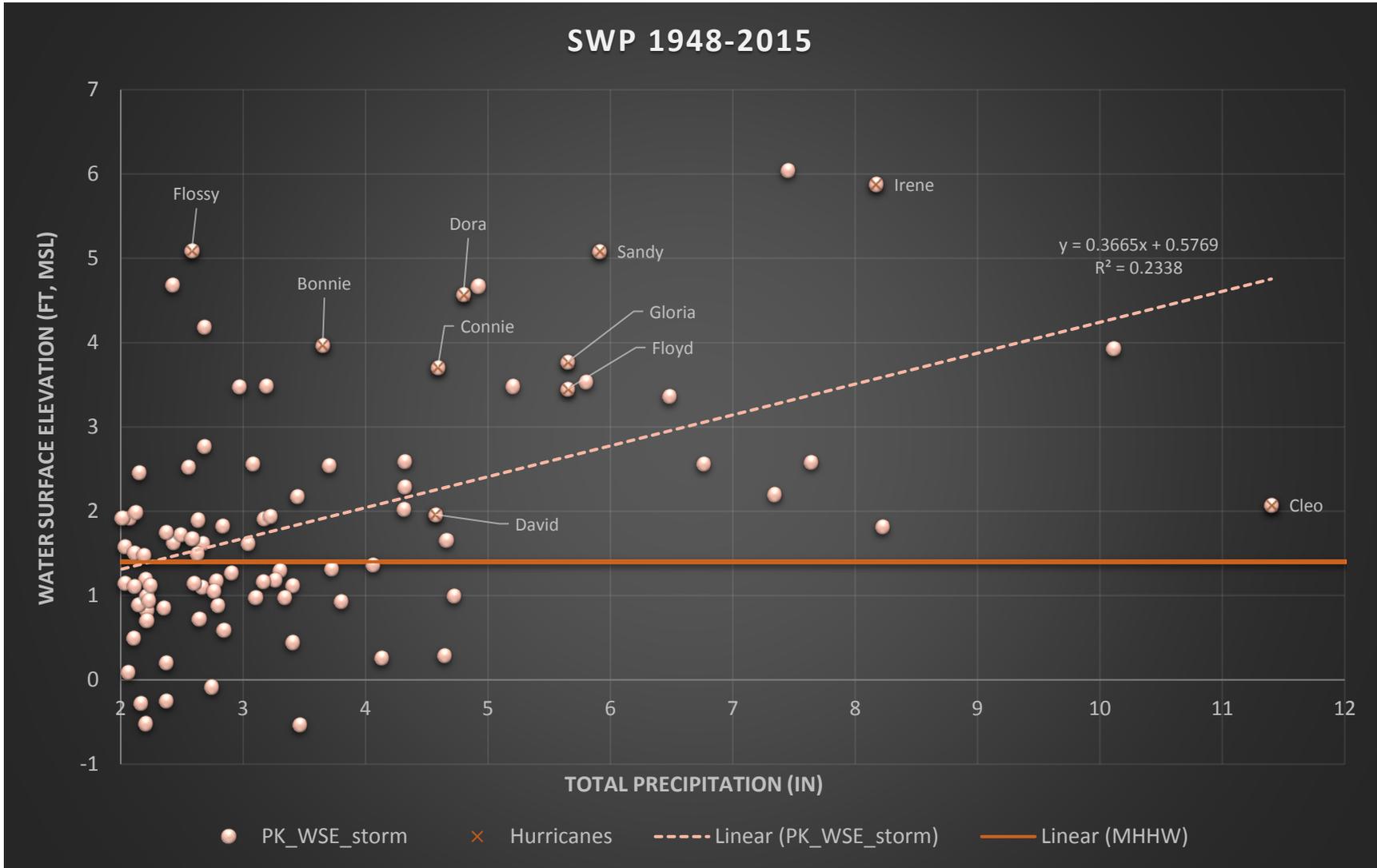


Figure 3. SWP water level station record totals between 1948 and 2015.

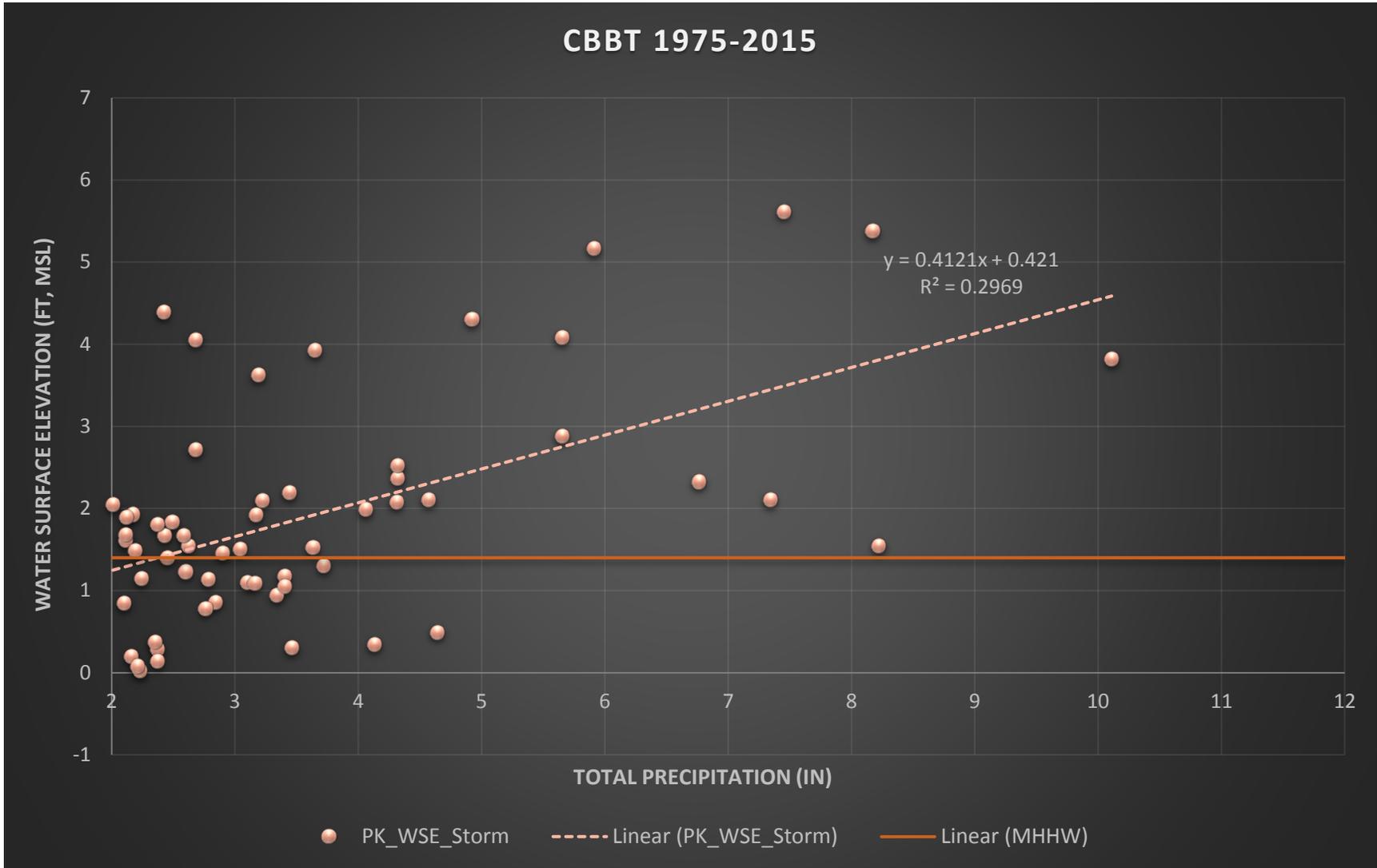


Figure 4. CBBT water level station record totals between 1975 and 2015.

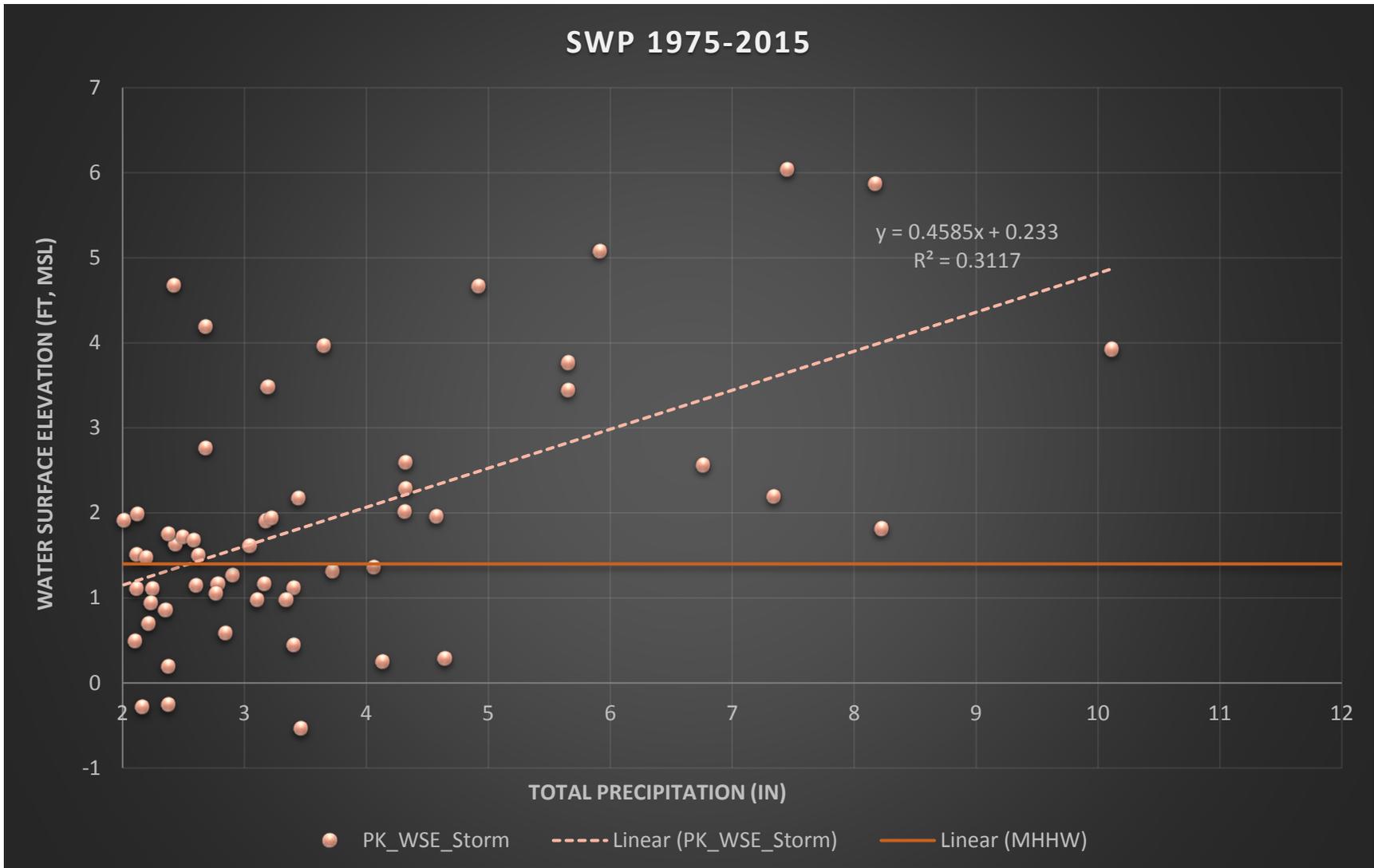


Figure 5. SWP water level station records and rainfall event totals between 1975 and 2015.

Discussion of Results

Current design guidance recommends using mean higher high water (MHHW) as the tailwater elevation for modeling streams hydraulically connected to coastal waters. Hydraulic models developed for the City's storm drainage system would assume a constant tailwater elevation of MHHW in adherence to this guidance. However, as indicated in Figure 3, recorded data at the water level and rain gauges indicate more than 50 percent of the rainfall events occurred while the water level was higher than the MHHW. This trend reflects the City's geographic location at the mouth of the Chesapeake Bay, with contribution of wind and wave-driven storm surge that accompany precipitation associated with tropical and extratropical events. Given this, it is very likely that tailwater elevations will be higher than MHHW when the City is experiencing a rainfall event.

It is recommended that the City design the storm water infrastructure to higher tailwater levels. Increasing the design recommendation would help improve confidence that the storm water system will maintain the ability to evacuate runoff even in the event of increase coastal water levels from a storm event. The empirical correlation analysis undertaken here provides a more conservative tailwater as compared to existing design guidance that provides a tailwater elevation better suited for a coastal area susceptible to combined flooding from rainfall and coastal storm surge.

Additional analysis should be undertaken to potentially improve correlation or provide a more robust statistical foundation for the adjustment of tailwater design guidance. The astronomical tide component highly influences the total water level experienced at the water level station during the periods of the observed rainfall events. Additional insight and better correlation could possibly be achieved through evaluation of residual water levels (de-tided water levels with only surge values) against the corresponding rainfall totals. An extension of this study to include additional rain/water level gauges in the Virginia Beach/Hampton Roads area, along with the application of joint probability principles would yield a statistically relevant result. This type of analysis would categorize the rainfall events by their duration and develop a set of varying tailwater levels and corresponding design rainfall values. The joint probability analysis would develop a series of tailwater elevations for frequency rainfall totals when statistically combined would result in a water surface elevation corresponding to the return period of the rainfall.

CHAPTER 2: JOINT PROBABILITY ANALYSIS

Background

The correlation study used rainfall depths for durations of up to three days, and drew a general conclusion regarding the correlation of tide elevation to rainfall depths. This particular study is more design-oriented and focuses on 24-hour rainfall depths. Consequently, this study builds on the correlation study result that inland rainfall and tide can and do occur simultaneously. Consequently, this study confirms the correlation between rainfall and tide. However, this correlation mainly impacts the results of the joint probability analysis of large rainfall events. Results from this joint probability analysis will provide statistically-based coastal water elevations and precipitation values to inform design tailwater elevations (outlet blockage), and are anticipated to be leveraged by ongoing efforts in the Comprehensive Sea Level Rise/Recurrent Flooding Analysis and the Stormwater Master Plan.

There are few studies on the tailwater evaluation based on joint probability analysis in Virginia. The Virginia Department of Transportation's drainage manual (VDOT 2002) includes a table for outlet blockage under the 10- and 100-year design. This table is based on a 1974 study by the Norfolk District of US Army Corp of Engineers; this study updates those results and expands them to more design levels. The recommended results of this study are compared to the table in the VDOT drainage manual.

Data Sources

Rainfall Data

Because engineering design commonly uses year-based recurrence interval of 24-hour rainfall, the main data used in this study is the maximum annual 24-hour rainfall at each station. Rainfall values for days other than the days with largest rainfall of the year were also considered if they coincided with relatively high tides for additional insight into the nature of the problem. The use of the 24-hour time period of rainfall requires analysis of tides during the same day. Thus, the tide (surge) values were also considered in the daily time period (maximum and average tide of the day).

The daily rainfall used in this study was based on the Norfolk International Airport location, same as that used for the correlation study (Figure 2). Daily rainfall was extracted from 1946 to 2015 and then completed back to 1927 using data from station at Diamond Springs and the NOAA Atlas 14 database for the Norfolk WSO Airport. Data for years prior to 1927 was not considered because simultaneous tidal data is not available for prior years. The July 31, 2016 rainfall event of 6.99" was assumed to be the largest 2016 event and was added to

the rainfall database. Data from other local rainfall stations at Oceana NAS and Norfolk NAS were also considered but not used because of shorter data period and lack of correlation with tidal data.

Collected Data vs. Published Design Rainfalls

A frequency analysis was performed using the data collected for the maximum annual 24-hour rainfall at Norfolk International Airport. This analysis showed design rainfall values would not be exactly the same as the official values that is obtained from NOAA Atlas 14 for the same station. One reason is the data period of NOAA Atlas 14 was from 1910 to 2000 while the data in this study is from 1927 to 2016. The second reason is that by default the NOAA Atlas 14 values are based on partial duration series while we used annual data series. Figure 6 shows the cumulative probability of maximum 24-hour rainfall data in this study and the Gumbel Distribution fit to it compared with the published values from NOAA Atlas 14 (see Table 6 for rainfall depths). While the two data sources closely match for large rainfall depth, they also start deviating from each other as the rainfall depth falls below 4.4” (almost the 5-year rainfall). To allow consistency with readily available published data, the NOAA rainfall values were used in the table of results relating tide to rainfall. The variation in the results is limited to the 1-year and 2-year return period rainfall values.

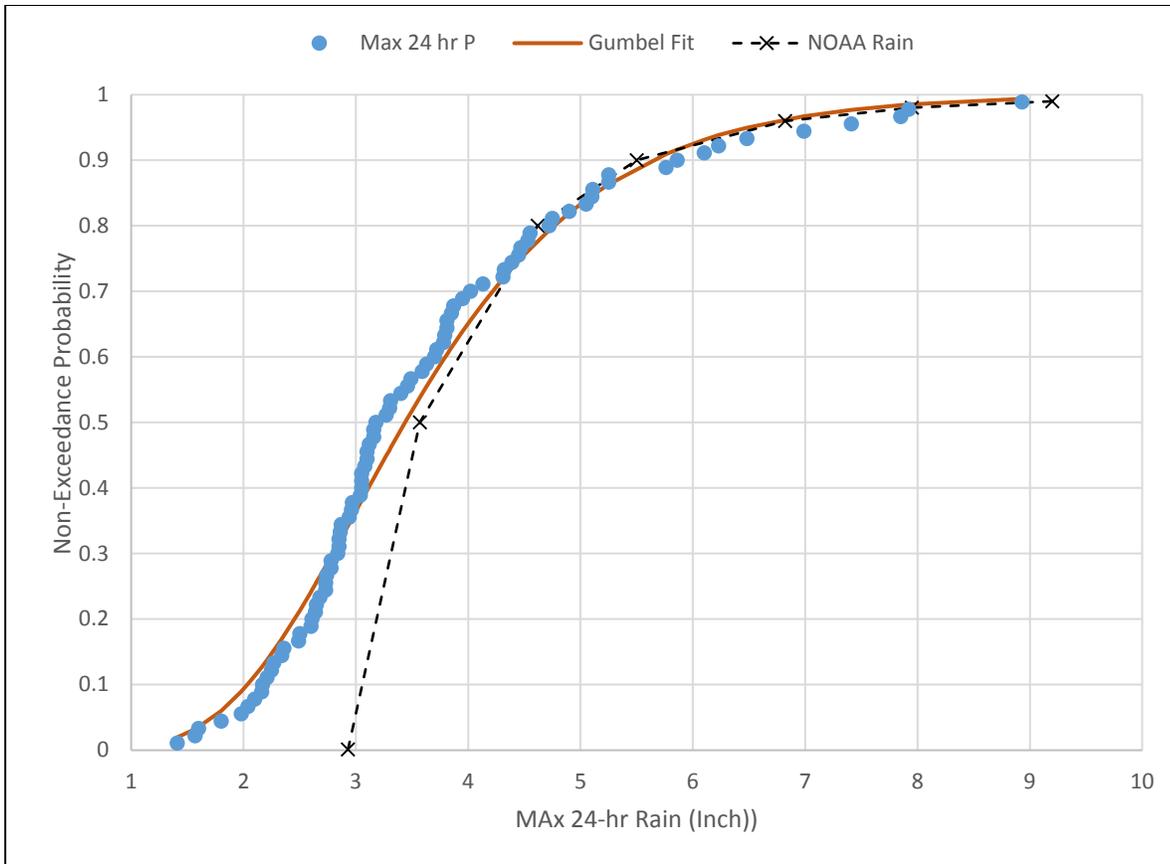


Figure 6. Cumulative probability of maximum 24-hour rainfall data in this study and Gumbel Distribution fit compared with the published values from NOAA Atlas 14.

Coastal Water Level Data

The coastal water level data, or “tide data” used in this effort is same as that used for analysis presented in Chapter 1 and taken from NOAA Station at Sewell’s Point, VA (Figure 7). Tide data from the station at Money Point, VA was also considered but not used due to shorter data period and lack of correlation to rainfall data. Data from Chesapeake Bay Bridge Tunnel (CBBT) station (Figure 2) was used in a limited fashion. CBBT record was used to fill in missing values for Sewell’s Point; regression analysis between the data from the two stations was used for this purpose.

Data from tide stations of inland tidal streams, such as Money Point on Southern Branch Elizabeth River, is beneficial in studying tailwater conditions for hydraulic structures on streams discharging into such streams. The inner land tidal water body data was not available for use for the current joint probability study.

High Tide vs. Mean Daily Tide

A wealth of tide data is available for the Sewell's Point station. Verified Hourly Water Level is available from 7-22-1927 to 8-25-1942 and again from 9-15-1943 to the current date. Verified High/Low Water Level, based on 6-minute data, is available starting August 01, 1979. The high tide (maximum daily tide) values for days corresponding to maximum 24-hour rainfall for each year were taken from this data. The mean daily tide was calculated for the same days as the average of hourly data for each day. The same data was also collected for all days when the 24-hour rainfall exceeded the 1-year 24-hour rainfall level of 2.93." Additional data for the largest recorded tidal events at the station was also collected to be able to examine the top 20 high tidal events, regardless of the rainfall. All tide data was taken in NAVD 88 ft.

When no storm surge is impacting the WSE at this station, the tide chart normally exhibits a double diurnal shape. However, during a storm surge, the WSE could be elevated for durations ranging from several hours to several days. This study focuses on daily time periods so the tide values were averaged only for each 24-hour period. As an example, Figure 7 shows the verified WSE fluctuations during the storm surge event on September 1, 2006. While the verified high for that day was 3.91 (ft., NAVD 88), the mean daily tide was calculated at 2.87 (ft., NAVD 88). To use the highest WSE of the day, which may last only for a few minutes as the tailwater elevation, would be an overestimation. Therefore, the mean daily tide value was assumed to better represent the average tailwater condition for a given day. However, the highest tide of the day is more appropriate to use for data analysis because it actually represents a measured tide elevation. Therefore, data analysis was performed on both the mean daily and the high tide data. The results from the analysis of the high tide data was converted to mean daily tide (to represent tailwater elevations) utilizing a regression equation developed between the two parameters for 56 daily values collected from 1979 to 2016. Figure 8 shows the relationship between the highest daily tide elevation and mean daily tide at the Sewell's Point station.

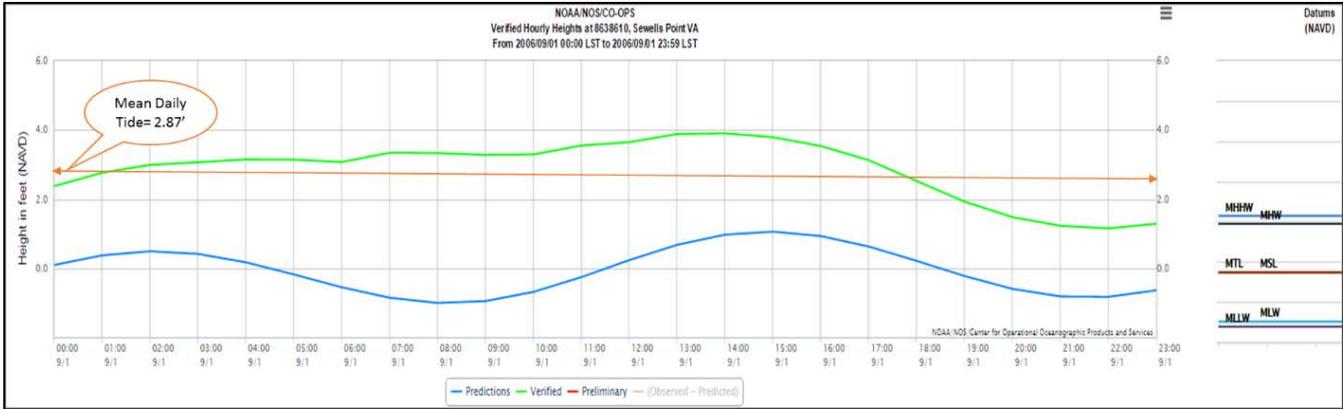


Figure 7. WSE fluctuation recorded at Sewell's Point during 9/1/2006 storm surge and the calculated mean daily tide.

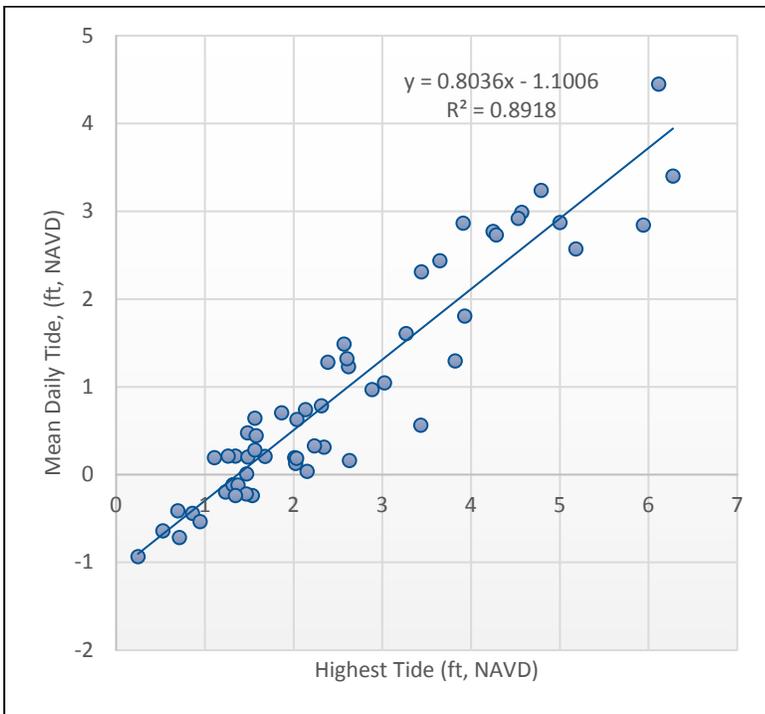


Figure 8. Mean daily tide versus highest daily tide at Sewell's Point.

High Tide for Days of Maximum 24-hour Rainfall versus Published Design Tides

Similar to the use of published design values for rainfall, tide levels are also taken from official NOAA website. For the Sewell's Point station, this information was taken from NOAA's website for the station, as reflected under the datum and extreme water level sections. The data were then converted to feet in NAVD 88, as shown in Table 9. The mean daily tide values were evaluated from high tides using the relationship depicted in Figure 8. All tide values in Table 9 are updated to the Year 2015.

Table 9. Design high tides from NOAA for Sewell’s Point and corresponding mean daily tides and rainfall depths for the same recurrence interval (T_r in years).

T_r	M (MSL) or (MHHW)	High Tide ft (NAVD 88)	Mean Tide Estimated from High Tide ft (NAVD)	24-hour Rainfall Depth (Inches)
1.01	0.97	2.92	1.25	2.93
2	1.27	3.91	2.04	3.57
5	1	4.75	2.72	4.62
10	1.64	5.12	3.01	5.50
25	1.36	5.93	3.67	6.82
50	1.52	6.46	4.09	7.95
100	2.25	7.12	4.62	9.20

Recorded Tide Elevations vs. De-trended Data

The recorded Mean Sea Level at NOAA Station Sewell’s Point exhibit an average rise of 4.59 mm/ year for the 1927 to 2015 period (see Figure 9).

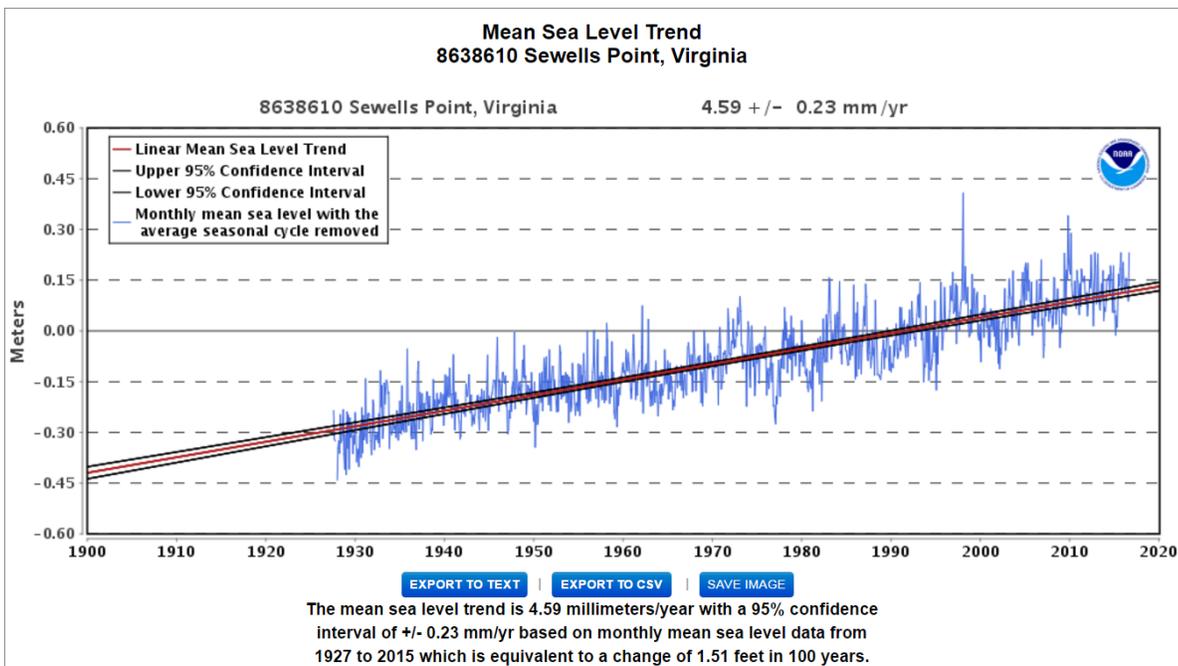


Figure 9. Mean sea level rise trend at Sewell’s Point.

The raw tide data that is available for the Sewell’s Point station does not account for the trend reflected in Figure 9. The tide elevation values were all updated to the 2015 value, same

as design tide values in Table 9, using the mean sea level rise of 4.59 mm/year. The updated tide values are hereinafter called “de-trended” tides.

The joint probability analysis considered three types of de-trended data to evaluate the joint probability of rainfall-tide, including:

- de-trended tide data for days with the highest 24-hour rainfall for each year
- de-trended maximum high tide of each year with the rainfall depth for the same day
- partial duration series of high tide data

The first data type consisted of the de-trended tide data for days with the highest 24-hour rainfall for each year. Both the mean daily tide and the highest daily tide values were tried in the calculations but only the mean daily tide values are discussed here for brevity. This data set would not include the large tide values that has occurred during days other than the day of maximum daily rainfall of each year.

Figure 10 shows the de-trended mean daily tide vs. maximum 24-hour rainfall depth of each year. This figure shows a general, but not distinctly strong correlation between the two

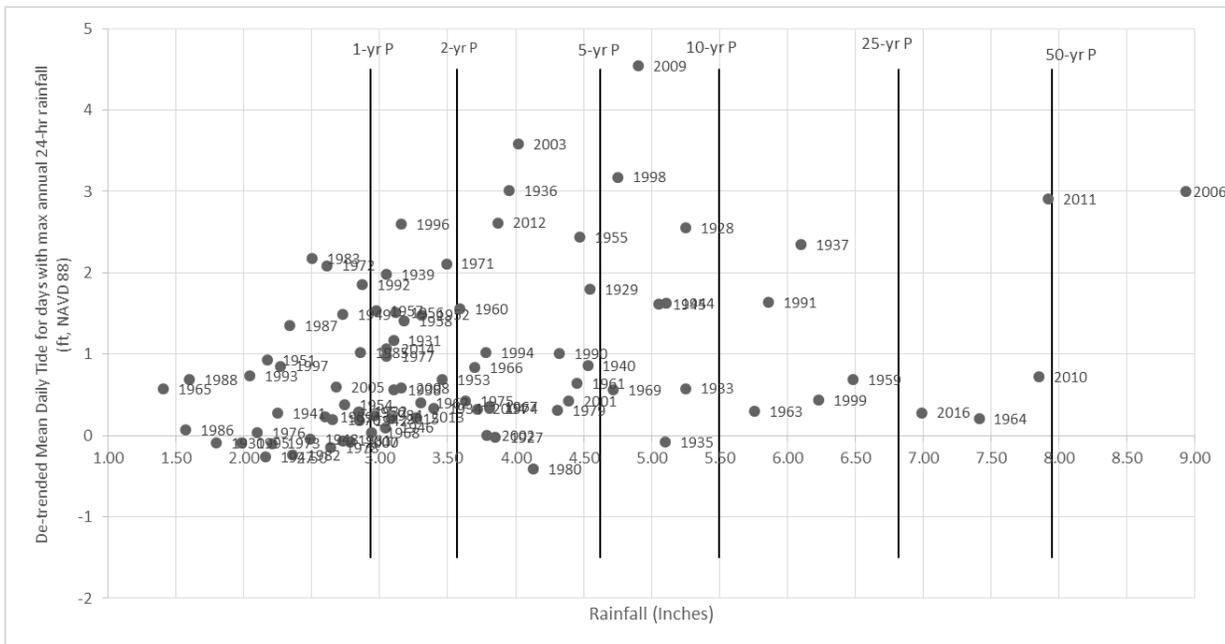


Figure 10. De-trended mean daily tide versus maximum 24-hour rainfall depth of each year.

factors. The correlation coefficient of 0.336 is significant to 0.001 levels, however, there is considerable scatter around a trend of increasing tide level with increasing rainfall. Figure 11 compares the cumulative probability distribution of the de-trended mean daily tide with

maximum 24-hour rainfall; it is then compared to the data for mean daily tide for Sewell's Point station (Table 9), which considers all tides. As seen in Figure 11, the two curves only approach each other at the extremely large tide values. Generally, the curve for mean daily tides for days with maximum rainfall show a larger non-exceedance probability (larger recurrence interval) for the same tide value than the published values that consider all tide data. For example, a mean daily tide of 3 (ft., NAVD 88) would represent an 18-year event for days of maximum rainfall, while for published data, it would only be approximately a 10-year event. A similar relationship was observed for high daily tide data. When using this data set, the marginal probability of rainfall would be similar to the published NOAA values (see Figure 6). However, the marginal distribution of the tide value needs to be set by a probability distribution, such as the Gumbel curve, as shown in Figure 11, or by empirical frequency of observed data. The marginal distribution for the de-trended mean daily tide used in the joint probability analysis leading to the final results was based on the empirical frequency analysis of the de-trended mean daily tide for days with maximum 24-hour rainfall.

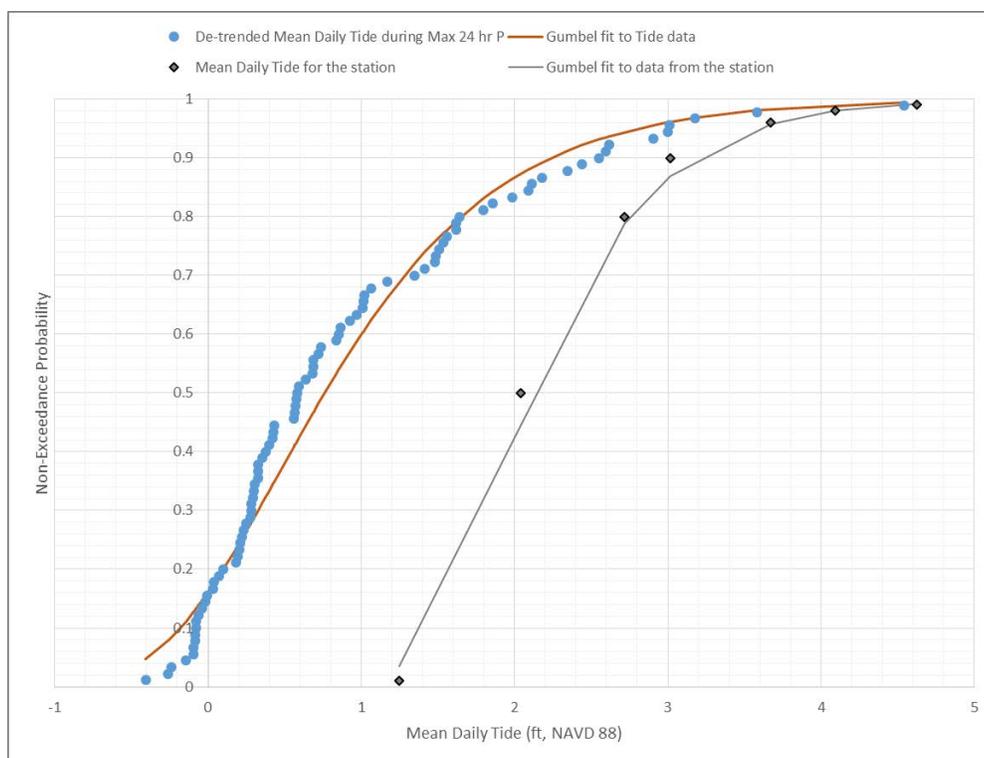


Figure 11. Comparison of cumulative probability of mean daily tide of published values and the de-trended values for days with maximum 24-hour rainfall.

The second data type consisted of the de-trended maximum high tide of each year with the rainfall depth for the same day. This data set would miss some of the large rainfall values that have occurred during the other days, but would include several zero rainfall values for days

with significant surge activity but no inland rainfall. The 2016 value for the maximum high tide was not available at the time of this study. Figure 12, on the following page, shows the de-trended maximum annual high tide vs. rainfall depth of the same day. Except for when rainfall was zero or nearly zero, Figure 12 shows a general, but not distinctly strong correlation between the two factors. The correlation coefficient of 0.446 is significant to 0.00001 levels, however, there is considerable scatter around a trend of increasing tide level with increasing rainfall. Also, very few data pairs are available for days with significant rainfall that is larger than 1-year value. Figure 13 compares the cumulative probability distribution of the de-trended maximum annual high tide and the published (theoretical) values for Sewell's Point Station from Table 9. The Gumbel distribution fit to the data closely matches the published values for the station and may be used as the tide marginal distribution in the joint probability analysis. NOAA has used Generalized Extreme Value (GEV) probability distribution function to estimate the design tide elevations. We used the same software package as NOAA (The extremes value analysis software package "in2extRemes") available from <http://www.assessment.ucar.edu/toolkit/>) with this data set and estimated the design tide values. The results were slightly different from tide values in Table 9. Because those values can be reproduced by any user, they were not updated. Furthermore, the results from fitting GEV to this data set indicated that the null hypothesis that the data follow a Gumbel distribution cannot be rejected, thus confirming the choice of the Gumbel distribution for the marginal distribution of tide data.

The rainfall depths during the days of maximum annual tide would have a probability distribution, drastically different from the published values, as shown in Figure 14. For example, the NOAA 10-year rainfall (non-exceedance probability of 90%) is 5.5 inches, but for this data set, it would only be 4 inches. The marginal distribution of the rainfall, during the days of maximum annual tide used in the joint probability analysis, was based on the empirical frequency analysis.

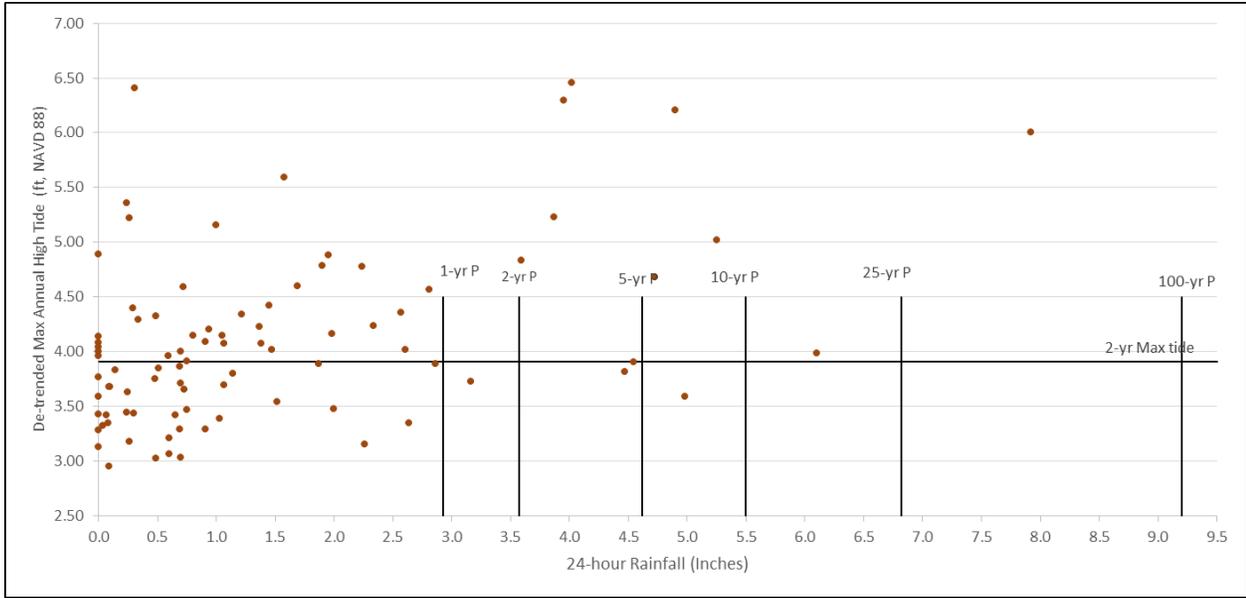


Figure 12. De-trended maximum annual high tide vs. rainfall depth of the same day.

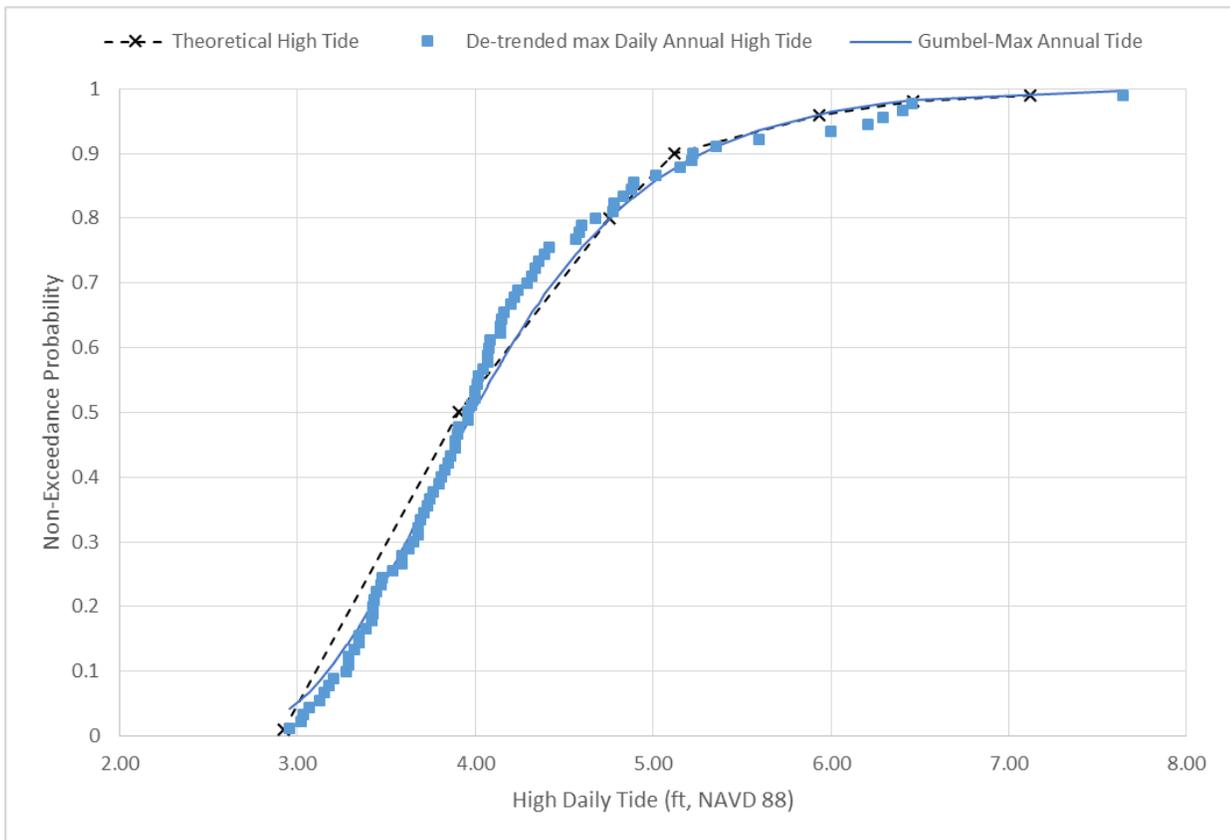


Figure 13. Cumulative probability of de-trended maximum annual high tide and the published (theoretical) data for Sewell's Point.

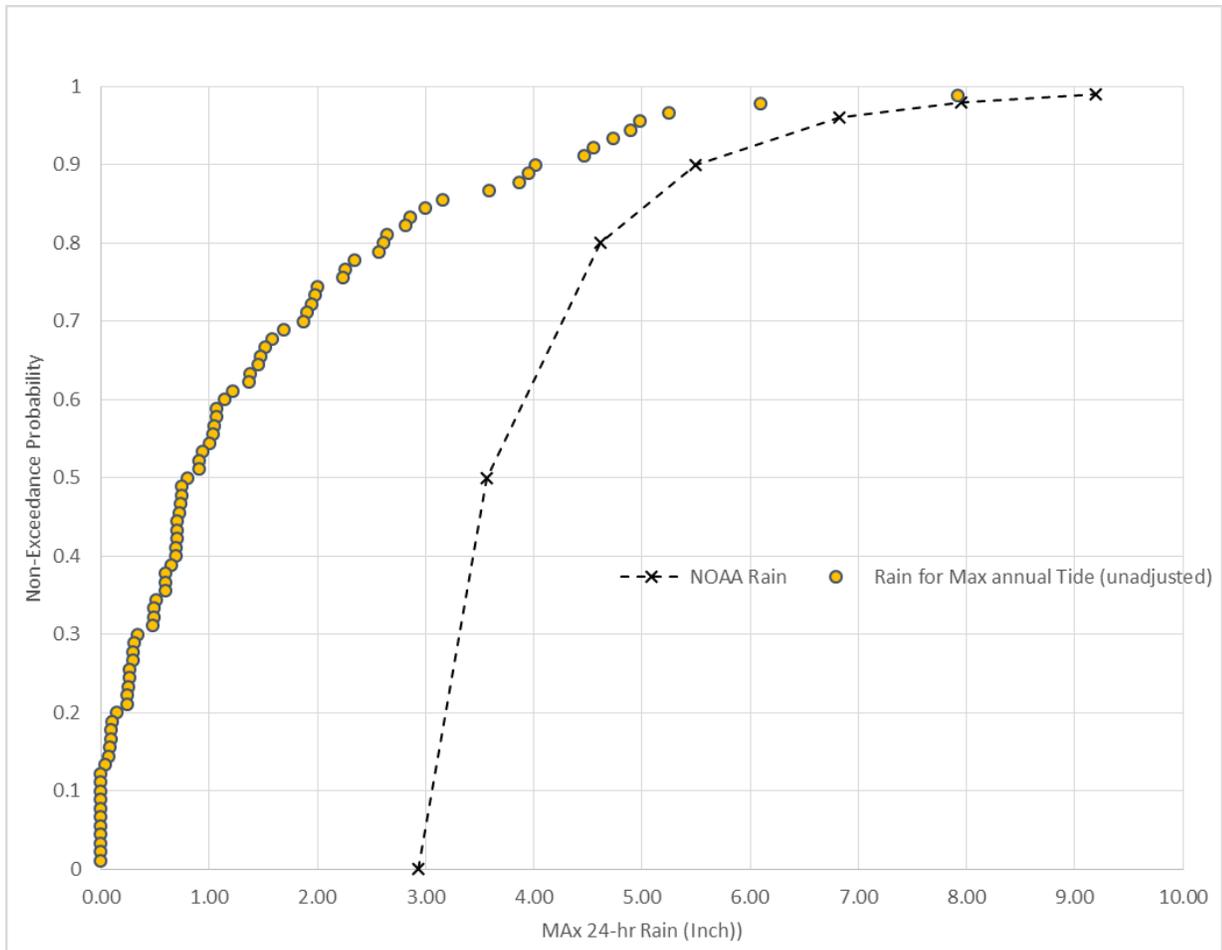


Figure 14. Cumulative probability of rainfall depths for the days with maximum annual tide and the published (NOAA) data.

The third data type consisted of the partial duration series of high tide data. Statistical analysis of the pairs of rainfall-tide data may be performed based on annual series or partial duration series, also known as Peaks Over Threshold (POT). The data types 1 and 2 discussed above are both based on annual time series. The partial duration approach allows consideration of all tide values that are larger than a given threshold value, thus the name, POT. This series may include more than one event per year for some years and no events at all for other years. Similarly, some of the tide values may belong to a day with a large rainfall while others may belong to a day with little or no rainfall at all.

The POT for the maximum daily tide data was extracted using the threshold value of 2.92' NAVD 88, which corresponds to the 1-year high tide elevation. This threshold was selected because it represents the minimum tailwater elevation utilized in practical design. Before extracting the data, the high tides of each year were de-trended, which means updated to 2015 values, using the process described before. Moreover, the partial duration series requires that

only independent events be included in the time series. Therefore, for each year of the analysis, the high tides belonging to consecutive days were analyzed and only independent events. This means that the day of the highest tide or a combination of high tide and large rainfall was selected for this time series. Figure 15 presents the de-trended and independent POT time series for the analysis period from 1927 to 2016. There are 379 data points in Figure 15, which represents an average of more than four events per year. Figure 16 plots the de-trended and independent POT maximum daily tide against the corresponding rainfall of the same day.

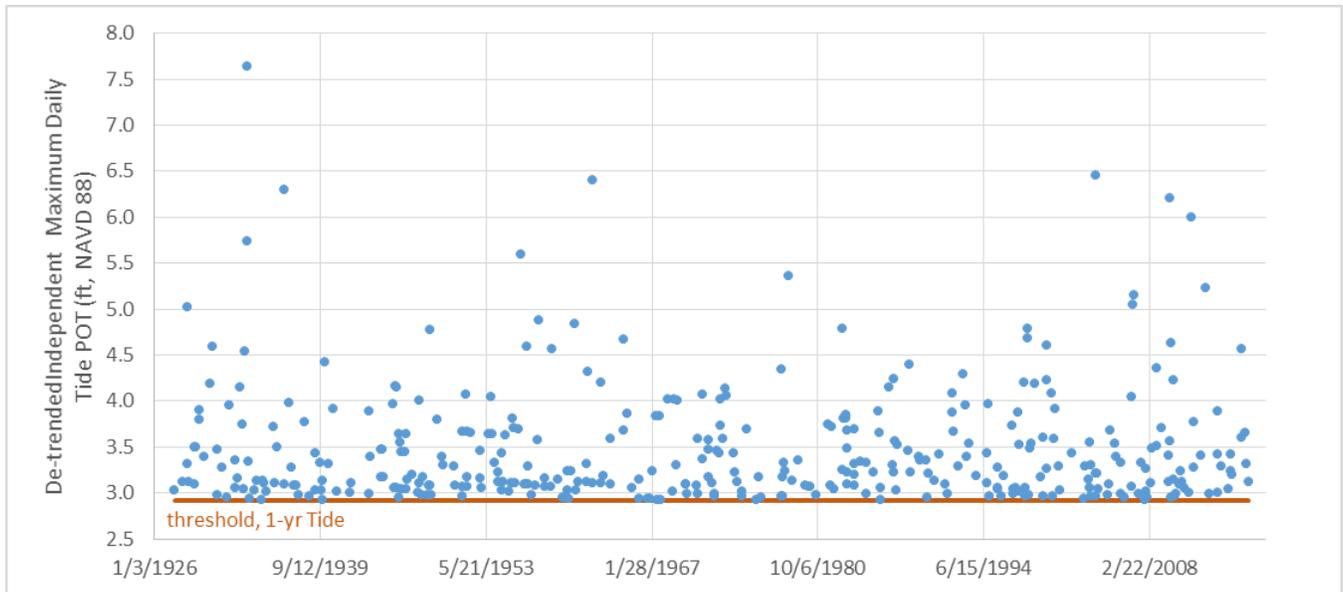


Figure 15. Time series of peaks over threshold independent de-trended maximum daily tides.

Except for when rainfall was zero or nearly zero, Figure 16 shows a general, but not distinctly strong correlation between the two factors. The correlation coefficient of 0.452 is significant, however, there is considerable scatter around a trend of increasing tide level with increasing rainfall. Notice that only a fraction of data points belongs to the region of our interest; tide elevation and rainfall both larger than 1-year level, thus making the potential use of this data set in evaluation of joint probabilities very limited.

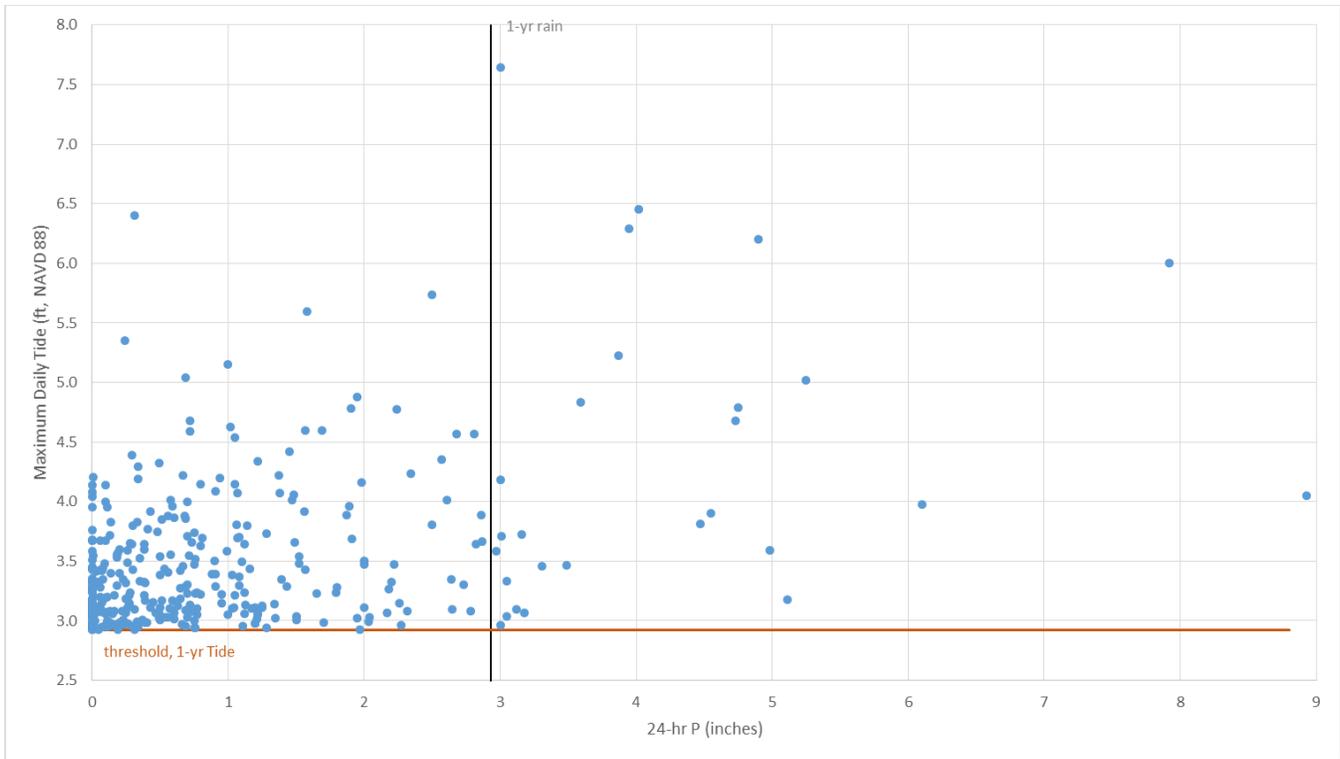


Figure 16. Independent peaks over threshold maximum daily tide versus rainfall depth of the same day.

Technical Approach

The Concept of Joint Return Period

The concept of Joint Probability and how it applies to coastal tailwater conditions could be explained through the following example. Suppose a culvert subject to tidal tailwater conditions needs to be designed for the 25-year recurrence interval. The overall design level of 25-years will be controlled by two marginal probability distributions for rainfall and tide elevation, as well as the joint probability distribution relating the two variables. The joint probability is a measure of the interdependence of two variables. Potentially a number of combinations of rainfall-tide values, larger rainfall with the smaller tide or smaller rainfall with larger tide, would result in the same overall level of design. The joint recurrence interval will be defined by the joint non-exceedance probability,

Where the joint non-exceedance probability = $F(x) + F(y) - F(x,y)$

Where F= Cumulative Probability, “x” would represent rainfall and “y” would represent tide. Therefore, F(x) and F(y) would represent the marginal distribution of rainfall and tide, respectively. If the two variables are completely independent, then the probability that both variables would be exceeded is simply a product of the two marginal exceedance probabilities or (1-F(x)) multiplied by (1-F(y)). For example, the overall recurrence interval, that a five-year

tide would be exceeded when rainfall is at 10-year level or higher, would simply be 5X10 or a 50-year design level. When the two variables show a considerable interdependence, the joint return period $Tr(x, y)$ of both rainfall and tide exceeding a certain value could be calculated by:

$$Tr(x,y) = 1 / (1 - (F(x) + F(y) - F(x,y)))$$

While the marginal distributions $F(x)$ and $F(y)$, for rainfall and tide could be approximated as described before for different data sets, the $F(x, y)$ or joint distribution is unknown, which needs to be evaluated. A good explanation of joint return period and conditional probability distribution, formulation can be found in Yang and Zhang (2013).

Joint Distribution of Rainfall and Tide

As explained above, the key to determining the proper combination of rainfall-tide values for a given design level is to find the joint distribution of the two variables. The previous section summarized the three types of data sets considered in this study in order to evaluate a reasonable joint probability between the two factors and determine proper design tailwater elevations. Data sets one and two were used in calculations, both in the uncensored and censored way. Uncensored data refers to the complete set of data without any omissions, and censored data refers to truncated data on left, or use of rainfall-tide data pairs for when rainfall exceeds certain limits. Both approaches, censored and uncensored, have been used in related coastal studies. Lian et.al. (2013) used the full set of uncensored data, while Pezzoli et. al. (2013) who studied coupling rainfall and tidal levels in a coastal floodplain, used the censored data with rainfall groups. In this study, the use of censored data was tried, but led to unacceptable results due to the small number of tides falling into the data groups with large rainfall values.

Conditional Probability versus Copulas

The required calculation approach for the joint probability of rainfall-tide range from simple, which is based on conditional probability, to complex, which involves copulas.

Conditional probability calculations involve finding the proportion of data exceeding certain limits of both rainfall and tide value at the same time. These calculations were carried out in this study using the bivariate plotting-position formulation, see Equation 2.64 in Zhang (2005); this approach is more suited when a large number of data points are available. Therefore, this method was applied to the de-trended POT data, which consisted of 379 data pairs. The results did not produce acceptable tailwater elevations, mainly because there were few data pairs with both the rainfall and the tide value exceeding the one-year level. Similar calculations using either of the two annual data sets discussed above also failed to lead to

acceptable results because the number of events for which both the rainfall and tide are relatively high were limited. Therefore, the conditional probability results were not selected as the final results of this study.

A more statistically rigorous approach than conditional probability was pursued through the application of various copulas. Copulas provide a convenient way to express joint distributions of two or more random variables. With a copula, you can separate the joint distribution into two contributions: 1) the marginal distributions of each variable by itself; 2) and the copula that combines these into a joint distribution. Application of copulas is mathematically relatively complex and could involve multi-variate analysis formulations, evaluation of statistical parameters, such as Kendall Tau Rank Correlation, and other association parameters for various models, uncommon empirical frequency plotting position equations, among others. Details of various copulas applied in this study are not included here. For a description of various copulas and their practical application, see Zhang (2005) and Venter (2003), Venter (2008), Lian et.al. (2013). In this study, full joint probability analysis was performed using all three types of data sets previously discussed. Four different copulas were tried in the calculations: 1) logistic copula; 2) GH (Gumbel-Hougaard) copula; 3) Clayton copula; 4) and Heavy Right Tail copula. These copulas were also applied to the censored data for rainfall class larger than 10-year level; larger than 25-year level class included too few data points. In search of better results, marginal distributions were tried using both distribution fitting and with empirical probability assumption using Weibull and Gringorton plotting positions.

Selection of Final Results

No matter what data set was tried, it was difficult to get a good copula fit to the data. The main reason is that if the data set was selected based on days with maximum 24-hour rainfall, the marginal distribution of tide values showed a very high cumulative probability at relatively low tide values. Conversely, for data set based on the maximum annual tide, the marginal distribution of rainfall exhibited large cumulative probability at relatively small rainfall values. Both of the above cases made the copula not fit very well to a number of rain-tide combinations tried. Application of copulas to POT data was even less productive because for many design level rainfalls, the results showed a smaller tide value than the complimentary tide, which is the theoretical minimum tide level needed to produce the target overall design level.

The most consistent and reasonable set of results were obtained through application of the GH copula to the de-trended mean daily tide data for days with maximum 24-hour rainfall. These results were organized into a design table format, which are presented in the Executive

Summary as Tables 1, 2 and 3. Figure 17 demonstrates a more in-depth look at these results by plotting the design curves and adding the original data points, as well as various rainfall and tide design thresholds. The curve for each overall design level starts on the X-axis at zero rainfall and the maximum daily tide for the same recurrence interval as the overall design on the Y-axis. The maximum daily tide is selected to make sure the tailwater is not underestimated when no rainfall is assumed. The curves for the 1- to 10-year overall design levels are free from any interdependence of the rainfall and tide values. As such, these curves intersect complimentary rainfall-tide values; the copula application gave a smaller tide value for these points. For example, the 10-year design curve passes through the point for the 5-year rainfall and 2-year mean daily tide. However, the main parts of the curves for the 25- to 100-year overall design show an inflation of the tide value over the tide value which is complimentary to the rainfall due to the interdependence of the two factors. For example, the intersection of the 10-year rainfall and 10-year tide, which would correspond to the 100-year design level under independence assumption, approximately falls on the 50-year design curve. This means the combination of the 10-year rain and 10-year tide only produces a 50-year design level and not a 100-year design level. To get to the 100-year design with a 10-year rainfall, the tailwater elevation would need to be set to 3.83' (NAVD 88), which approximately corresponds to a 30-year tide.

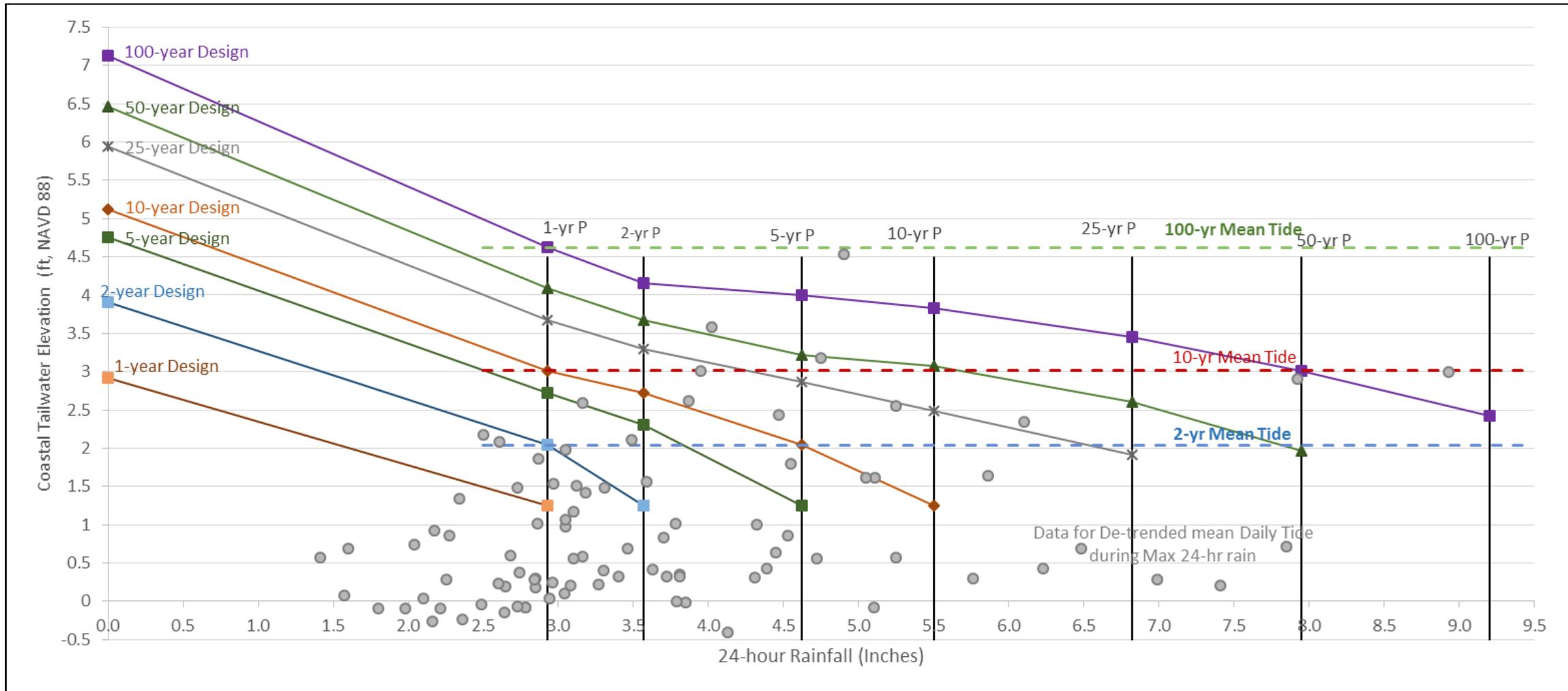


Figure 17. Tailwater design curves showing the data points and rainfall and tide threshold levels.

Comparison of the Results with VDOT Drainage Manual

As explained previously under the “Background” section, the Virginia Department of Transportation’s drainage manual (VDOT 2002) includes a table for outlet blockage under the 10- and 100-year design. Figure 18 below is a clipping from Chapter 8 of the VDOT Drainage Manual showing this table.

c) Outlet blockage

Tides –The Norfolk District has developed a coincidental frequency analysis of the tide and precipitation. The results of this study are shown in appendices 6I-2 and 6I-3. A stage-frequency analysis of all tides is shown in appendix 6I-4. Tide and precipitation are not totally independent and in fact, the severity of joint occurrences is less than if the variables were total independent.

For design purposes the following combinations of tide and precipitation may be used.

Frequencies for Coincidental Occurrences
(Norfolk Harbor)

10-Year Design		100-Year Design	
Tide	Ppt.	Tide	Ppt.
6.3	0.0	8.4	0.00
2.5	1-year	5.4	1-year
2.0	5-year	4.2	5-year
1.5	10-year	1.5	100-year

The combinations of events at the extremities of the tables will usually be critical and often the intermediate combinations may be ignored.

Figure 18. Tailwater coincidental occurrence table in VDOT Drainage Manual.

This table is based on a 1974 study by the Norfolk District of US Army Corp of Engineers, and is limited to the 10- and 100-year design levels with tide elevations in feet above Mean Sea Level (MSL). However, the MSL has changed from 5.39’ (above station datum for epoch of 1960-1978) to 5.74’ for epoch 1983-2001. Thus, 0.35’ was added to the values in the VDOT table to update the elevation above MSL, and then 0.259’ was deducted to convert the values to feet in NAVD 88, same as the results of this study. This study updates the values in VDOT table and expands them to five additional design levels for four additional rainfall levels. Table 10 compares the results from this study to the tide values in the VDOT table with values adjusted and converted to feet in NAVD 88. Because the VDOT values were only available for two design levels and four rainfall levels, only a limited comparison of the new results is possible. As seen in Table 4, the tide elevation results of this study are generally lower than the adjusted VDOT values except for two points. The first point is for the 10-year design with 1-year rainfall for which the adjusted VDOT value of 2.59’ seems too low (less than a 4-year tide instead of a 10-year tide). The second point is for the 100-year design with 100-year rainfall. For this point, the

VDOT value seems to have been set based on MHHW of the station, and our value was set by curve fitting to the points in the 100-year curve that were evaluated by joint probability.

Table 10. Comparison of the results (in black) to the adjusted values from VDOT Table (in red).

10-year Design			100-year Design	
Tide	Rainfall		Tide	Precip
6.39	No Rain		8.49	No Rain
5.12	No Rain		7.12	No Rain
2.59	1-yr P		5.49	1-yr P
3.01	1-yr P		4.62	1-yr P
2.09	5-yr p		4.29	5-yr p
2.04	5-yr p		4.00	5-yr p
1.59	10-yr P		1.59	100-yr P
1.25	10-yr P		2.42	100-yr P

Evaluation of Data Sources for Southern Virginia Beach

A data search was performed, followed by a brief data analysis to identify defensible options for inferring design conditions from the available and applicable information for southern Virginia Beach. However, the limited extent of applicable data and lack of correlation to the longer tidal data used for the aforementioned analysis precluded developing any defensible results.

The following section briefly describes the data sources considered and explains why the data was insufficient to allow statistically viable analysis of tailwater conditions applicable to the southern portion of Virginia Beach.

Data Sources Considered

Because engineering design is commonly based on year-based recurrence interval for 24-hour rainfall, the main data used in for the joint probability analysis is the maximum annual 24-hour rainfall at each station, and the tide elevation for the same days when the largest

rainfall of each year occurred. Thus, the tide (surge) values were also considered in the daily time period (maximum and mean daily tide). Rainfall-tide values for days other than the days with largest rainfall of the year could also be considered if they coincided with extremely high tides for additional insight into the nature of the problem.

In cooperation with local towns and cities including the City of Virginia Beach, USGS is operating several stations to record rainfall and tidal water surface elevations on Atlantic Coastal bays. The stations within Virginia Beach include London Bridge Creek at Rt. 58, Little Neck Creek at Pinewood Rd., and Lake Rudee near Bells Road. Unfortunately, all these stations operate on inland tidal water bodies and have started recording data only recently in 2016. Once these stations collect adequate data they could be key to future studies regarding sea level rise and tidal tailwater conditions in the area.

The closest NOAA tidal station on the south side of Virginia Beach is the station at Duck, North Carolina. However, this station is simply too far from Virginia Beach to be applicable.

The USGS runs a tidal station at Currituck Sound on East Bank at Corolla, North Carolina. Although this station is closer than the Duck station to our study area, it is not close enough to be directly applicable to this study. Lacking any viable station closer to the study area, the use of the tidal water surface elevation data at this station along with the rainfall data from the NOAA station at Corolla, NC and rainfall data from the NOAA station at Naval Air Station Oceana, VA was considered. The problem with Currituck station is that the data period is relatively short starting on 08/26/2011, which is simply not sufficient for our purpose. We then attempted to extend the period of data by trying to correlate the data for maximum and mean daily tide to data from the NOAA station at Sewell's Point, VA, which has a much longer record. Figure 19 and Figure 20 show the relationship between the maximum and mean daily tide between the two stations, respectively. Both show very poor correlation between the data from the two stations which precludes extending the data at Currituck station. In contrast, Money Point, VA station, which is much closer to Sewell's Point, shows a very strong correlation to data from Sewell's Point, not shown here. The data from Money Point station is not applicable to this study because it is not on the south side of the city, but the point is that lack of correlation of data from Currituck Station to Sewell's Point, indicates that it is probably too far from it and that coastal surge activities are not well coordinated between the two stations.

A data analysis using the limited rainfall-tide data available, which is from the Currituck station in combination with the two rainfall stations mentioned above, showed very poor correlation between the daily maximum or the mean tide elevations with the rainfall. For

example, Figure 21 plots the maximum and mean daily tide at Currituck stations for days when recorded rainfall at Corolla station exceeded one inch. However, due to inadequate data period, this does not indicate that the tidal surge process is independent from the rainfall process.

We contacted the USGS to check for any other local data sources and they verified there are none.

In conclusion, adequate data is not available to allow a joint analysis of rainfall-tide with the purpose of estimating statistically defensible tailwater elevation for areas on the South side of the City of Virginia Beach.

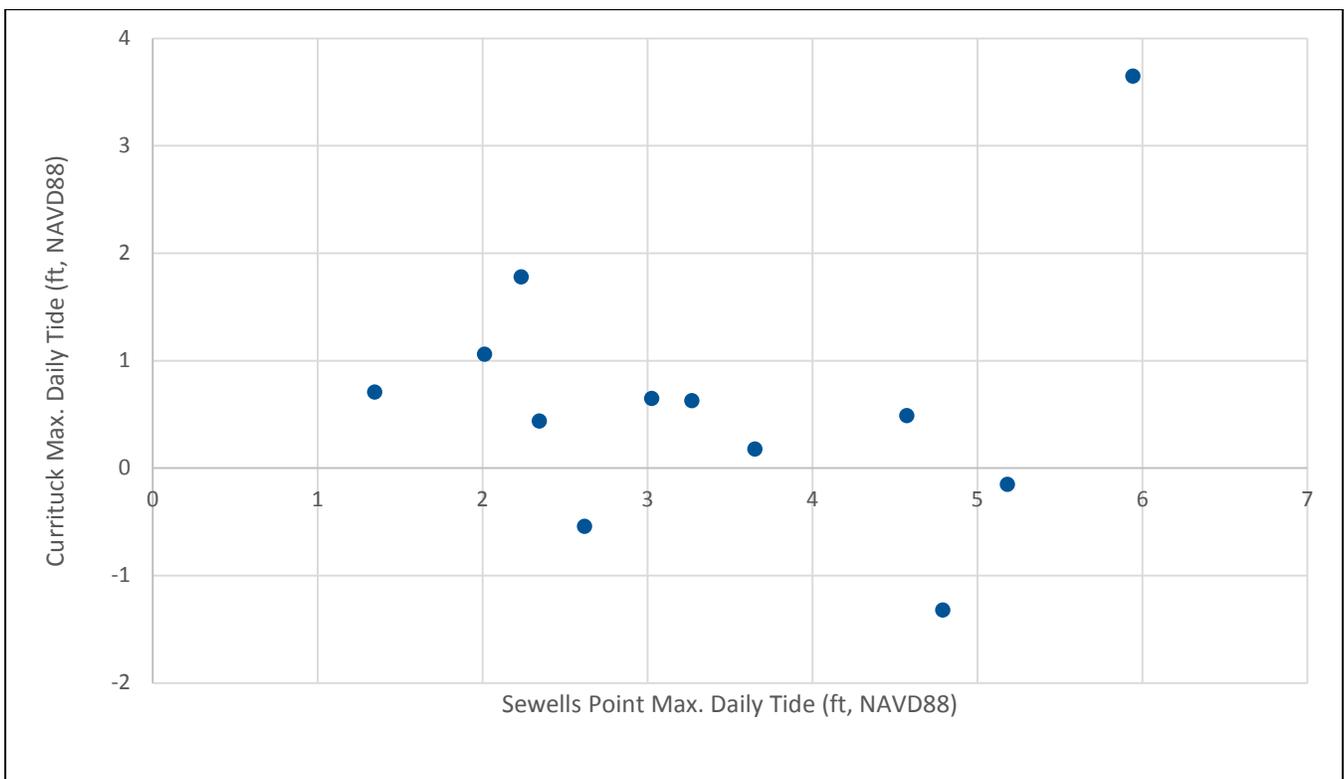


Figure 19. Maximum daily tide at Currituck versus Sewell's Point.

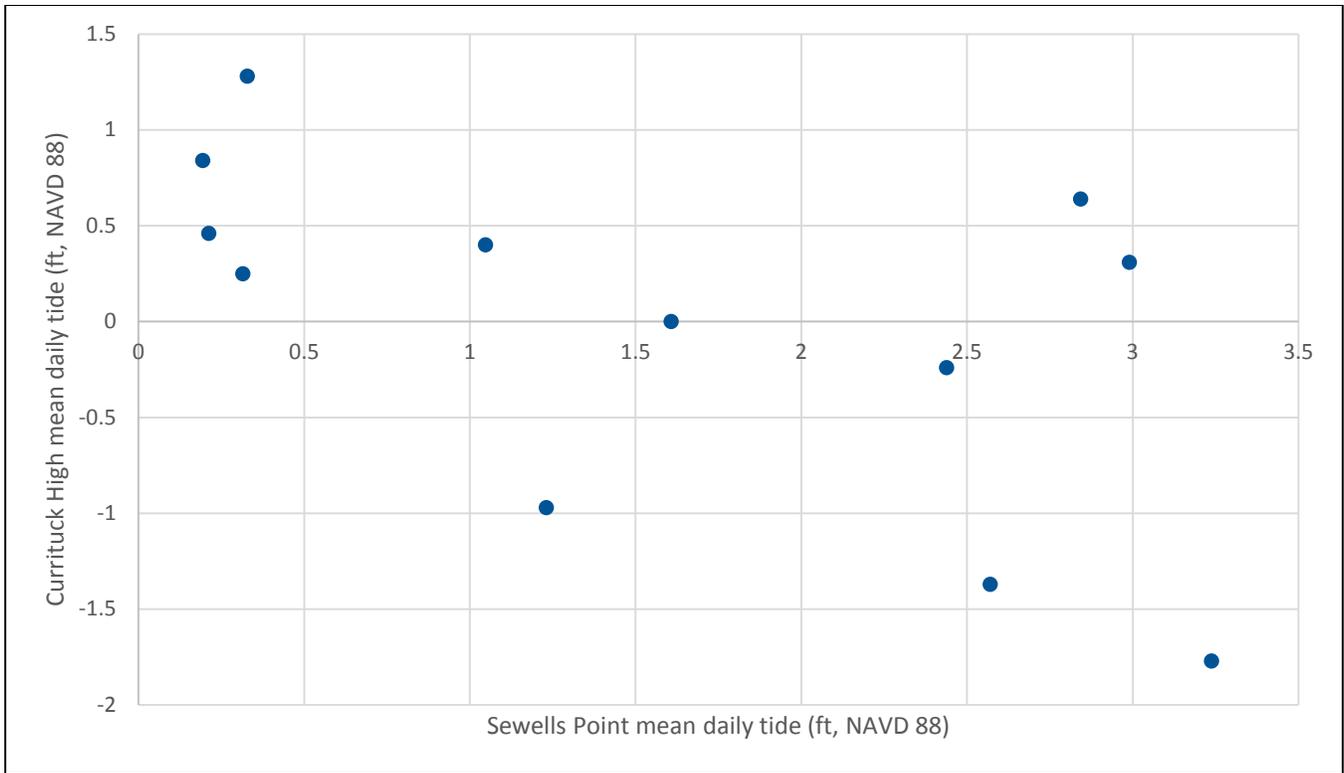
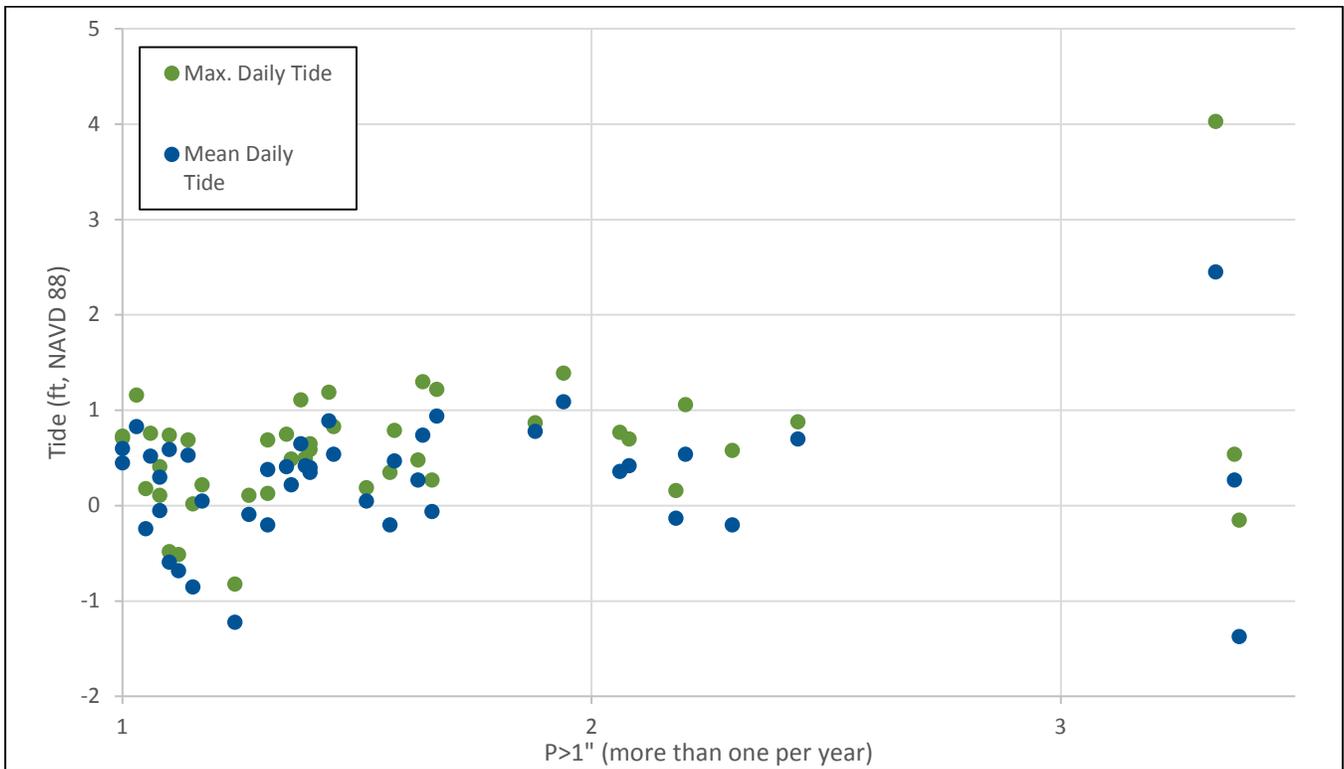


Figure 20. Mean daily tide at Currituck versus Sewell's Point.



RECOMMENDED FUTURE STUDIES

Other helpful additional studies the City of Virginia may pursue include:

- Extending the results of this study to the 500-year design level;
- Considering a similar tailwater study for local inland tidal streams, such as Southern Branch Elizabeth River, for design of hydraulic structures on streams discharging into such water bodies.
- Revising the results of this study to consider sea level rise. As described in Zomorodi (2015), the impact of sea level rise could be included using the equivalent rise method because the tailwater elevations are primarily applicable to engineering design. This approach allows evaluating the impact of sea level rise in design tidal elevations while keeping the failure risk at standard levels for a given structure useful life.
- Modifying design rainfall depths for climate change. Climate change may lead to an increase in design rainfall and subsequently an increase in design discharge for culverts in the Virginia Beach area. The adjusted rainfall depths would alter the rainfall-frequency relationship used in this study, and as a result, may be more appropriate to use with tide elevations adjusted for sea level rise.

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APPENDIX A - RAINFALL EVENTS RECORDED AT NORFOLK AIRPORT RAIN GAUGE AND CORRESPONDING WATER LEVELS

- Note: MHHW = 1.4 feet MSL.
- CBBT – Chesapeake Bay Bridge Tunnel water level station – water level records begin in 1975.
- SWP – Sewell’s Point water level station – Record begins at 1935; however, water levels were not recorded for the year 1975.
- WSE – highest water level recorded in MSL.

Table: Rainfall Events Recorded at Norfolk Airport Rain Gauge and Corresponding High Water Levels

Dates of Storms		Rainfall		MSL	MSL
Rain Start	Rain Stop	Precipitation (in)	Duration (hr)	SWP_PK (WSE)	CBBT_PK (WSE)
8/23/1949 21:00	8/23/1949 21:00	2.63	1	1.90	N/A
7/9/1950 9:00	7/9/1950 9:00	2.2	1	-0.52	N/A
7/15/1950 21:00	7/15/1950 21:00	2.79	1	0.88	N/A
8/22/1950 15:00	8/22/1950 15:00	2.03	1	1.58	N/A
8/13/1953 12:00	8/14/1953 13:00	5.8	26	3.54	N/A
8/29/1954 4:00	8/29/1954 6:00	2.74	3	-0.08	N/A
8/11/1955 22:00	8/13/1955 0:00	4.59	27	3.71	N/A
9/26/1956 15:00	9/27/1956 11:00	2.58	21	5.09	N/A
8/19/1957 3:00	8/19/1957 21:00	2.97	19	3.48	N/A
8/25/1958 11:00	8/27/1958 4:00	4.66	42	1.66	N/A
7/14/1959 10:00	7/15/1959 1:00	2.03	16	1.15	N/A
7/29/1960 5:00	7/30/1960 1:00	2.55	21	2.53	N/A
8/12/1960 5:00	8/12/1960 10:00	2.21	6	0.83	N/A
1/14/1961 14:00	1/15/1961 6:00	2.07	17	1.92	N/A
5/11/1961 0:00	5/11/1961 13:00	2.67	14	1.62	N/A
7/31/1962 10:00	7/31/1962 16:00	2.66	7	1.10	N/A
10/3/1962 17:00	10/4/1962 1:00	3.3	9	1.30	N/A
6/2/1963 1:00	6/3/1963 10:00	7.64	34	2.59	N/A
9/15/1963 10:00	9/16/1963 8:00	5.2	23	3.48	N/A
8/31/1964 13:00	9/1/1964 12:00	11.4	24	2.07	N/A
9/12/1964 19:00	9/14/1964 0:00	4.8	30	4.57	N/A
7/30/1966 6:00	7/31/1966 1:00	3.7	20	2.54	N/A
1/8/1967 0:00	1/8/1967 18:00	3.8	19	0.93	N/A
7/21/1967 13:00	7/21/1967 19:00	2.64	7	0.72	N/A
8/10/1967 17:00	8/11/1967 17:00	2.83	25	1.83	N/A
6/15/1969 18:00	6/16/1969 4:00	2.14	11	0.89	N/A
7/27/1969 9:00	7/27/1969 17:00	4.72	9	1.00	N/A

Dates of Storms		Rainfall		MSL	MSL
Rain Start	Rain Stop	Precipitation (in)	Duration (hr)	SWP_PK (WSE)	CBBT_PK (WSE)
10/2/1969 14:00	10/3/1969 2:00	2.2	13	1.19	N/A
6/25/1970 16:00	6/26/1970 13:00	3.26	22	1.18	N/A
8/27/1971 3:00	8/28/1971 0:00	3.08	22	2.56	N/A
9/30/1971 6:00	10/1/1971 19:00	6.48	38	3.36	N/A
7/10/1973 15:00	7/10/1973 18:00	2.21	4	0.99	N/A
8/3/1973 16:00	8/3/1973 22:00	2.06	7	0.09	N/A
9/6/1974 3:00	9/7/1974 2:00	2.15	24	2.46	N/A
7/5/1975 4:00	7/5/1975 8:00	2.45	5	#N/A	1.40
7/12/1975 4:00	7/12/1975 14:00	2.17	11	#N/A	1.93
7/16/1975 10:00	7/16/1975 18:00	3.63	9	#N/A	1.53
8/17/1977 17:00	8/18/1977 11:00	2.9	19	1.27	1.46
6/8/1978 16:00	6/9/1978 12:00	3.1	21	0.98	1.10
4/13/1979 7:00	4/13/1979 23:00	2.68	17	2.77	2.72
7/29/1979 20:00	7/29/1979 21:00	2.16	2	-0.28	0.20
9/5/1979 2:00	9/6/1979 3:00	4.57	26	1.96	2.11
5/24/1980 15:00	5/24/1980 21:00	3.4	7	1.12	1.18
8/15/1980 17:00	8/16/1980 1:00	4.13	9	0.26	0.35
9/8/1981 16:00	9/8/1981 22:00	2.43	7	1.63	1.68
10/25/1981 3:00	10/25/1981 17:00	2.11	15	1.51	1.62
8/11/1982 8:00	8/12/1982 1:00	2.24	18	1.12	1.15
10/24/1982 17:00	10/25/1982 15:00	2.42	23	4.68	4.40
4/15/1984 12:00	4/15/1984 14:00	2.23	3	0.94	0.02
9/26/1985 14:00	9/27/1985 7:00	5.65	18	3.77	4.09
1/18/1987 21:00	1/19/1987 16:00	2.49	20	1.72	1.84
8/12/1989 2:00	8/12/1989 18:00	2.6	17	1.15	1.23
8/24/1990 8:00	8/24/1990 15:00	4.32	8	2.29	2.37
3/29/1991 3:00	3/30/1991 5:00	2.01	27	1.92	2.05
10/16/1991 19:00	10/17/1991 12:00	3.17	18	1.91	1.93
8/16/1992 7:00	8/16/1992 15:00	2.37	9	1.76	1.81
9/4/1993 20:00	9/5/1993 3:00	2.1	8	0.50	0.85
3/1/1994 16:00	3/2/1994 21:00	4.31	30	2.02	2.08
7/2/1994 15:00	7/2/1994 17:00	2.84	3	0.59	0.86
7/25/1994 18:00	7/25/1994 20:00	3.46	3	-0.53	0.31
7/12/1996 17:00	7/13/1996 8:00	2.12	16	1.99	1.90
10/7/1996 19:00	10/8/1996 18:00	3.19	24	3.48	3.63
2/4/1998 0:00	2/4/1998 23:00	4.92	24	4.67	4.31
6/28/1998 6:00	6/28/1998 8:00	2.37	3	0.20	0.29
8/27/1998 10:00	8/27/1998 23:00	3.65	14	3.97	3.93
9/15/1999 1:00	9/16/1999 3:00	5.65	27	3.45	2.88

Dates of Storms		Rainfall		MSL	MSL
Rain Start	Rain Stop	Precipitation (in)	Duration (hr)	SWP_PK (WSE)	CBBT_PK (WSE)
10/17/1999 9:00	10/18/1999 5:00	7.34	21	2.20	2.11
7/29/2001 7:00	7/29/2001 21:00	2.62	15	1.50	1.55
9/16/2002 12:00	9/16/2002 20:00	3.72	9	1.32	1.31
10/11/2002 13:00	10/12/2002 0:00	3.44	12	2.18	2.20
7/14/2003 4:00	7/14/2003 13:00	3.34	10	0.98	0.95
10/28/2003 16:00	10/29/2003 8:00	2.58	17	1.68	1.67
7/24/2004 17:00	7/24/2004 20:00	2.21	4	0.70	0.08
10/7/2005 16:00	10/8/2005 16:00	3.04	25	1.62	1.51
6/14/2006 3:00	6/14/2006 21:00	4.06	19	1.36	1.99
8/31/2006 12:00	9/1/2006 14:00	10.11	27	3.93	3.82
11/12/2006 11:00	11/13/2006 3:00	6.76	17	2.57	2.33
10/24/2007 14:00	10/24/2007 21:00	2.78	8	1.17	1.14
9/11/2008 2:00	9/11/2008 6:00	3.16	5	1.17	1.09
9/25/2008 6:00	9/26/2008 3:00	2.68	22	4.19	4.06
8/5/2009 21:00	8/6/2009 4:00	2.76	8	1.06	0.79
8/22/2009 15:00	8/22/2009 20:00	3.4	6	0.45	1.05
9/7/2009 22:00	9/8/2009 12:00	4.32	15	2.59	2.52
11/11/2009 0:00	11/13/2009 9:00	7.45	58	6.04	5.62
7/29/2010 18:00	7/29/2010 22:00	4.64	5	0.29	0.50
9/30/2010 1:00	10/1/2010 5:00	8.22	29	1.82	1.55
1/17/2011 17:00	1/18/2011 5:00	2.11	13	1.11	1.68
7/24/2011 22:00	7/25/2011 1:00	2.37	4	-0.25	0.14
7/25/2011 20:00	7/26/2011 0:00	2.35	5	0.86	0.38
8/27/2011 1:00	8/28/2011 3:00	8.17	27	5.88	5.38
6/22/2012 17:00	6/23/2012 0:00	2.19	8	1.48	1.49
10/27/2012 14:00	10/30/2012 1:00	5.91	60	5.08	5.17
7/22/2013 17:00	7/22/2013 21:00	3.22	5	1.94	2.10

