# Appendix B
# Projections for Sea Level Rise and Storm Surge

# Memorandum


**To:** Jennifer Fogliano, Jeff Perlman | North Jersey Transportation Planning Authority (NJTPA)

From: Qitao Gao, Frannie Bui, P.E., Lauren Miller, Melissa Harclerode, PhD BCES (CDM Smith)


Date: April 4, 2018

Re: Task 2-1 Technical Memo for NJTPA Passaic River Basin Climate Resilience Plan: Projections for Sea Level Rise and Storm Surge, Revision No. 2

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## Purpose

This technical memorandum summarizes the analysis conducted for Task 2-1: Determine Climate Change Impacts in the Passaic River Basin for the NJTPA Passaic River Basin Climate Resilience Plan. The purpose of this task is to quantify and summarize projected impacts of climate change on sea level rise and storm surge in the study basin with a focus on selected key vulnerability metrics. This memo provides a review of available data to determine which datasets will be utilized to evaluate impacts of sea level rise and storm surge in the Passaic River Basin. The selected datasets are utilized as direct inputs into the hydraulic and hydrological (H&H) model. A map of the area of the Passaic River that is tidally influenced and is therefore subject to sea level rise and storm surge is shown in **Figure 1**, below.

As discussed in the February 23, 2018 Technical Memorandum "Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Events", climate change is predicted to occur in this part of the country in various forms.

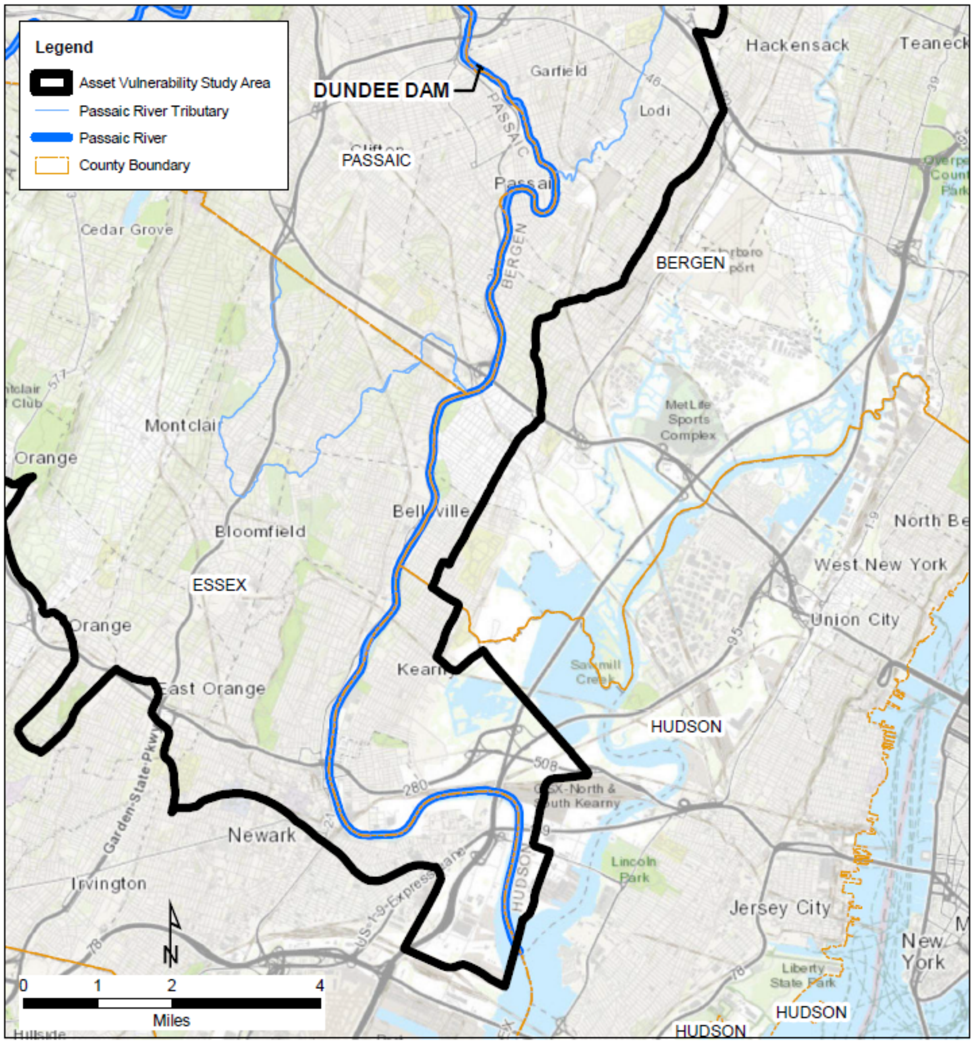


Figure 1. Section of the Passaic River with Tidal Influences

## Sea Level Rise

Sea level rise is caused by the melting of land ice in places such as Greenland and Antarctica, the thermal expansion of ocean water caused by increased temperatures, and changes in land water storage. Local subsidence can also contribute to higher flood depths and can vary significantly by location due to localized groundwater levels, soil types, depth to bedrock, and other geophysical factors.

Two primary sources of sea level rise calculations and information are referred to:

1. The U.S. Army Corps of Engineers (USACE) and the National Oceanic and Atmosphere Administration (NOAA) Sea-Level Change Curve Calculator[1], and
2. The 2016 report "Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms" by the NJ Climate Adaptation Alliance[2].

The USACE/NOAA calculator tool computes potential sea level rise curves for tide gauges across the United States. The models use existing historical tide gauge data as a baseline and calculate future sea level rise values based on different Representative Concentration Pathway (RCP) scenarios[3] from Global Climate Models. USACE uses three sea level rise curves to establish a basis of design for any planning and engineering study. NOAA recently expanded their global median sea level rise curve projections to include six sea level projection scenarios[4]. Each of these scenarios are defined further below and are available using the USACE/NOAA sea level rise calculator[1].

## Review of Tide Gauge Data

The state of New Jersey has three long-term, NOAA tide gauges (Sandy Hook, Atlantic City, and Cape May). However, the nearest long-term tide gauge to the Passaic River Basin study area is The Battery gauge located in the vicinity of Battery Park, New York City. The 2016 report "Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms" by the New Jersey Climate Adaptation Alliance states that the three New Jersey long-term, NOAA tide gauges have relatively higher sea level rise projections than the sea level projections at The Battery, primarily due to the different rates of land subsidence and groundwater withdrawal[5]. Among the three NJ tide gauges, there is minimal difference in sea level projections.

Although the nearest long-term tide gauge to the Passaic River Basin study area is The Battery gauge, our recommendation is to use the sea level rise projections at Sandy Hook as a the most appropriate representation for the study area subject to coastal flooding. This is because parts of the Passaic River Basin study area are susceptible to subsidence (i.e., have compactable

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[1] United State Army Corps of Engineers Sea-Level Change Curve Calculator. (2017, July 18). Retrieved Jan 15, 2018, from http://www.corpsclimate.us/ccaceslcurves.cfm

[2] Kopp, R.E., A. Broccoli, B. Horton, D. Kreeger, R. Leichenko, J.A. Miller, J.K. Miller, P. Orton, A. Parris, D. Robinson, C.P. Weaver, M. Campo, M. Kaplan, M. Buchanan, J. Herb, L. Auermuller and C. Andrews. 2016. Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel. Prepared for the New Jersey Climate Adaptation Alliance. New Brunswick, New Jersey.

[3] See the memo submitted by CDM Smith to NJTPA on February 23, 2018: "Task 2-1 Technical Memo for NJTPA Passaic River Basin Climate Resilience Plan: Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Events" for further explanation of RCP scenarios.

[4] National Oceanic and Atmosphere Administration (2017). Global Sea level Rise Scenarios for the United States.

[5] Miller, K. G., Kopp, R. E., Horton, B. P., Browning, J. V, Kemp, A. C., & Al, M. E. T. (2013). A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. Earth's Future, 3–18. http://doi.org/10.1002/2013EF000135.

sediments) while other areas like New York City are not (i.e., presence of shallow, non-compactable bedrock), as shown in **Figure 2**[5]. The rate of land subsidence can be based on the type and thickness of geologic sediments and glacial isostatic adjustment.

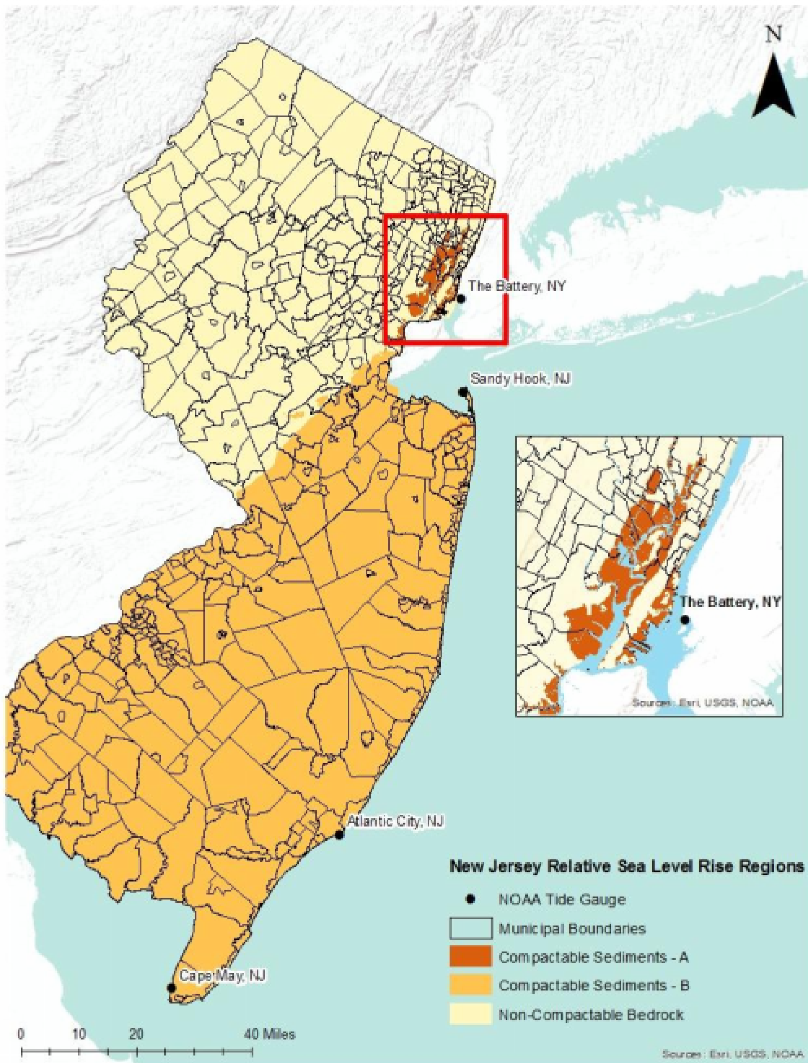


Figure 2. Map of Compactable Sediments in NJ[2]

For demonstration and comparison purposes, the sea level projections from The Battery gauge are also presented in this memo.

NOAA estimates the vertical land movement (VLM) is the process of land subsidence or uplift due to a response to natural processes such as sediment compaction, or anthropogenic processes such as local-to-regional groundwater withdrawal over time. NOAA produces published and regionally corrected VLM rates through the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) and are estimated by global positioning systems. This is important when discussing sea level rise, because accounting for local VLM gives a more accurate representation of how global sea level rise will impact a local area – this is called relative sea level change (RSLC). The VLM based on the NOAA 2017 sea level change projections at Sandy Hook, NJ is an estimated 0.00699 feet/year whereas for New York, the VLM is an estimated 0.00423 feet/year. These VLM estimates further support our recommendation to use the Sandy Hook gauge instead of The Battery gauge for the study area.

## Relative Sea Level Change

The relative sea level change (RSLC) projections at the Sandy Hook, NJ and The Battery, NY gauges from 2000 to 2100 are shown in **Figure 3 and Figure 4**, respectively. The two vertical grey, dotted lines are shown to demarcate the years 2045 and 2080, which are the two planning horizons determined for NJTPA Passaic River Basin Resiliency Study. The three horizontal dashed lines represent the USACE potential SLR projections and the dotted curves represent the seven NOAA SLR projections.

The following sea level projections are shown in **Figures 3 and 4**, as well as **Table 1**:

- NOAA 2017 Extreme (defined as the upper boundary of Global Mean Sea Level (GMSL) rise in 2100 with GMSL of 8.20 feet ± 0.50 feet)
- NOAA 2017 High (defined as 2100 GMSL rise of 6.56 feet ± 0.16 feet)
- NOAA 2017 Intermediate High (Int High) (defined as 2100 GMSL rise of 4.92 feet ± 0.16 feet)
- NOAA 2017 Intermediate (Int) (defined as 2100 GMSL rise of 3.28 ± 0.07 feet)
- NOAA 2017 Intermediate Low (Int Low) (defined as 2100 GMSL rise of 1.64 ± 0.07 feet)
- NOAA 2017 Low (continuation of current rate of sea level rise)
- NOAA 2017 Vertical Land Motion (VLM)
- USACE Low (projection of observed sea level rise)
- USACE Intermediate (projections accounting for ocean warming)
- USACE High (projections accounting for a more rapid loss of the ice sheet)

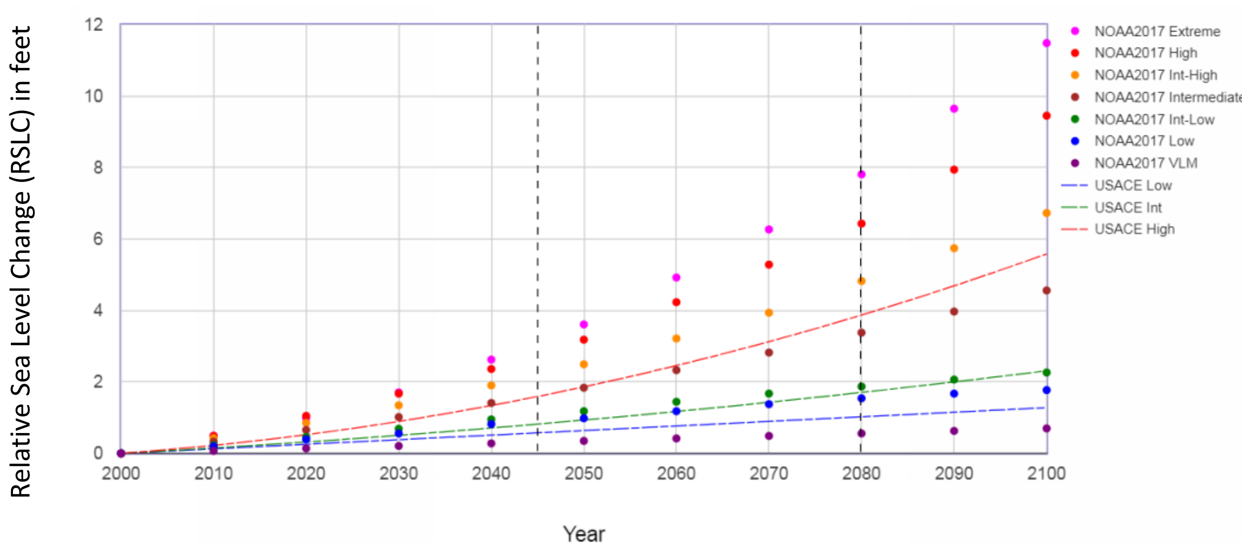


Figure 3. Sea Level Rise Projection Curves at Sandy Hook, NJ[1]

*Note: This is the recommended gauge to evaluate the impacts on sea level rise for the study basin.*

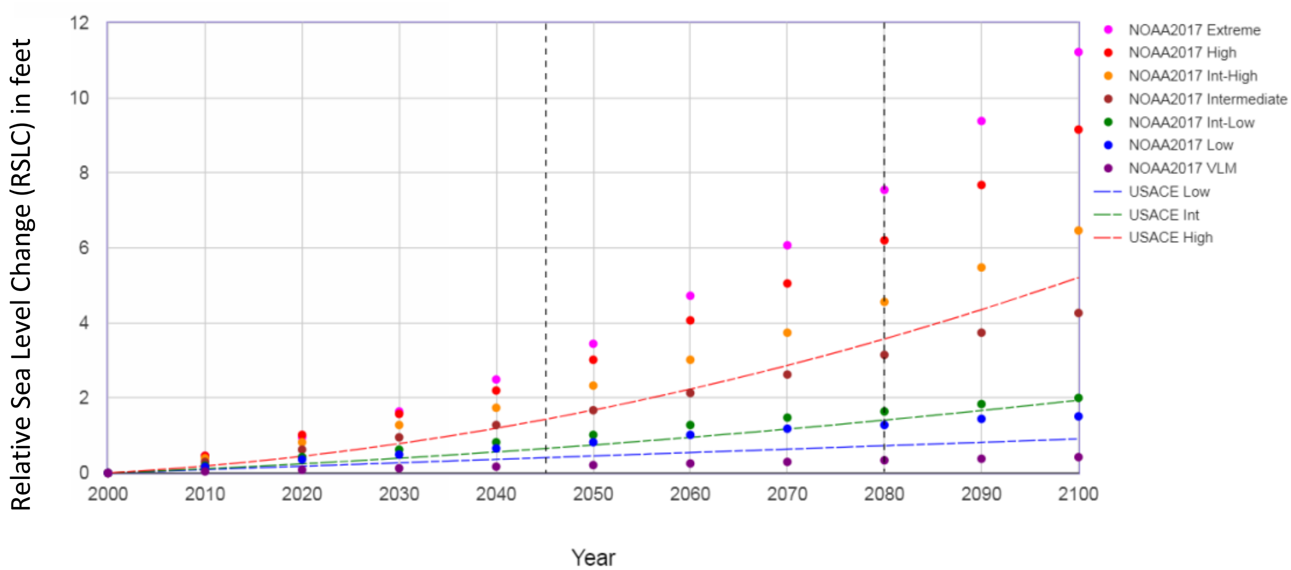


Figure 4. Sea Level Rise Projection Curves at The Battery, NY[1]

*Note: This figure is shown for comparison purposes for areas that may be situated on bedrock.*

**Table 1** summarizes the projected RSLC since 2000 using the NOAA and USACE curves for 2018, 2045 and 2080. The results from the USACE/NOAA sea level change calculator using the 2017 NOAA curves is decadal, thus in order to calculate 2018 and the 2045 planning horizon, the sea level change results are linearly interpolated.

Table 1. Sea Level Rise Projections at The Battery, NY and Sandy Hook, NJ[1]

| Datum | Year | NOAA 2017 | | | | | | | USACE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | VLM | Low | Int-Low | Int | Int-High | High | Extreme | Low | Int | High |
| RSLC at Sandy Hook | 2018 | 0.13 | 0.35 | 0.41 | 0.59 | 0.77 | 0.94 | 0.88 | 0.23 | 0.29 | 0.46 |
| | 2045 | 0.32 | 0.90 | 1.07 | 1.63 | 2.20 | 2.77 | 3.11 | 0.57 | 0.82 | 1.60 |
| | 2080 | 0.56 | 1.54 | 1.87 | 3.38 | 4.82 | 6.43 | 7.81 | 1.02 | 1.71 | 3.87 |
| RSLC at The Battery | 2018 | 0.07 | 0.32 | 0.38 | 0.56 | 0.73 | 0.91 | 0.85 | 0.16 | 0.22 | 0.40 |
| | 2045 | 0.19 | 0.74 | 0.92 | 1.48 | 2.04 | 2.61 | 2.97 | 0.41 | 0.66 | 1.44 |
| | 2080 | 0.34 | 1.28 | 1.64 | 3.15 | 4.56 | 6.2 | 7.55 | 0.73 | 1.41 | 3.57 |

*Note: All values are expressed in feet.*

**Using the sea level change calculator at the Sandy Hook gauge, sea level rise projections for the 2045 time horizon range between 0.57 feet (ft) (USACE Low) to 3.11 ft (NOAA Extreme**). **For the 2080 time horizon, the sea level rise projections range between 1.02 ft (USACE Low) to 781 ft (NOAA Extreme).** The broad range of projected sea level rise for future planning purposes pose a challenge for communities at both a local and global scale.

## Findings from the New Jersey Climate Adaptation Alliance Science Report

The 2016 New Jersey Climate Adaptation Alliance Report[2] is a reputable and defendable source of information from the top climate change scientists in New Jersey. The Report presents a detailed discussion about the rates of sea level rise, and the science, policy, and impact to practitioners. While this report precedes the release of the NOAA 2017 data, which present more severe sea level rise projections, the findings are useful to inform our decision making on which sea level rise projection to utilize for the study area. The following summarizes the Report findings about sea level rise (based on the current USACE curves and the previous NOAA curves) in New Jersey that are applicable to the Passaic River Basin study area:

1. New Jersey coastal areas are likely – about a 2-in-3 chance - to experience SLR of 1.0 to 1.8 feet by 2050 and a 1-in-20 chance that SLR will exceed 2.0 feet by 2050.
2. Differences in SLR projections are relatively minor before 2050; after 2050, projections increasingly depend upon the evolution of future global greenhouse gas emissions over the current and future decades.
3. The coastal areas of New Jersey are likely - about a 2-in-3 chance - to see SLR of 2.4 to 4.5 feet and about a 1-in-20 chance that SLR will exceed 5.3 feet by 2100 under a high greenhouse gas emissions scenario.
4. The coastal areas of New Jersey are likely about a 2-in-3 chance to see an increase in SLR of 1.7 to 3.1 feet by 2100 and about a 1-in-20 chance that SLR will exceed 3.8 feet by 2100, under a low emissions scenario.
5. A worst-case SLR (defined as a 1 in 1000 chance) of 2.8 feet by 2050 and 10 feet by 2100 is physically possible in New Jersey.

## Storm Surge

Storm surge is the rise of water above tide levels that occurs during storms such as hurricanes, tropical storms, and nor'easters. The extent of coastal flooding is determined by three general factors:

1. The nature of the storm's intensity, duration, and path;
2. Astronomical tide conditions at the time the storm surge reaches the shore; and
3. The physical geometry, topography, and bathymetry of a particular area, which affects the time and passage of storm surge.

The flood levels in the absence of wave effects are referred to as stillwater elevation. Two stillwater elevation data sources are reviewed: the 2013 Federal Emergency Management Agency (FEMA) Hudson County Preliminary Flood Insurance Study and the 2015 USACE North Atlantic Coast Comprehensive Study. These stillwater elevation levels can be used independently or in conjunction with sea level rise projections to understand flood risk.

### Findings from the FEMA Hudson County Preliminary Flood Insurance Study

In 2009, FEMA commenced a coastal flood risk study within the New York and New Jersey region, which involved storm surge and wave modeling. The purpose of a FEMA Flood Insurance Study (FIS) is to develop flood risk data for various areas of the community that are used to establish actuarial flood insurance rates. The FIS is also used to update existing floodplain regulations, and by local and regional planners to further promote responsible land use and floodplain development. The results from that study were the development of preliminary flood maps. However, the 2009 modeling efforts included a limited number of historic and representative storms, and did not include Hurricanes Irene or Sandy. In 2017, the FIS and preliminary flood maps were updated for select riverine portions of the study basin, such as Essex County; however, this study did not incorporate additional analysis for coastal stillwater elevations. As of 2018, FEMA is in the process of reevaluating the coastal flood risk study for New Jersey and New York[6]. Since this coastal reanalysis is ongoing, the data from the FEMA study is presented for demonstration and comparison purposes.

Floods are often defined according to their likelihood or chance of occurring in any given year at a specific location. The most commonly used definition is the "100-year flood." This refers to a flood level or peak that has a 1 in 100, or 1 percent chance of being equaled or exceeded in any year. Therefore, the 100-year flood is also referred to as the "1 percent flood," or as having a "recurrence interval" or "return period" of 100 years. In general, these FEMA studies use advanced statistical methods to determine stillwater elevations based on an annual chance of

[6] Note: The FEMA modeling efforts do not and will not consider the effects of global climate change on storm intensity or frequency. They do not incorporate any projected sea level rise.

exceedance (e.g., 10-percent and 1-percent annual chance stillwater elevations) based on existing conditions.

The Hudson County FIS determines the preliminary – due to ongoing coastal reanalysis – 10-, 2-, 1-, and 0.2-percent (i.e., the 10, 50, 100, and 500-year) annual chance stillwater elevations. This stillwater elevation includes tidal influence and the effects of wind during storms. In the Hudson County FIS, coastal transects are used to designate where coastal engineering analyses are performed to determine stillwater elevations as shown in **Figure 5** [7].

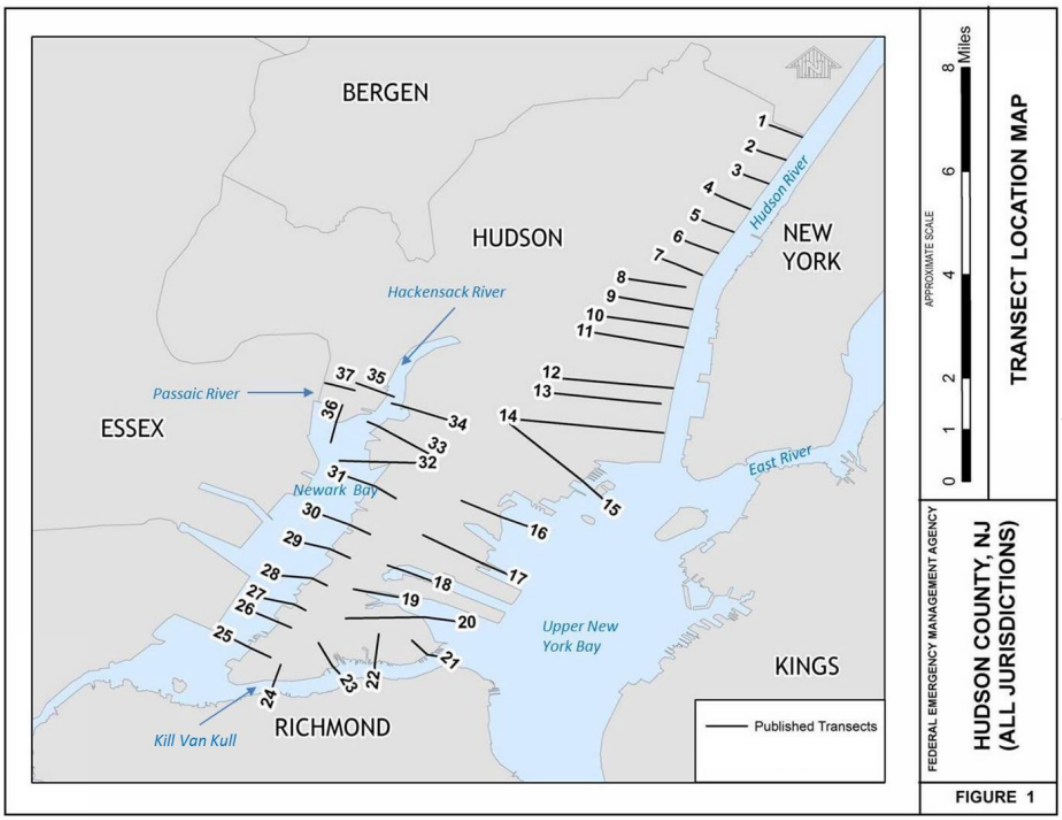


Figure 5. Map from Hudson County FIS Report[6]

For the Passaic River Basin, the nearest representative coastal transect is #37. The results for the starting stillwater elevation for the Passaic River (in Hudson and similar in Essex County) are summarized in **Table 2**.

[7] FEMA Preliminary Flood Insurance Study for Hudson County NJ, 2013.

Table 2. Preliminary FEMA Stillwater Elevation Data for Passaic River[6]

| Flood Source | Transect | Starting Stillwater Elevations (feet NAVD88) and Range of Stillwater Elevations | | | | |
|---|---|---|---|---|---|---|
| | | Coordinates | 10% Annual Chance | 2% Annual Chance | 1% Annual Chance | 0.2% Annual Chance |
| **Passaic River** | 37 | N 40.7278<br>W 74.1177 | 6.8 | 9.5 | 10.8 | 13.9 |
| | | | 6.6 – 8.0 | 9.2 – 9.5 | 10.6 – 10.8 | n/a |

*Note: For transects with a constant stillwater elevation, only one number is provided to represent both the starting value and the range.*

## Findings from the USACE North Atlantic Coast Comprehensive Study

After Hurricane Sandy, USACE was instructed by Public Law 113-2 to conduct a comprehensive study to address flood risk of vulnerable coastal populations from Virginia to Maine. A core component of the USACE North Atlantic Coast Comprehensive Study (NACCS) was to perform comprehensive coastal flood risk modeling. This study was completed in January 2015. The NACCS used high-fidelity, coupled wave and storm surge models (i.e. WAM, STWAVE, and ADCIRC), using elements of the aforementioned 2009 FEMA study, to determine updated storm surge and wave annual exceedance probabilities for extreme coastal storm events. The model results, modeling methodology report, and statistical analysis results are available online[8] through the USACE Coastal Hazards System Database Web Tool. Products from this study are incorporated into the Coastal Hazards System database and include simulated winds, waves, and water levels for approximately 1,050 synthetic tropical events and 100 extratropical events. These storm events are determined to span the range of practical storm probabilities and consider Hurricanes Irene and Sandy. This modeling study was completed more recently than the FEMA study and is considered the final analysis, the USACE data will be used to seed the H&H modeling efforts.

A representative model node at the mouth of the Passaic River was identified in the Coastal Hazards System database. The results from the USACE NACCS statistical analysis with a 95% confidence limit from this model node are shown in Table 3 below for the representative 100-, 10-, 2-, 1-, and 0.2-percent annual chance stillwater elevation.

[8] https://chswebtool.erdc.dren.mil/

Table 3. USACE NACCS Stillwater Elevation Results for Passaic River

| Flood Source | Coordinates | Stillwater Elevations (feet NAVD88) | | | | |
|---|---|---|---|---|---|---|
| | | 100% Annual Chance | 10% Annual Chance | 2% Annual Chance | 1% Annual Chance | 0.2% Annual Chance |
| **Passaic River at ADCIRC Model Node # 4206** | N 40.716 W 74.1179 | 4.95 | 8.68 | 11.95 | 13.35 | 16.05 |

**The 100-percent annual chance stillwater elevation (4.95 feet North American Vertical Datum [NAVD]88) represents an elevation that is expected to occur in a given year. This will be used as the tidal tailwater boundary condition, representing the water level at the mouth of river, for the hydrologic and hydraulic (H&H) modeling representing existing conditions.** Coupling the 100-percent annual chance *stillwater elevation* with the 1-percent annual chance *precipitation* (i.e., 100-year rainfall) represents the *combined probability* of a 1-percent chance event (i.e., 1 * 0.01 = 0.01 or 1%); this represents the potential water height (which includes storm surge) that is expected at during a 1-percent annual chance event. The combination of an extreme precipitation event and a stillwater elevation other than the 100-percent annual chance stillwater elevation would represent a rarer event.

## Summary

This memo summarizes the potential range of impacts of sea level rise and storm surge that may affect the Passaic River Basin and other coastal transportation assets. Based on guidance from the NJ Climate Adaptation Alliance, the Sandy Hook gauge is considered an appropriate representation of projected sea level rise for the Passaic River Basin. Relative sea level rise in the region encompasses a broad range of possible future scenarios. Based on the conversation with NJTPA on March 30, 2018, CDM Smith will use the NOAA Intermediate High sea level rise projections for this study based, which show a 2.2 feet change by 2045 and a 4.82 feet change by 2080.

The results from this consensus on sea level rise will then be considered during the next steps of H&H modeling efforts. As discussed in the H&H memo (dated March 5, 2018), the chosen sea level rise projection will be modeled for Tier 1 assets by generating a new depth grid using the HEC-RAS model, resulting in a new hydraulic profile. The H&H model representing existing conditions will use the results from the USACE NACCS modeling efforts of the stillwater elevation expected to occur every year (100-percent annual chance stillwater elevation). For future conditions, the tidal tailwater boundary condition from the available FEMA H&H models will be modified using a combination of the 100-percent annual chance stillwater elevation and the selected sea level rise projections for a composite tidal boundary condition for both planning horizons.

The H&H analysis will include six scenarios:

1. Existing 25-year precipitation event
2. Existing 100-year precipitation event
3. 2045 25-year precipitation (All RCP) + 1 stillwater elevation (NACCS 100% annual chance) + 2045 sea level rise (NOAA int-high)
4. 2045 100-year precipitation (All RCP) + 1 stillwater elevation (NACCS 100% annual chance) + 2045 sea level rise (NOAA int-high)
5. 2080 100-year precipitation (RCP 2.6, to show the worst case scenario) + 1 stillwater elevation (NACCS 100% annual chance) + 2080 sea level rise rise (NOAA int-high)
6. One additional 2080 TBD-year precipitation + 1 stillwater elevation +1 2080 sea level rise value