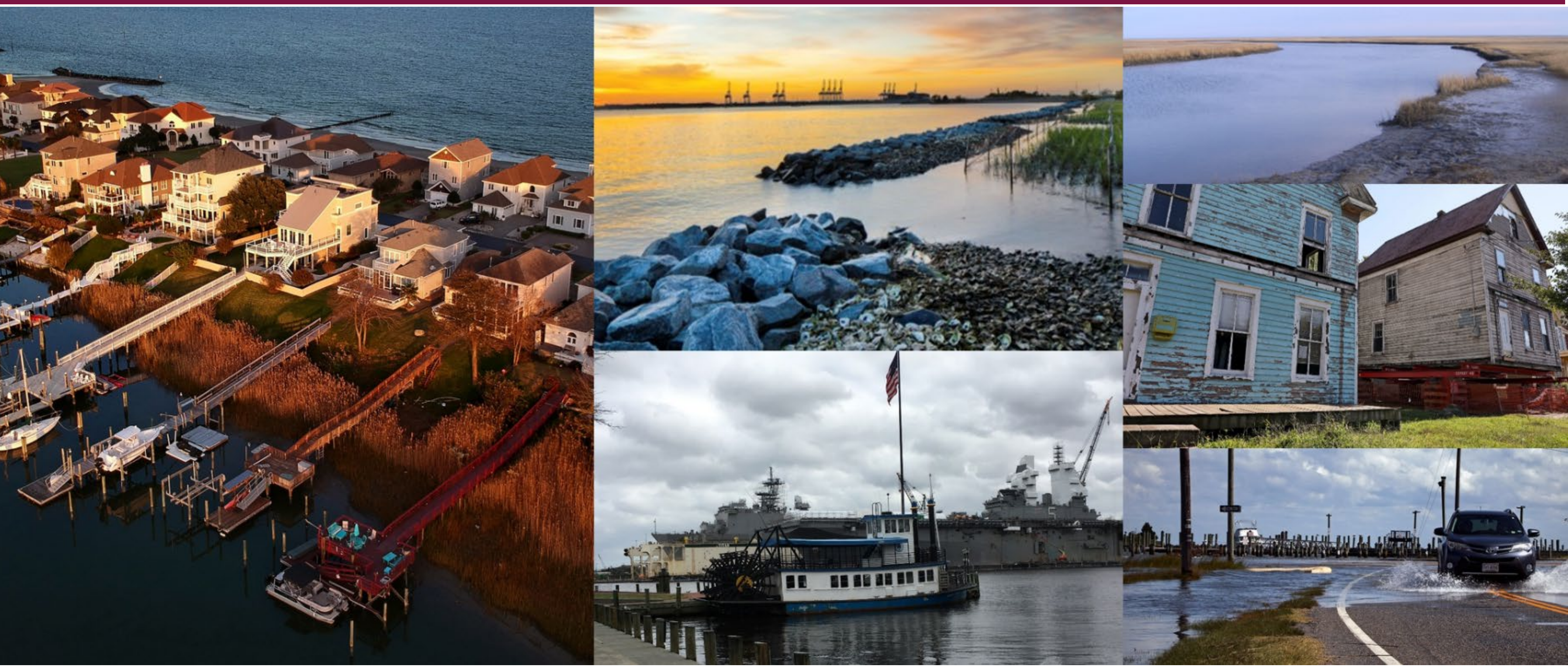
VIRGINIA COASTAL RESILIENCE MASTER PLAN

Task 3: Coastal Flood Hazard Framework

MARCH 23, 2022



FINAL REPORT

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REVISION HISTORY

Revision Date	Revision Notes
3/23/2022	Adjustments made to relevant sections of report to reflect production of flood hazards for the 2100 time horizon.

1. INTRODUCTION

The Virginia Coastal Resilience Master Planning Framework (hereafter referred to as the "CRMP Framework") lays out the core principles of the Commonwealth's approach to coastal adaptation and protection, and the process by which the Commonwealth will develop and begin implementing Virginia's first Coastal Resilience Master Plan (CRMP) by the end of 2021. To drive towards the CRMP Framework goals, the Study Conceptual Model was established to inform the analytical approach to the CRMP (Figure 1).

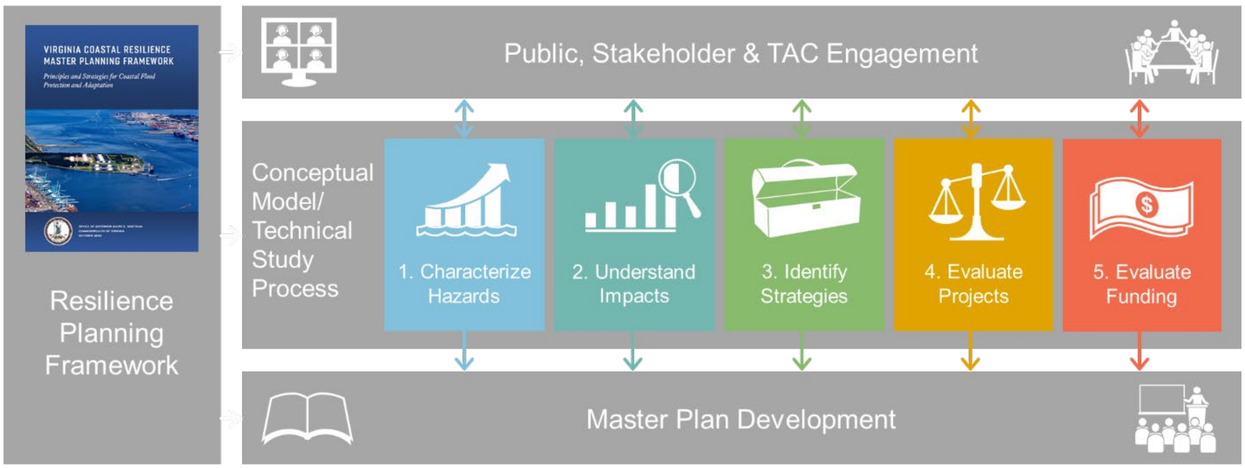

Figure 1: Study Conceptual Model alignment with the CRMP Framework and consensus-built outcomes to inform the CRMP development.

The foundation of the CRMP analysis is the **Coastal Hazard Framework**, which completes Step 1 in the Study Conceptual Model. The Coastal Hazard Framework identifies and characterizes the various components of the coastal flood hazard through the production of flood extents and depths for existing conditions and future condition sea level rise (SLR) scenarios. The outputs will provide the ability to characterize the vulnerability of Virginia's coast from a range of events.

The products of the hazard assessment will serve as the input to the **Impact Assessment** phase where a range of impact types will be evaluated. These include impacts on the community fabric, underserved populations, the built environment, critical infrastructure, and natural infrastructure (ecosystems).

This Technical Memorandum provides an overview of the Coastal Hazard Framework, including an overview of the proposed approach, key data, components, and production approach for generating the flood hazard elevation and extent data.

2. APPROACH

2.1. OBJECTIVES

The objective of the Coastal Hazard Framework is to create a consistent set of coastal flood hazard data to enable a state-wide vulnerability assessment for the CRMP. The following requirements were identified to fulfill this objective:

- Provide flood elevation, extent, and depth products to facilitate the assessment of impacts;
- Represent minor, but frequent flood events;
- Include a representation of the range of storm minor to major storm surge events; and
- Include a baseline existing condition and representation of increases in flood hazards due to SLR in future conditions from the 2040s to the 2080s.[1]

Given the timeframe allowed for the data development in this first iteration of the CMRP, the initial Coastal Hazard Framework relies on existing, best-available public datasets. The study area is subject to other flood hazards, from riverine, rainfall-runoff, and groundwater, as well as erosion. These processes are the drivers of risk in certain areas of the state, rather than coastal hazards. These limitations are acknowledged and accepted for the first iteration of the Virginia CRMP. Future iterations of the CRMP will improve the evaluation of the potential consequences of individual and combined occurrences of these complicated processes.

2.2. FRAMEWORK OVERVIEW

The Coastal Hazard Framework is a conglomerate of best available information on known sources of vulnerability overlayed to produce an accurate picture of vulnerability for the horizons required by the CRMP. To be spatially comprehensive, temporally coherent, and numerically accurate, a robust data collection process is necessary. Collected data will be reviewed and analyzed for appropriateness of use. The next step is a geospatial analysis that entails overlaying the various components of hazard to develop products for the Impact Assessment.

[1] During CRMP Planning District/Regional Commission workshop meetings, stakeholders expressed interest in a coastal flood hazard coverage for 2100. Such information would benefit communities in providing a data resource that could be integrated into resilience planning and also provide credits through FEMA's Community Rating System. Hazard data for the 2100 time horizon was produced in Winter 2022.

2.2.1. KEY DATA

The following table summarizes the key datasets for establishing the Coastal Hazard Framework. The data collection is intended to make the data holdings current and comprehensive as part of this master planning effort. Key data sources are from the National Oceanic and Atmospheric Administration (NOAA), United States Army Corps of Engineers (USACE), United States Geological Survey (USGS), and Federal Emergency Management Agency (FEMA).

Table 1: Reviewed data elements.

Key Data Element	Source	Dataset	Date
Topographic/Bathymetic Data	NOAA National Geospatial Service	Various Topographic/Bathymetric LiDAR Digital Elevation Models	2017-2019
	USGS National Elevation Database	Various	2003-2015
	USGS Coastal National Elevation Database	USGS CoNED Topobathymetric Model (1859 - 2015)	2016*
Storm Surge Flooding	FEMA	FEMA Region III Storm Surge Study - Coastal Storm Surge Analysis, Storm Surge Results: Intermediate Submission No. 3	2013
SLR Scenarios	NOAA	Global and Regional SLR Scenarios for the United States and Gridded Representations	2017
Amplification of Storm Surge in Future Conditions	USACE	North Atlantic Coast Comprehensive Study - Probabilistic Storm Surge Modeling of SLR	January 2015
Tidal Flooding	NOAA-NOS-OCM	Inundation Mapping Tidal Surface - Mean Higher High Water	2016

** Published date of the dataset and not the underlying collection date of each underlying data set.*

2.2.2. COMPONENTS

Coastal hazards are composed of several components, including flood and erosion processes, as illustrated in Figure 2. For the first iteration of the CRMP, a balance of full representation of the coastal hazards was required given the short timeframe of the study effort. A key focus area of the CRMP was SLR-driven increases to coastal flooding. This focus area was also supported by existing resources from several federal data investments by the FEMA, the USACE, and NOAA. These data provide robust information on tidal and probabilistic storm surge elevations (storm surge, as used here, is inclusive of wave setup). Wave effects (wave crest elevations, wave runup, and overtopping) are typically calculated using a different set of models than storm surge. While methods exist to estimate wave crest elevations across large spatial scales, wave runup and overtopping require site-specific modeling and are excluded from the CRMP assessment.

Coastal erosion processes can be episodic (event-driven) or in response to long-term changes in conditions, such as increases sea levels and changes in the sediment budget. While historical shoreline change rates are available in Virginia, there are no state-wide resources available for future conditions. Projection of future shoreline change is complex and requires significant time and resources which are not available for this first iteration of the CRMP. The Commonwealth recognizes the importance of this process and intends to evaluate approaches to include representation of this hazard in future iterations of the CRMP.

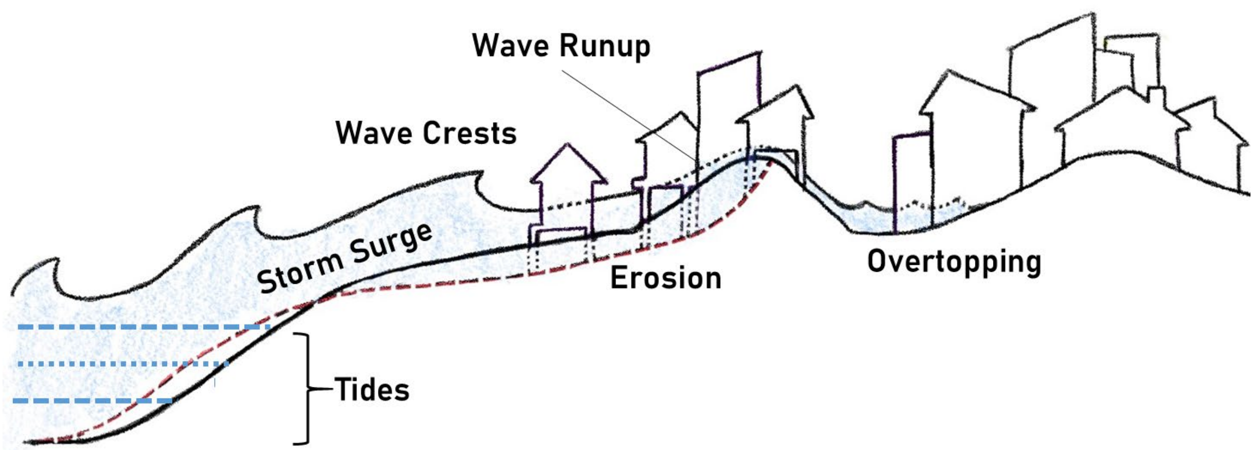

Figure 2. Components of the coastal flood hazards that may be employed in impact assessments.

The following is a breakdown of the subtasks completed for the initial Coastal Hazard Framework development and implementation:

1. Collect and standardize available data for various factors influencing coastal flood hazard, including:
    a. Topographic and bathymetric data
    b. Tides
    c. Storm surge
    d. SLR and associated potential non-linearities
    e. Tides
    f. Waves

2. Identify and resolve discrepancies between datasets, including but not limited to:
    a. Coverage (extents, overlaps, limitations)
    b. Vertical datums, including epoch adjustments
    c. Horizontal projections
    d. Data resolution
3. Develop processes and tools to eliminate discrepancies and ensure validity and usability of datasets (accuracy, spatial coverage, and temporal consistency) for composite hazard estimation.
4. Generate multi-pathway, multi-horizon flood hazard datasets capturing and the various components of coastal flood hazard.

Figure 3 shows key components of the coastal hazard framework. The following sections summarize Dewberry's approach for performing the required analysis, as understood at the time of development of this draft memo.

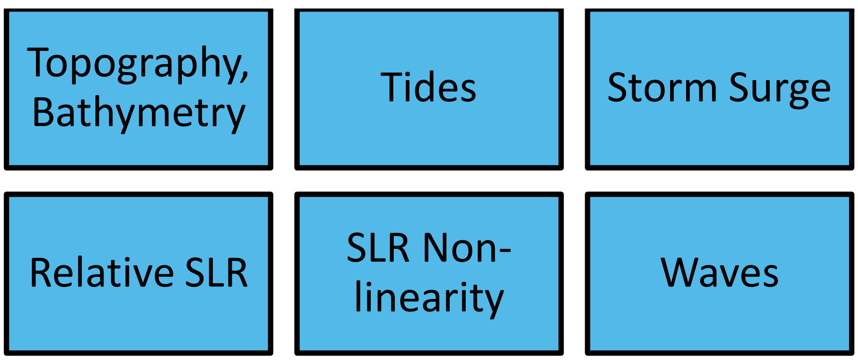

Figure 3: Components of coastal flood hazard for the CRMP.

3. DATA PREPARATION

The following sections document the source and preparation of the essential data components of the Coastal Hazard Framework:

3.1. DATUMS

Geographic projections and coordinate systems spanning the study geography which comprises Virginia's coastal Planning District and Regional Commissions (PDCs, RCs) were reviewed for suitability for the study. A planar geographic projection system was preferred to facilitate the large amount of raster processing required for the hazard assessment. Given this, the preferred options included VA State Plane and Universal Transverse Mercator (UTM) coordinate systems. It was desired to keep all units consistent, and in feet. Given this, the VA State Plane Coordinate System was chosen.

As shown in Figure 4, parts of the study geography are in VA State Plane North and South coordinate systems. As most of the study area was in VA South. Analysis indicated non-measurable differences in GIS between the two projection systems, as such, VA State Plan South was chosen to serve as the processing coordinate system. The datums and coordinate systems for the hazard analysis were:

- Horizontal: North American Datum (NAD) 1983, VA State Plane South, units of feet
- Vertical: North American Vertical Datum of 1988 (NAVD88), units of feet

All input data were projected and/or converted to the study datums to support the CRMP Hazard Assessment. Data outputs may be re-projected after the study, as needed, to support dissemination in web applications.

3.1. TOPOGRAPHIC AND BATHYMETRIC DATA

High-resolution coastal elevation data serve as the basis for flood hazard mapping, determination of flood depth, and analyses of flood impacts. Both topographic elevations and bathymetric depths were required for aspects of the CRMP analyses. The CRMP encompasses the large state-wide geography of Virginia, and as such, no single dataset is available for the entire study area. Rather, topographic/bathymetric data coverage is composed of a patchwork of individual datasets collected at discreet periods.

The coverage, dates, and quality of these data were identified, cataloged, and then assembled into a single, seamless Digital Elevation Model (DEM) through a semi-automated proprietary process. The essential aspects of the process include:

- a search of key data repositories (e.g., NOAA Digital Coast, USGS NED, etc.)

- creation of a data catalog, including spatial extent coverage, dates, resolution, etc.
- prioritization of source datasets by date and resolution
- creation of a reference grid across the study area, at the desired final resolution of the topographic/bathymetric DEM (10 ft for the CRMP)
- resampling, re-projection, and moasaicing the datasets in the specified, prioritized order, while snapping raster cells to the reference grid
- identification of no data areas in the offshore areas and replacing values with bathymetric datasets
- manual quality review of the product for completeness across the desired extent, dataset or tile seam issues, gaps, and anomalous values
- correction of issues identified in quality control
- generation of the final product

The final CRMP data composition is shown in Figure 5. The USGS Coastal National Elevation Database (CoNED) served as the primary data resource across the study area. Although the NOAA Sea Level Rise DEM provided similar coverage, it was found that the metadata did not include spatial coverage of the source datasets. Therefore, the preferred source was identified as the CoNED data, supplemented by USGS National Elevation Database (NED) and other elevation datasets sourced from USGS and NOAA Digital Coast with discreet metadata footprints.

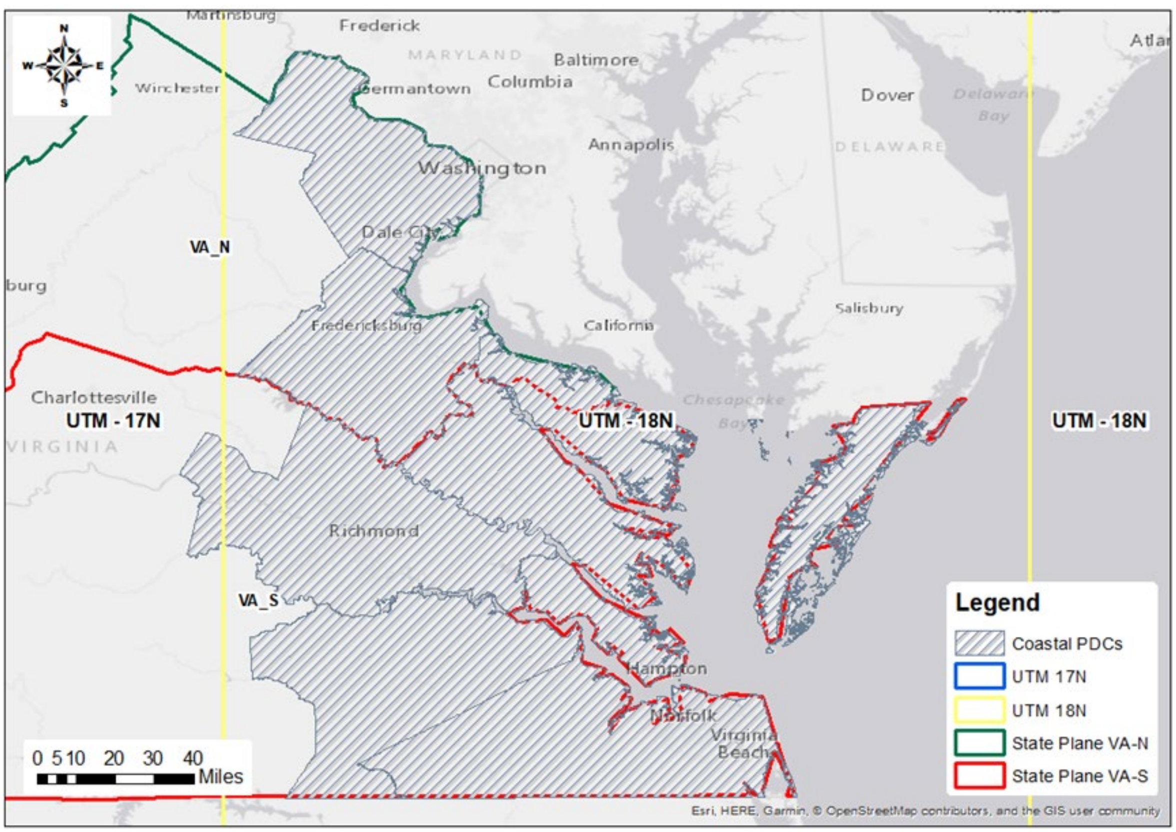

Figure 4: Geographic projection systems in the study geography and vicinity.

The CoNED product was developed under a collaborative effort between the USGS National Geospatial Program (NGP), and NOAA. The outcome of this effort was a three-dimensional (3D) 1-meter topobathymetric elevation model for the Chesapeake Bay region. The data consists of the best available topographic and bathymetric elevation data for the District of Columbia, states of Delaware, Maryland, Pennsylvania, and Virginia, and the adjacent coastline. It integrates over 261 different data sources including topographic and bathymetric LiDAR point clouds, hydrographic surveys, side-scan sonar surveys, and multi-beam surveys obtained from USGS, NOAA, USACE, FEMA, and other state and local agencies. The LiDAR and bathymetry surveys were sorted and prioritized based on survey date, accuracy, spatial distribution, and point density to develop a model based on the best available elevation data. Because bathymetric data are typically referenced to tidal referenced datums (such as Mean High Water or Mean Low Water), all tidally-referenced heights were transformed into orthometric heights that are normally used for mapping elevation on land (based on the NAVD88). The temporal range of the input topography and bathymetry is 1859 to 2015, a listing of included datasets is provided in the Appendix.

It was noted that USGS collected updated LiDAR in 2018 for areas of the Virginia Coast. This data was not able to be acquired, inquiries into the status found that the Virginia portion of the 2018 LiDAR products have not been submitted to USGS.

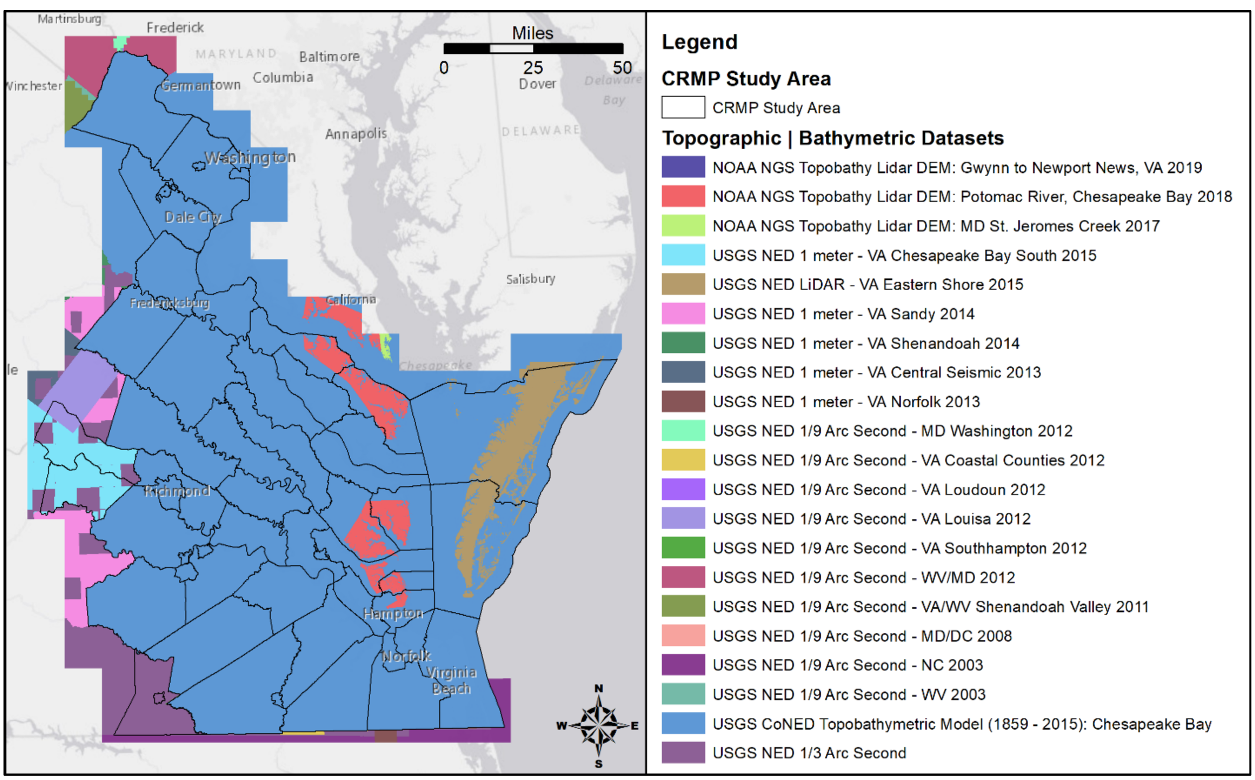

Figure 5: Topographic and bathymetric integrated into the final seamless terrain representation of the CRMP study area.

3.1. SEA LEVEL RISE

3.1.1. SEA LEVEL RISE CURVES

An essential element of the CRMP is to assess how SLR will increase the coastal flood hazard and the associated impacts across Virginia's coast. The Framework identifies 2020, 2040, 2060, and 2080 planning time horizons for the CRMP, emphasizing that it is essential for the state to acknowledge and plan for the future conditions in the 2040s and beyond that will see increasing flood hazards due to rising sea levels as well as other climate change-related processes, such as increased precipitation. The primary factor evaluated in this first CRMP process will be SLR.

Existing state guidance by the Virginia Institute of Marine Science (VIMS) (Mitchell, 2019) establishes that the SLR scenarios presented in a 2017 report "Global and Regional Sea Level Rise Scenarios for the United States" produced by the NOAA (Sweet et al. 2017) serve as the best source of reference for Virginia. As part of the Commonwealth of Virginia Executive Order 45, the state released guidance for specific SLR scenarios as part of supporting guidance for freeboard standards for state-owned buildings (Considine et al. 2019). For that effort, the NOAA Intermediate-High curve was selected, in the context that the state-owned structures were "not typically designed to be flooded" and had a lower tolerance for risk, in alignment with the VIMS guidance (Mitchell 2019). The CRMP Framework presents the Intermediate-High curve in the context of the 2019 ODU report supporting the implementation of Executive Order 45 (Considine et al. 2019). Further, the Framework states that this curve "reflects the most likely SLR scenario of Coastal Virginia." The Intermediate-High curve was later implemented in a state-wide assessment of flood exposure to tidal and nuisance flooding by the Commonwealth Center for Recurrent Flooding Resiliency at Old Dominion University (ODU) (McLeod et al. 2020). Given the above, the Intermediate-High curve from the 2017 NOAA guidance is adopted for use in the CRMP.

3.1.2. RELATIVE SEA LEVEL RISE SCENARIOS

Relative SLR (RSLR) projections include considerations of regional and local changes in sea level processes, such as vertical land motion, which vary across the study geography. Dewberry consulted NOAA (W. Sweet personal communication, April 14, 2021) to determine the current effective practice for representing spatial differences in RSLR. The study team was pointed to the companion data product of Sweet et al. 2017 that provided RSLR projections across the U.S. on a 1-degree spatial grid. The product was retrieved, and RSLR projections for the Intermediate-High scenario were extracted, converted to feet, and then spatially gridded and related to the CRMP Planning Regions, as shown in Figure 6. The Commonwealth CRMP leadership team and select members of the Technical Advisory Committee (TAC) were consulted and agreed that the gridded data provided the most appropriate spatial representation of RSLR scenarios for application in the Coastal Hazard Framework.

The RSLR values for each future time horizon were spatially represented in GIS through the creation of a spatially interpolated raster surface at a 1,000-ft resolution across the study geography. The source values represent projections from the year 2000. The source water level data used for the Hazard Assessment are referenced to the National Tidal Datum Epoch (NTDE). The RSLR values were increased by 0.1 ft to adjust them to the NTDE (discussed in further detail in the following section). The surface was then added to the flood hazard data to each time horizon (2040, 2060, 2080, 2100) to implement the RSLR condition in the Coastal Hazard Framework.

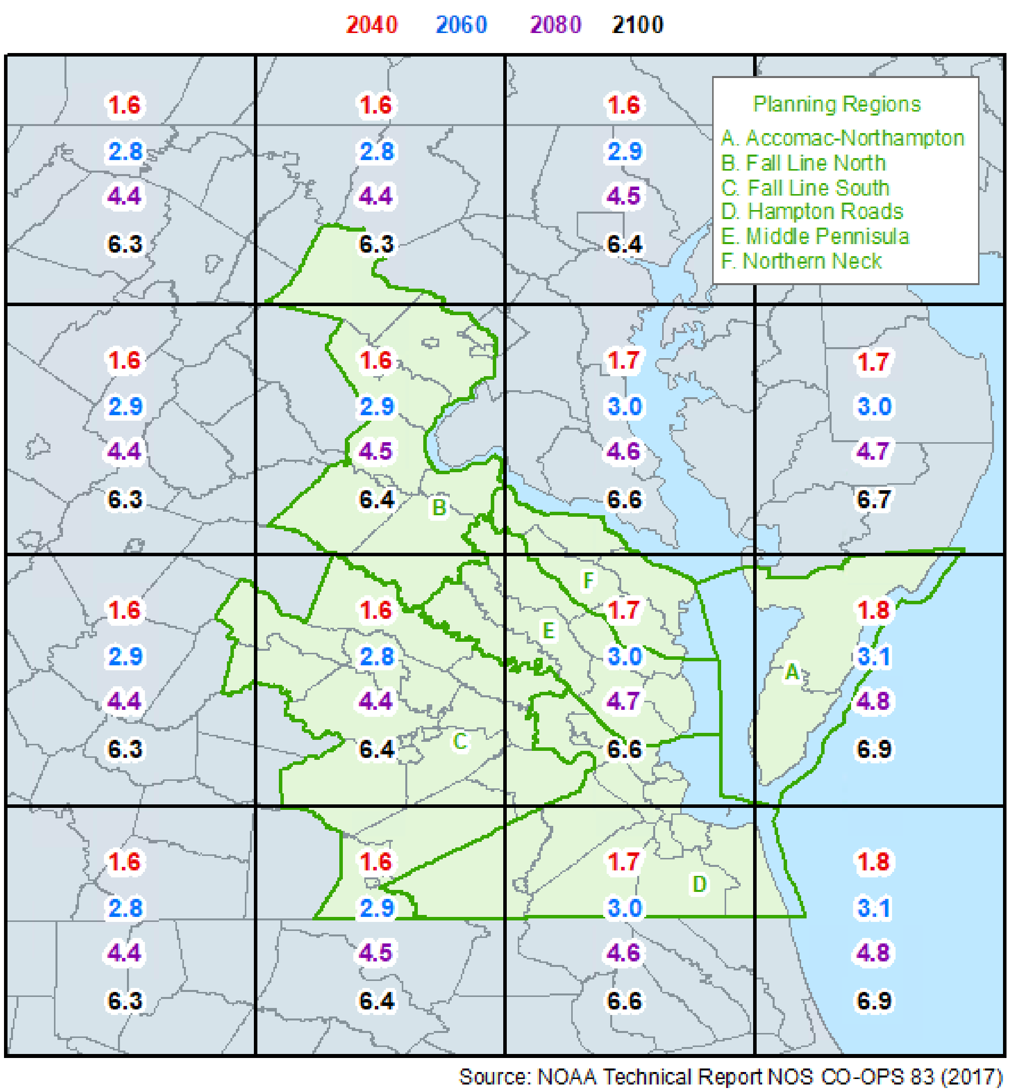

Figure 6: Gridded representation of RSLR projections from 2000 for the NOAA Intermediate-High scenario, in units of feet.

3.2. TIDAL DATUM EPOCH ADJUSTMENT

Tidal datum epoch adjustments were made to the data to ensure the correctness of water level elevations for existing and future conditions. The NTDE is defined by the NOS as a 19-year period that NOAA collects water level observations, representing the epoch between 1983 to 2001. Existing tidal elevations are referenced to the mid-point of the epoch – the year 1992. The NTDE is adjusted periodically to account for long-term changes in vertical land movement, SLR, and tidal constituents. NOAA is currently in the process of updating NTDE, with an anticipated release date of 2025 (NOAA 2021a).

Current tidal datum relationships provided by NOAA, which are used for datum conversions, are all relative to the current NTDE. All water level elevation data employed in the Coastal Hazard Framework employed these relationships to provide water elevations relative to the geodetic NAVD88 vertical datum.

Two tidal datum adjustments were required to ensure that appropriate epoch adjustments were applied to data prior to application in the CRMP:

1. Existing conditions (2020): Adjustment of the existing water level data from the NTDE referencing to present day conditions to accommodate RSLR in the intervening time period; and

2. Future conditions (2040, 2060, 2080, 2100): Adjustment of the RSLR scenarios to current NTDE to match water level data

These adjustments are described in the following sections:

3.2.1. EXISTING CONDITIONS ADJUSTMENT

The epoch adjustment for the period 1992 to 2020 was determined by retrieving long-term sea level trend data from 14 tidal stations within or immediately adjacent to the study geography (NOAA 2021b), as outlined in Table 2. As this adjustment should be primarily derived from the RSLR trends over the corresponding timer period, an initial selection of six of the 14 stations (Kiptopeke, Lewisetta, Sewells Point, Wachapreague, Washington DC, Cambridge, MD) was made for the adjustment. For each of these six stations, the modern RSLR trend was calculated through a linear-regression trendline fit to reported monthly mean sea level value across the period of record. Monthly mean sea level data were analyzed as provided by NOAA. Values for the period varied from 0.3 to 0.5 ft (Table 2).[2]

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[2]A reviewer noted that the data products from the Permanent Service for Mean Sea Level (PSMSL) may provide a more accurate modern short-term rates than NOAA. Differences between the data sources for short-term rates of RSLR were reviewed at sub-sample of three stations. While the PSMSL values were observed to be greater, the difference was small (0.12 ft, or 1.44 inches). It is suggested that future efforts should review both data sources.

Given the large geography involved and use of the spatially-variable RSLR scenarios it was desired to also provide for the best spatial representation possible for the epoch adjustment. Long-term trend data were available for 14 stations across the state of Virginia and adjacent location of Cambridge, MD. A direct comparison of the short to long-term derived values (Table 2) for the showed that the largest difference was less than 0.1 ft.

Although best practice typically would to be to use values reflecting the modern rate of RSLR over the period of adjustment and standardized lengths of record, it was decided that the values derived from the long-term trends were suitable for this application given the small observed difference. On average, the epoch adjustment provides for an increase of 0.4 ft in water levels for 28 years between 1992 and 2020. The epoch adjustment was implemented only for the 2020 existing condition water levels, through the creation of a continuous raster surface created in the GIS environment.

3.2.2. FUTURE CONDITIONS ADJUSTMENT

As discussed in Section 3.1, the RSLR scenarios employed in the CRMP are relative to the year 2000 and should be referenced back to NTDE to align with the water level data. The same sea level trend data discussed in the preceding section was also leveraged for calculation of this adjustment. In a similar fashion, both short- and long-term trends were analyzed to provide for the adjustment value. Given the short amount of time, all values were relatively small, and values predominately equaled 0.1 ft (with 1 exception in both the short and long-term trends) when rounded to 1 significant figure. Given the minimal variance, this single value was used for the adjustment across the study geography.

Table 2: Summary calculated epoch adjustment for NOAA water level stations across or adjacent to the Virginia geography.

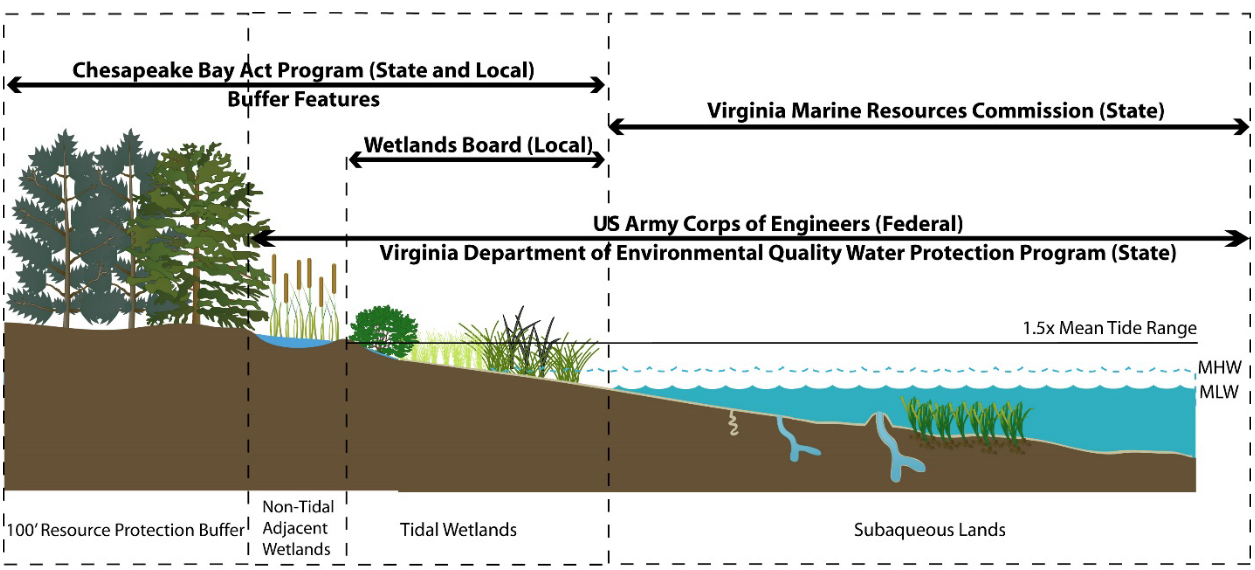
Station ID	Station Name	Epoch Adjustment, Calculated Short-term Trend, ft (1992 – 2020)	Epoch Adjustment, Reported Long-term Trend, ft (1992 – 2020)
8632200	Kiptopeke, VA	0.3	0.3
8635027	Dahlgren, VA		0.5
8635150	Colonial Beach, VA		0.4
8635750	Lewisetta, VA	0.5	0.5
8637624	Gloucester Point, VA		0.3
8637689	Yorktown, VA		0.5
8638610	Sewells Point, VA	0.5	0.4
8638660	Portsmouth, VA		0.3
8638863	Chesapeake Bay Bridge Tunnel, VA		0.5

Station ID	Station Name	Epoch Adjustment, Calculated Short-term Trend, ft (1992 – 2020)	Epoch Adjustment, Reported Long-term Trend, ft (1992 – 2020)
8631044	Wachapreague, Virginia	0.5	0.5
8594900	Washington DC	0.4	0.3
8571892	Cambridge, MD	0.4	0.4

3.3. TIDAL FLOODING AND BOUNDARIES

3.3.1. TIDAL DATUMS

The CRMP tidal datum elevations are for planning purposes only and are not intended to represent future regulatory or jurisdictional limits. The Commonwealth requested that the tidal datums align with those in the Code of Virginia VAC § 28.2-1300, and shown below in Figure 7, be delineated for the CRMP existing and future time horizons. Specifically, mean low water (MLW), mean high water (MHW), and 1.5 times the mean tidal range (1.5xMTR)



Virginia Shorezone Jurisdictions: legally defined shoreline resources and the relevant local, state and federal authorities. Note that some authorities cross resource boundaries and most resources have at least two responsible regulatory authorities. Symbols courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science.

Figure 7: Virginia shorezone legally defined shoreline jurisdictions (Mason et al. 2020).

In the state code, the definition of vegetated wetlands is: “lands lying between and contiguous to mean low water and an elevation above mean low water equal to the factor one and one-half times the mean tide range at the site of the proposed project” and the definition of "Non-vegetated wetlands" means unvegetated lands lying contiguous to mean low water and between mean low water and mean high water, including those unvegetated areas of Back Bay and its tributaries and the North Landing River and its tributaries subject to flooding by normal and wind tides but not hurricane or tropical storm tides. In practice, existing biologic indicators such as wetlands plant species are used to define jurisdictional boundaries. If needed, a tide gauge survey can be used to determine existing tidal elevations and jurisdictional limits. To estimate potential wetlands habitat for planning purposes, the tidal datum elevations calculated for the CRMP include a tidal datum epoch and RSLR adjustment to represent the tidal datum elevation for the specified timeframe.

MLW represents the average of all low water heights– or, in other words, an approximation of the daily minimum water level. MHW represents the average of all high water heights. MHW differs from mean higher high water (MHHW) in that MHHW represents the average of the higher high water heights. 1.5xMTR represents the elevation above mean low water equal to the factor one and one-half times the mean tide range. It serves as the legal upper boundary for vegetated tidal wetlands in Virginia Code.

Most of Virginia’s coast experiences mixed semidiurnal tides, or two daily high/low tides, where one of the tides is slightly higher. A review of MHW against MHHW elevations across the state showed that the maximum difference was 0.4 ft on the open coast, and typically 0.2 ft in the Chesapeake Bay and tributaries. Flood extents derived from MHW also provide a delineation of what land and/or property is “permanently inundated” on a daily basis or lost to flooding with SLR.

The NOAA Vertical Datum Transformation Application (VDatum) delineated the CRMP tidal elevations described above. Geo-locations for the storm surge data, described in the following section, were input into VDatum. For MLW and MHW, VDatum was applied to convert 0 feet MLW and 0 feet MHW to feet referenced to NAVD88. This process establishes the spatially variable elevation values for MLW and MHW relative to the current NTDE (1983-2001) relative to NAVD88 across the state. To delineate the tidal wetland boundaries, the reference elevations were then established as described in the state code using VDatum. A water elevation surface relative to NAVD88 was then created from the resulting values and used in the delineation process described in Section 4.

3.4. STORM SURGE DATA

The most comprehensive source of surge data for the study geography is FEMA Region III’s storm surge study. The study was initiated in 2008 and completed in 2013 to update the coastal storm surge elevations within the states of Virginia, Maryland, Delaware, and Pennsylvania, including the Atlantic Ocean, Chesapeake Bay (including its tributaries), and the Delaware Bay (Hanson et al. 2013). This study is the most extensive one for this region and formed the basis for new coastal hazard analyses and mapping and ultimately resulted in updated Flood Insurance Rate Maps (FIRMs). Storm surge modeling was performed using the ADvanced CIRCulation Model for Oceanic, Coastal, and Estuarine Waters (ADCIRC), coupled with a two-dimensional wave model, Simulating WAves Nearshore (SWAN), to calculate the combined effects of surge and wave-induced setup. A seamless modeling grid was developed to support the storm surge and wave modeling efforts using the most updated topography and bathymetry at the time. The analysis included extratropical and tropical storm statistical analyses, treatment of tidal influences, validation to historic storms, and final water level recurrence interval results.

To accurately account for the storm surge contributions from each, the FEMA study incorporated different statistical approaches to address the storm surge and wave hazard from tropical and extratropical storms. Tropical storms were parametrically represented via the Joint Probabilities Method (JPM). This approach produced a set of candidate tropical storms and tracks that each have a probability of occurring based on historic events. A total of 156 tropical storms were specified with an annual occurrence rate of 156 storms/yr. The storms were divided into three classes: (a) Virginia, Delaware, and New Jersey Landfalling, (b) North Carolina Landfalling, and (c) by-passing. Extratropical storms were analyzed using the Empirical Simulation Technique (EST), where 30 historical extratropical storms were simulated, and frequencies calculated. The tropical and extratropical frequencies were then added together to get combined storm surge frequencies throughout the region. The values provide the total stillwater elevation (SWEL) that includes storm surge and wave setup. Individual waves are not represented (Representation of waves is included in Section 3.7)

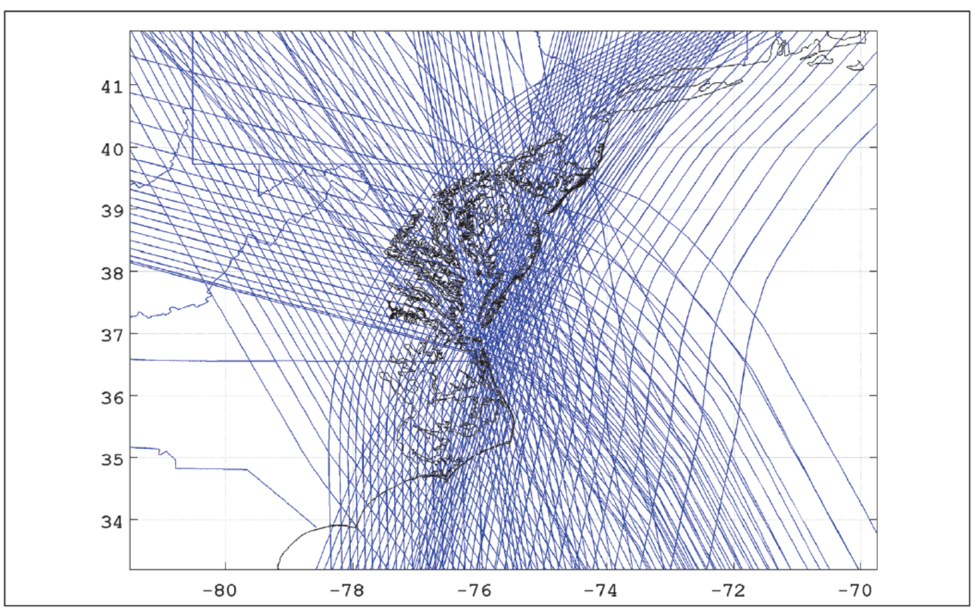


Figure 8: Hurricane tracks used in the FEMA Region 3 study JPM storm suite

The FEMA Region III storm surge data was supplemented with data developed through a similar process from the North Carolina Floodplain Mapping Program (NCFMP) state-wide storm surge study (Blanton et al. 2014). NCFMP data were used to represent flood sources entering Virginia from North Carolina's Currituck Sound, North River, Pasquotank River, and Chowan River. NCFMP data were also used within the Back Bay and North Landing River areas in Virginia Beach, based on prior findings (City of Virginia Beach, 2020).

Both FEMA and NCFMP datasets consisted of coastal flood recurrence intervals across all nodes in the source coastal hydraulic model (ADCIRC, e.g. Figure 9). The point shapefiles representing the data were transformed into the project datum. Elevations were available in units of feet relative to NAVD88. These data provide the state-wide storm surge flood elevations at the 10-, 25-, 50-, 100-, and 500-yr recurrence intervals.

High-frequency flood conditions are critical to flood loss estimations in the context of RSLR, as they drive repetitive losses for low-lying properties. To capture this process in the loss estimation approach, Dewberry specified the inclusion of the 2- and 5-year storm surge elevations, which are not available from the source storm surge studies. The elevations at the 2- and 5-year intervals were estimated using a log-linear extrapolation based on the 10- to 500-year recurrence interval data sourced from the surge studies. Extrapolation was performed for each surge value geolocation, best exemplified in Figure 9. Values were quality controlled against the MHW tidal elevations to ensure that a logical progression of flood elevation was maintained. The extrapolated elevations were reviewed against NOAA stage-frequency values at the Colonial Beach, Sewells Point, Dahlgren, Kiptopeke, Yorktown USCG Training Center, and Lewisetta, VA, and found to have an RMSD of 0.4 ft.

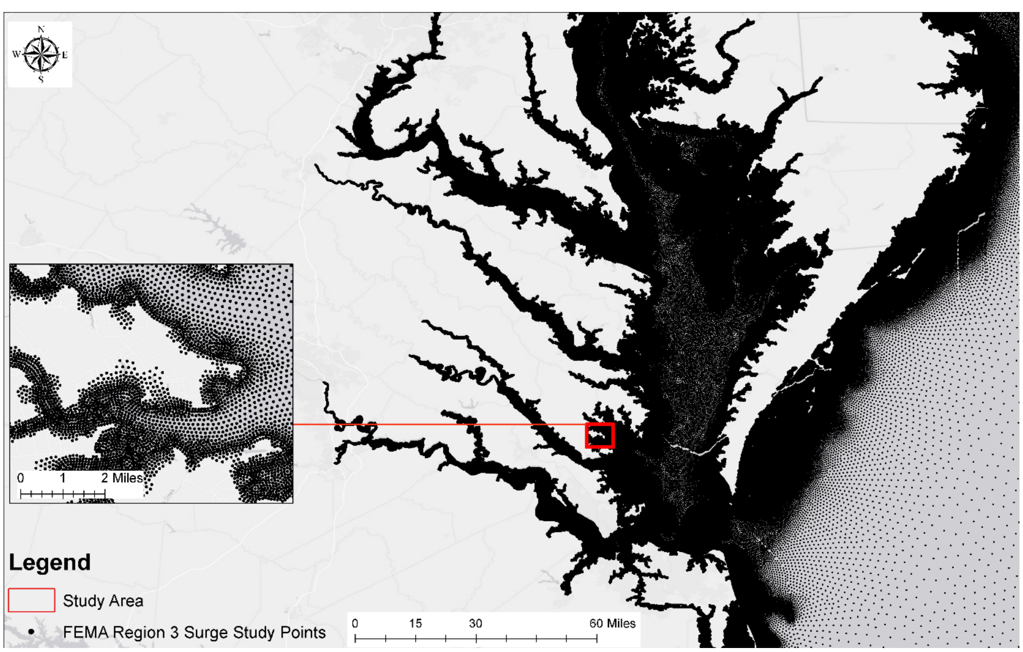


Figure 9: State-wide coverage of FEMA Region 3 Storm Surge Study statistical output.

3.5. AMPLIFICATION OF STORM SURGE WITH SLR

Many factors influence coastal water levels in future conditions. Past studies have found that sometimes change is linear, meaning SLR can be simply added to existing conditions (known as linear superposition, or "bathtub" approaches) and provide a reasonable estimate for the future conditions (Orton et. al 2014). In other cases, dynamics may change due to increased depths, or long-term compounding changes in the coastal landscape such as erosion, barrier island breaching, overtopping of features, and/or marsh degradation (Smith et al. 2010; Batten et al. 2015). Studies have also evaluated potential changes to tropical storm conditions with varying conclusions (i.e., Knutson et al. 2015; Emanuel 2013); however, the science remains premature to provide definitive future conditions scenarios (NOAA 2020).

Quantification of such changes requires numerical modeling that integrates the sea level increase with the landscape changes and then statistical analysis of the resultant surge propagation and peak elevations (i.e., Smith et al. 2010). Such analyses are not possible in this first iteration of the Virginia CRMP due to time constraints. While future efforts will consider how best to integrate and quantify these processes, this first iteration leverages existing modeling to provide a representation of potential future dynamic changes to storm surge.

The USACE North Atlantic Comprehensive Coastal Study (NACCS) conducted a detailed numerical modeling study of probabilistic coastal surge hazards from Maine to Virginia (USACE 2015). The study used a robust suite of storm events and a probabilistic approach similar to a FEMA coastal Flood Insurance Study. Although the NACCS focused modeling efforts on existing conditions, a single SLR scenario of 3.28 ft (1 m) was modeled using only tropical storms and lacking integration of coastal landscape change. Statistical model outputs from the NACCS were previously provided to Dewberry for use in coastal studies. NACCS data products can be used to represent additional increases (non-linear amplification) of surge elevations due to changes in future condition hydraulics using the equation (Batten et al. 2015):

$$Non-linearity\ Index = \frac{Dynamic\ Modeled\ Surge\ Elevation}{Linear\ Superposition\ Surge\ Elevation}$$

The non-linearity index provides a factor, or percent increase, to represent the non-linear increase in storm surge as opposed to the simple addition of the scenario to the existing water level. The concept has also been used by Orton et al. (2014) and identified for use in design practices for the National Cooperative Highway Research Program (referred to as an "amplification factor", Kilgore et al. 2019). The factor is applied to the data by:

$$Future\ Surge\ Elevation = (Existing\ Surge\ Elevation + SLR\ Scenario) * Non-linearity\ Index$$

An amplification factor was used for the 2060, 2080, and 2100 scenarios. The 2060 scenario value will be on the order of 3 ft, in close alignment with the NACCS modeling scenario of 1 m (3.28 ft). The 2080 scenario is anticipated to be in the range of 4 to 5 ft, which is higher than the NACCS 1 m SLR scenario. It could be expected that the non-linear amplification of surge observed for the 2060 scenario will also be present, if not exacerbated, in the 2080 and 2100 scenarios. Past work modeling progressively higher SLR scenarios noted that non-linear changes and amplification of storm surge increased with higher SLR scenarios (Batten et al. 2015).

The amplification factor was calculated from the NACCS storm surge point dataset containing a range of statistically derived (methods similar to the FEMA Region III Storm Surge Study) probabilistic coastal storm surge elevations for both existing and the 1 m (3.28 ft) SLR scenario. The factor was calculated for both the 10- and 100-yr recurrence intervals to investigate if the value varied across the flood frequencies. The root mean square deviation (RMSD) was calculated at 0.06 between the two values, indicating a negligible statistical difference across the over 2,000 points sampled in the area of study. The factor for the 100-year recurrence interval was selected for use.

The calculated values were screened to remove outliers and anomalous points through a combination of statistical and visual assessment. Values less than 1 were removed to ensure full representation of each SLR scenario. The average and maximum factors were 1.05 and 1.18, respectively. For a SLR scenario of 3 ft, and a storm surge of 7 ft, a simple "bathtub" application would provide for a future condition value of 10 ft, whereas application of the mean and maximum factors would amplify this value to 10.5 and 11.8 ft, respectively. The final step was the creation of an interpolated raster surface from the mean factor to provide a spatial representation of the amplification factor across the CRMP study area for use in the Data Production effort. An example of the factor applied to water levels in a single location across the study SLR scenarios is provided below in Table 3.

Table 3: Comparison of "bathtub" and non-linear index approaches for representing future water level conditions at two example locations. Note - the NTDE epoch-adjusted RSLR scenario values from Wachapreague have been used at both sites for consistency in this comparison.

Location	RI (Year)	2020	2040 (1.9 ft RSLR)		2060 (3.2 ft RSLR)		2080 (4.9 ft RSLR)	
			Bathtub	N-L Factor	Bathtub	N-L Factor	Bathtub	N-L Factor
Reedville (Non-linear index = 1.03)	10	3.5	5.4	5.5	6.7	6.9	8.4	8.6
	100	4.6	6.5	6.7	7.8	8.0	9.5	9.8
Wachapreague (Non-linear index = 1.11)	10	6.0	7.9	8.8	9.2	10.3	10.9	12.1
	100	8.1	10.0	11.1	11.3	12.5	13.0	14.4

3.6. REPRESENTATION OF WAVES

Storm surge elevations from the FEMA Region III study provide a probabilistic representation of a range of coastal storms from minor coastal storms, to nor'easters and intense hurricanes. Model outputs consist of total stillwater elevations (SWEL), which include both the storm-driven surge elevation and wave setup. These values do not include the additional elevation from individual waves propagating inland across the water surface. Depending on the site condition, the coastal total water elevation (TWL) could include wave crest heights, wave runup elevations, and/or overtopping (e.g., Figure 2). Given limitations previously stated in Section 2.2.2, TWL representations for the present iteration of the CMRP will include only estimations of the additional wave height component.

Wave heights were prioritized as they were a needed component for downstream analysis in the Impact Assessment. The Impact Assessment employed an improved suite of depth-damage functions as part of ongoing research and development by FEMA for Coastal Probabilistic Flood Risk Assessment (CPFRA). These depth-damage functions reflect changes in building damages in different wave environments, as identified from past post-disaster assessments. These wave environments also correspond with FEMA coastal hazard zones, include the VE (Coastal High Hazard Zone), Coastal A (Area of Moderate Wave Action), and A (Area of Minor Wave Action), as depicted in Figure 10.

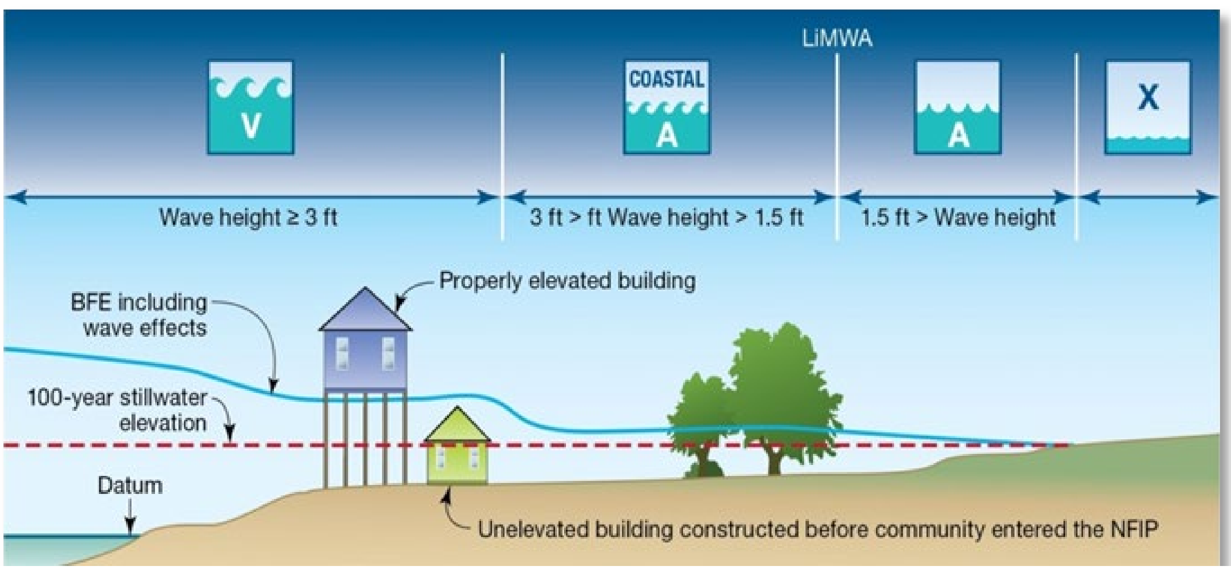


Figure 10: FEMA definitions for coastal hazard zones, reflecting wave conditions and potential building damage.

The total wave hazard, including overland wave heights over stillwater can be calculated via 1- or 2-D numerical models or estimated through depth-limited wave calculations. Numerical modeling is not feasible within the time constraints of the initial CRMP study;

therefore, depth-limited methods must be employed. The breaking wave height wave can be calculated through solitary wave theory and the depth-limited (DL) equation: $H_b = i * d$, where H_b = wave height, i = DL index, and d = depth. A DL index of 0.78 is typically used to determine the maximum breaking wave height which occurs at a given depth. Factors such as nearshore slope and bottom roughness can change the ratio (USACE 1984). Additionally, only 70% of the wave height is above stillwater, thus, adjustments can be made to the factor to properly represent this condition.

The depth-limited method, when applied with the standard 0.78 coefficient will tend to overpredict wave heights because the standard coefficient represents open water conditions. Coastal obstructions, such as buildings and vegetation, attenuate wave energy and create conditions that would be more accurately represented by a lower coefficient. As such, a spatially variable coefficient allows the use of the depth-limited method under a variety of coastal conditions. Batten et al. (2016) utilized approaches to adjust the depth-limited equation to estimate wave hazards for SLR, where improved accuracy was accomplished by establishing adjustments to the equation based on spatial clustering analysis of observed depths of breaking wave heights sampled from model data. This method was later improved upon in a FEMA pilot study (FEMA 2018) by increased sampling of Flood Insurance Study (FIS) overland wave model outputs. Similarly, FEMA CPFRA methods use a ratio approach to improve wave height approximation over simple depth-limited approaches. This allows selection of the appropriate CPFRA damage function for coastal flood loss estimation relative to the local hazard. This approach was adapted for use in the CRMP.

The CRMP utilizes FIS-calculated wave heights and surge elevations from the 100-yr recurrence interval to identify spatial adjustments to the DL index from the standard (0.78) value. First, the DL equation was modified to use the portion of wave height above stillwater (H_s) instead of breaking wave height (H_b): $H_s = i * d$. Because the portion of the wave height above SWEL is 70% of the breaking wave height, the values of the DL index will also be adjusted by 70%, with a new maximum value of 0.55.

A wave-height-above-stillwater raster was derived by subtracting the current 100-yr recurrence interval stillwater heights from the static base flood elevations provided by FEMA National Flood Hazard Layer (NFHL). A depth grid then was derived by subtracting topo-bathymetry elevation from the current 100-yr recurrence interval surge elevation. The ratio of the two grids, wave-height-above-stillwater / depth, is a gridded DL index value, i, representing wave height variability due to environmental conditions such as obstructions. Because base flood elevation values are cartographically smoothed to exhibit relatively low spatial variability, combined with the high spatial variability of topography and depth, the value of the computed ratio at any location can fall outside the expected domain of the DL index. Therefore, the index was corrected so that all values less than zero are set to zero, and all values greater than 0.55 are set to 0.55.

Because this gridded index is made using current 100-yr recurrence interval stillwater and base flood elevation data, the derived data is constrained to the coastal portion of the current 100-yr floodplain. These data need to be propagated inland to allow waves to be calculated for the full extent of larger floodplains, both present, and future. Point breaklines were added inland to prevent the DL index from crossing watershed divides and the gridded values were spatially interpolated across the entire study area. This grid was then smoothed twice, using a 3x3 mean filter to further reduce high spatial contrast.

With this wave coefficient grid, wave-height-above-stillwater can be estimated as a function of the water depth at any location for any event. However, wave production in this study is excluded from events of higher frequency than 10% and sheltered areas of limited fetch. Wave production areas were determined by buffering each floodplain extent seaward by 0.25 miles, then buffering again landward by 0.25 miles. The resulting polygons represent those portions of the floodplain with at least 0.5 miles of open water to allow wind to build waves. The approach allows approximation of the coastal TWL for areas with propagating overland waves, as the stillwater elevation is added to the estimated wave height above stillwater. The TWL in such areas is roughly equivalent to the FEMA BFE at the 100-yr recurrence interval (except where wave runup is the dominant coastal flood hazard).

3.7. EXAMPLE OF COMPILED WATER LEVELS

The coverage for the full set of compiled water levels across the state is shown in Figure 12. The range of elevations across the selected CRMP water levels for four discreet locations (Figure 12) across the state's geography are provided in Table 4. These data allow the CRMP to effectively capture the full range of coastal water levels differences in dynamics across Virginia's diverse coastal zone.

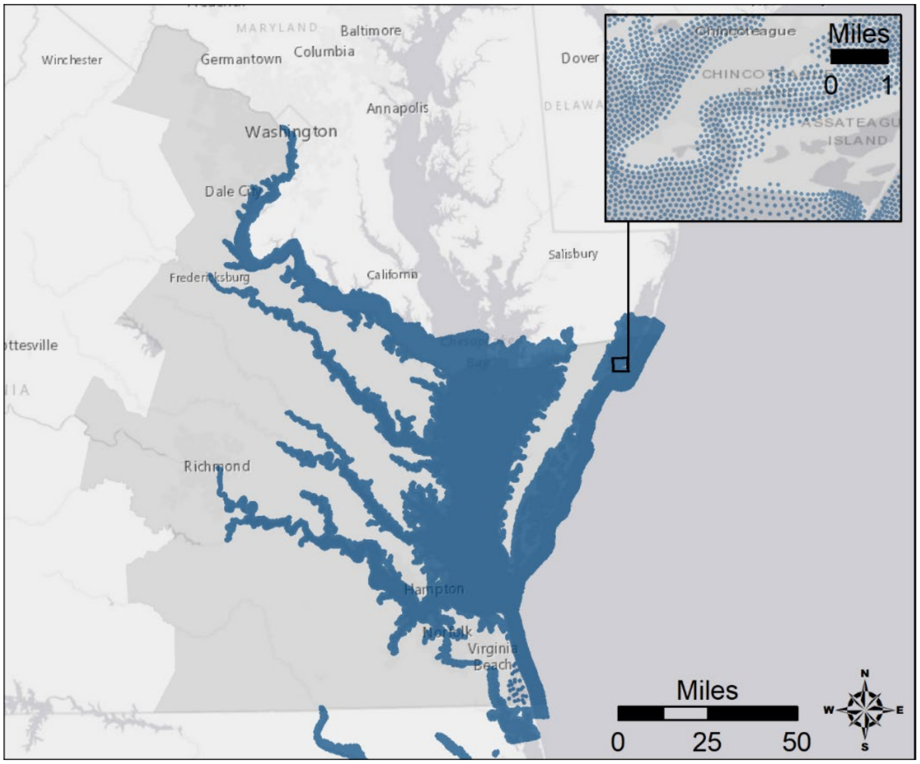


Figure 11: CRMP water elevation base point coverage used for WSEL interpolation.

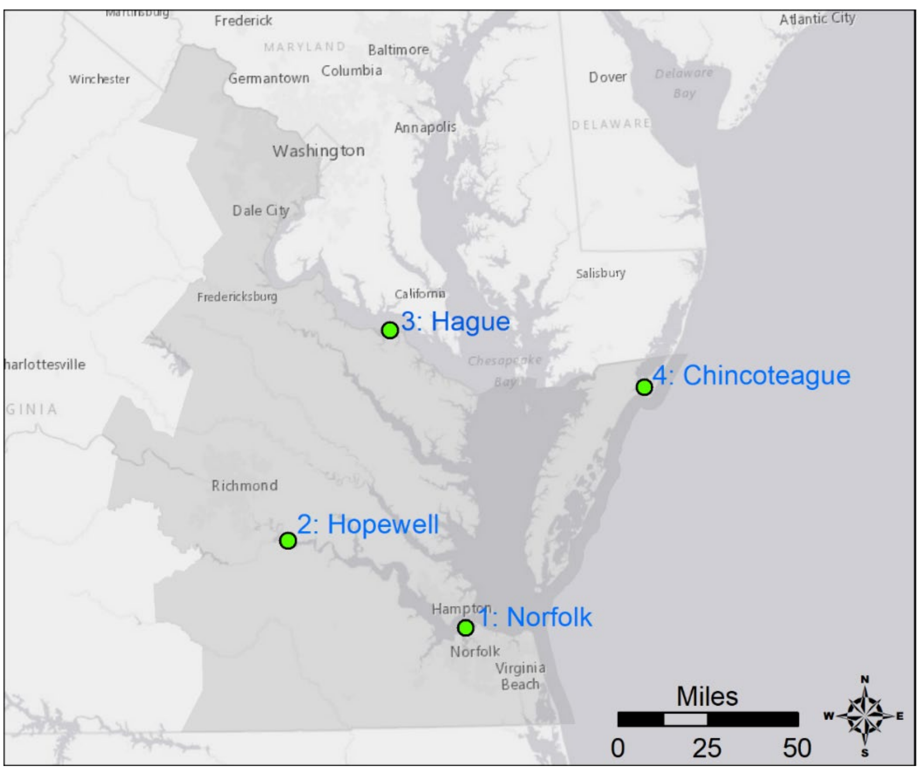


Figure 12: Example locations for compiled CRMP water levels across Virginia.

Table 4: Example locations across VA for compiled water levels identified for application in the CRMP. All values in units of feet, relative to NAVD 88, and adjusted from NTDE to 2020 to account for RSLR in that period.

Coastal Flood Level	Description	Location 1. Chesapeake Bay, near Norfolk Water Elevations	Location 2. James River, near Hopewell Water Elevations	Location 3. Potomac River, near Hague Water Elevations	Location 4. Atlantic Ocean, near Chincoteague Water Elevations
MLW	Daily Low Tide	-1.1	-1.0	-0.3	-1.2
MHW	Daily High Tide	1.3	1.5	1.2	1.9
1.5xMTR	Potential Upper Vegetated Wetland Limit	2.6	2.7	2.0	3.5
2-yr RI (50% AEP)	High Frequency Coastal Flood Events	4.2	5.6	3.1	2.6
5-yr RI (20% AEP)		5.0	6.3	3.8	3.5
10-yr RI (10% AEP)		5.7	6.6	4.1	4.7
25-yr RI (4% AEP)	Minor to Moderate Coastal Storms	6.5	7.7	4.8	5.0
50-yr RI (2% AEP)	Severe Nor'easters, Tropical Storms, Hurricanes	7.2	8.1	5.4	5.4
100-yr RI (1% AEP)		7.8	8.4	5.8	6.1
500-yr RI (0.2% AEP)		9.3	9.7	6.7	8.6

4. DATA PRODUCTION

This section summarizes the various tasks and the steps under each task necessary to produce the composite coastal flood hazard products due to the various components. The components and workflow of these tasks are illustrated in Figure 12, and a short description follows. The outputs of the data production process will be the foundational information that will be intersected and utilized to identify, quantify, and characterize impacts to the social, natural, and built environments.

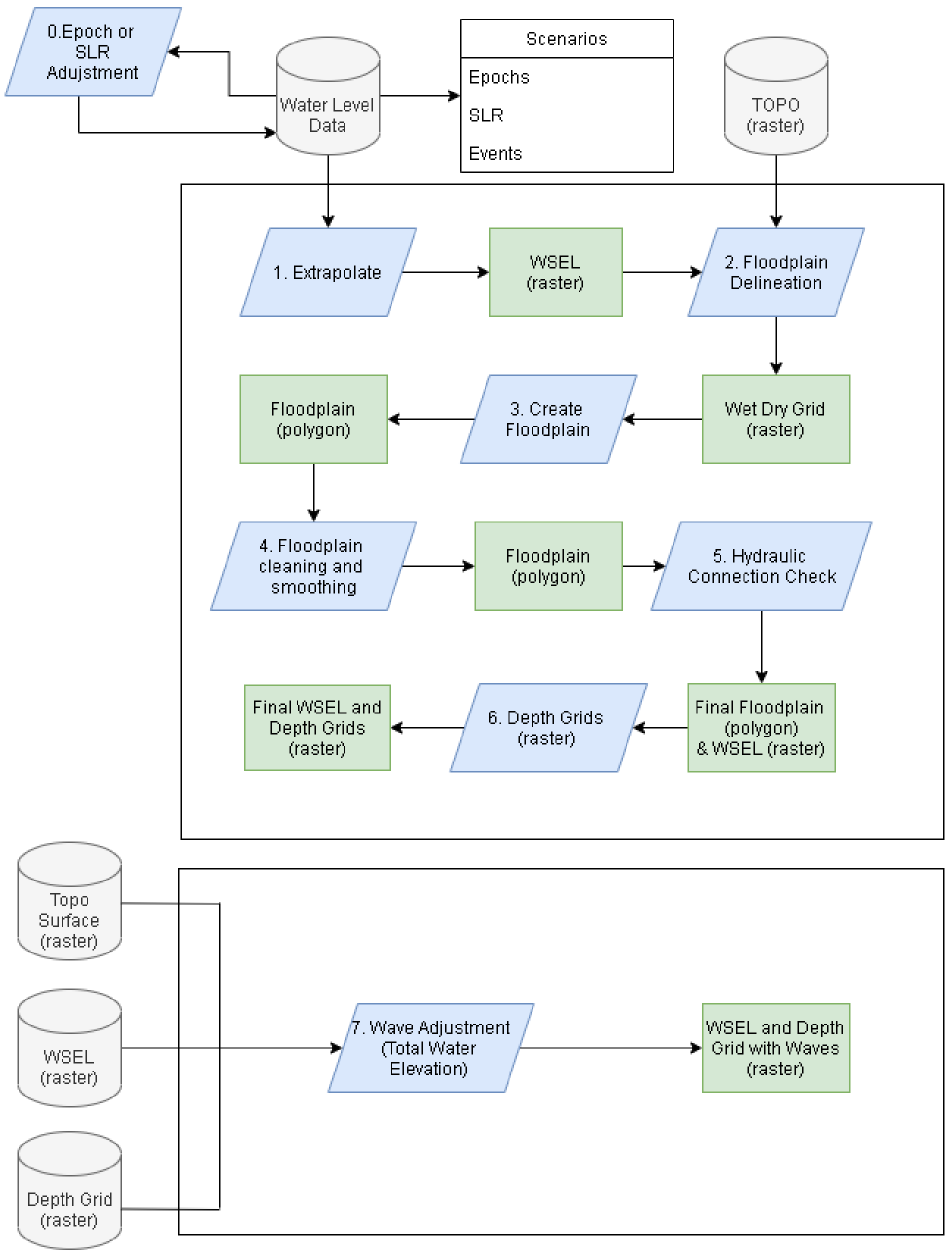


Figure 13: *Data production process, including tasks and components. Note: Gray stacks – data sources, blue parallelogram – operations, green rectangles – intermediate and final products.*

Data preparation methods are explained in Section 3. Individual processing steps and products (intermediate and final) shown in Figure 8 are summarized below:

0. Before production, the epoch adjustment (2020) or sea level rise scenario (2040, 2060, 2080, 2100) will be added to the base water level data point coverage. The non-linear SLR amplification factor will be applied to the 2060, 2080, and 2100 scenarios.
1. Water level point coverages will be extrapolated to ensure coverage over the entire flooded area through inverse distance weighting, producing a water surface elevation (WSEL) raster.
2. The flood extent, or floodplain, will be delineated by a GIS overlay on the topographic digital elevation model (DEM) raster, producing a raster coverage of flooded (wet) and non-flooded (dry) areas.
3. The flooded raster is converted to a vector polygon layer
4. The floodplain polygon is post-processed to remove artifacts, producing a seamless, clean floodplain.
5. The clean floodplain is reviewed to remove areas that are distant from the main floodplain and have no apparent hydraulic connection to the source of flooding, producing the final clean floodplain. Disconnected polygons in close vicinity to the floodplain may have hydraulic connections – given this uncertainty these polygons are not removed. The extrapolated WSEL is reduced to the floodplain.
6. A depth grid without wave effects is calculated from the water surface elevation and topographic DEM within the extent of the floodplain.
7. Wave effects are estimated using the depth-limited approach, a total water surface elevation and depth grid with wave effects are produced.

On completion of the processing, each water elevation for the four scenarios will be represented by the following geospatial products:

- Water surface elevation, without waves (raster)
- Water surface elevation, with waves (raster)
- Flood extent (polygon)
- Depth grid, without waves (raster)
- Depth grid, with waves (raster)

5. QUALITY CONTROL

Data production will be conducted in compliance with Dewberry's Plan, Do, Check, Act quality management plan cycle. Key elements of quality management applied for the Coastal Hazard Framework included:

- Up-front team discussion of potential sources of quality issues in the production processes
- Mitigation of quality risk through up-front quality assurance mechanisms, including:
  - Open communication in the production team
  - Documentation of data sources
  - Documentation of production processes and decision-making, dissemination to the production team.
  - Scripting key production steps to enforce consistent application of production processes for all datasets
  - Establishing a central data repository for final products for the production process, validating final status of products before production
  - Establishing a raster reference grid to snap all raster surface data products and avoid re-interpolation of raster values
- Established quality checklists and independent review of the following:
  - Review and rectification of the merged topographic\bathymetric elevation surface for poor transitions and/or anomalous elevations.
  - Check of epoch adjustment surface to source data, ensuring correct calculations and reasonable representation of source data, before application to 2020 scenario water level data.
  - Check of SLR scenario surfaces to source data, ensuring epoch adjustment (1992-2000) before application to water level data.
  - Review of SLR non-linear amplification factor source points for anomalies/outliers, resulting raster surface representation for reasonable representation of source data.

- Review of extrapolated 2- and 5-yr water level values, including review of extrapolation process and resultant values. Resultant values reviewed against independent NOAA gauge-based data for reasonableness, and against elevations MHW to check and ensure that water elevations incrementally increase as expected (e.g., MHW < 2-yr surge < 5-yr surge, etc.).

- Check for existing and future condition water level source data for application of proper epoch adjustment (2020) or SLR scenario values.

- Review of resultant water surface elevations, floodplain delineations, and depth products to ensure:

    - Water level surfaces match source data, values increase by water level type as expected.

    - Proper extrapolation/interpolation of water level data, to identify and rectify issues such as stair steps, poor transitions, jagged/unnatural edges where two flood sources merge under future conditions.

    - Floodplains increase, as expected, by decreasing flood frequency and from existing to future condition. Includes:

        - initial basic check across the flood frequencies (lowest to highest, e.g., 500-yr to MHW) for decreasing floodplain.

        - initial basic check across each scenario data, to ensure logical increase in flood extents with increasing SLR.

        - Quality assurance procedure that iteratively clips floodplains from low to high frequency, and clips same frequencies from high to low scenario, to ensure topological correctness.

    - Review of final cleaned floodplain against raw floodplain to ensure that post-processed layer form is as expected, and that disconnected, flooded areas were retained and/or removed in compliance with the production standards.

    - Depth grids match water surface and topographic elevations, anomalously high values correspond to pits and/or borrow areas.

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APPENDIX

Table A-1: CoNED Data Summary

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
1/3 Arc-Second Elevation Eastern US	NAD83	NAVD88	3DEP_1/3AS_DEM	Varies
Chesapeake Bay	NAD83		Tidal Marsh Inventory (2010-2016)	2009-2013
Three small areas without lidar between Swanns point and the Jamestown-Scotland Ferry	NAD83	NAVD88	Coastal_Inundation_Model_5m	1996-2016
Ocean City, Delaware, Virginia, Maryland, East Coast	WGS84	MHW	MD_Ocean_City_NOAA_10m	1880-2009
Coastal Virginia	NAD83 (2011)	NAVD88	2014 NOAA Post Hurricane Sandy Topobathymetric LiDAR Mapping for Shoreline Mapping	2014
Coastal Virginia and Maryland	NAD83 (2011)	NAVD88	2014 NOAA Post Hurricane Sandy Topobathymetric LiDAR Mapping for Shoreline Mapping	2014
Hanover, Spotsylvania, Caroline, Henrico, Chesterfield, Dinwiddie, Sussex, etc. counties, Richmond City, Hopewell City, ...VA	NAD83 (2011)	NAVD88	VA_EasternVirginia_2014Mar_USGS_1m_trim	2014
Charles County, Prince Georges County, Saint Marys County, Arlington	NAD83	NAVD88	MDVADC_SandyLot5_2014Apr_USGS_1m_wm	2014

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
County, Fairfax County, Falls Church County, Manassas Park City - Washington, D.C., Maryland, Virginia				
Delmarva Peninsula, Maryland and Virginia	WGS84	MLLW	DELMARVA_Bathy_USGS5-meter bathymetric data collected in 2014 by the U.S. Geological Survey along the Delmarva Peninsula, MD and VA_10m	2014
Norfolk County, Chesapeakes County, Hampton County, etc ...Virginia	NAD83	NAVD88	VA_Norfolk_2013Mar_USGS_1m_wm	2013
Loudoun County, Virginia	NAD83	NAVD88	VA_LoudounCo_2011Dec_FEMA_1m_wm	2012
Accomack, Dorchester, Somerset, Sussex, Wicomico, and Worchester Counties in Maryland, Deleware and Virginia	NAD83 (2007)	NAVD88	MD_5Counties_2012FebMar_NRCS_1m_wm	2012
Essex, King George, Prince William, Richmond, Stafford, Westmoreland, Manassas, Manassas	NAD83	NAVD88	VA_NorthCounties_2011Apr_FEMA_1m_wm	2012

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
Park, Fredericksburg counties, VA				
Charles City County, New Kent County, Prince George County, VA	NAD83	NAVD88	VA_MiddleCos_2011May_FEMA_1m_wm	2012
Southampton County, Franklin City, Virginia	NAD83	NAVD88	VA_SoHamptonCo_2012Jan_FEMA_1m	2012
Fairfax County, Fauquier County, Frederick County, Jefferson County, Virginia, Maryland, West Virginia	NAD83	NAVD88	VAWVMD_R3Lot5_2012Mar_FEMA_1m	2012
King William County, VA	NAD83	NAVD88	VA_KingWilliamCo_2011Apr_FEMA_1m_wm	2011
Accomack County, Northampton County, Eastern Shore, Virginia	NAD83	NAVD88	VA_EasternShore_2010Mar_USGS_1m_wm	2010
Northumberland, Lancaster, Middlesex, King and Queen, Matthews, Gloucester, James City, Williamsburg, Surry, Isle of Wight, and Suffolk Counties in Virginia	NAD83	NAVD88	VA_11Counties_2010Apr_USGS_1m	2010

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
Washington DC	WGS84	NAVD88	MD_DistrictColumbia_2008Mar_USGS_1m_wm	2008
Virginia Beach	WGS84	MHW	VA_Virginia_Beach_2005_NOAA_10m	2005
Beaverdam Swamp	WGS84	MHW	VA_Virginia_Beach_2005_NOAA_10m	2005
CHESAPEAKE BAY, CHESAPEAK CHANNEL	NAD83	MLLW	H10952	2000
SOUTHERN CHESAPEAKE BAY, VICINITY OF TAIL OF THE HORSESHOE	NAD83	MLLW	F00450	1999
CHESAPEAKE BAY, NAUTILUS SHOAL	NAD83	MLLW	D00129	1998
CHESAPEAKE BAY, VICINITY OF CAPE HENRY VIRGINIA	NAD83	MLLW	F00439	1998
CHESAPEAKE BAY, NAUTILUS SHOAL	NAD83	MLLW	H10745	1997
Chesapeake Bay	NAD83	MLLW	F00415	1995
Chesapeake Bay	NAD83	MLLW	F00412	1995
Chesapeake Bay	NAD83	MLLW	F00413	1995
CHESAPEAKE BAY	NAD83	MLLW	F00408	1995
CHESAPEAKE BAY	NAD83	MLLW	F00410	1995
CHESAPEAKE BAY	NAD83	MLLW	F00394	1994
CHESAPEAKE BAY	NAD83	MLLW	F00388	1994
CHESAPEAKE BAY	NAD83	MLLW	F00387	1994

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
Chesapeake Bay	NAD83	MLLW	H10529	1994
Chesapeake Bay, 3.5 NM West of Cape Charles Harbor	NAD83	MLLW	F00371	1992
Elizabeth River, NOAA-AMC Ship Base	NAD83	MLLW	F00369	1992
ATLANTIC OCEAN, 5 NM EAST OF CAPE HENRY	NAD83	MLLW	H10340	1990
ATLANTIC OCEAN, 1.5 NM NORTHEAST OF CAPE HENRY	NAD83	MLLW	H10343	1990
ATLANTIC OCEAN, NE APPROACH TO CHESAPEAKE BAY	NAD83	MLLW	H10356	1990
CHESAPEAKE BAY ENTRANCE, APPROACHES TO THIMBLE SHOAL CHANNEL	NAD83	MLLW	H10372	1990
ELIZABETH RIVER, TOWN POINT	NAD83	MLLW	F00336	1989
YORK RIVER, WORMELY CREEK	NAD83	MLLW	H10275	1988
CHESAPEAKE BAY, VICINITY OF LYNNHAVEN ROADS	NAD83	MLLW	F00300	1987

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
CHESAPEAKE BAY, LITTLE CREEK	NAD83	MLLW	F00294	1987
	NAD83	MLLW	D00052	1985
CHESAPEAKE BAY, MIDDLE GROUND TO LAHMER SHOAL	NAD83	MLLW	H10127	1984
CHESAPEAKE BAY, TAIL OF THE HORSESHORE	NAD83	MLLW	H10116	1983
ATLANTIC OCEAN, PARRAMORE BANKS	NAD83	MLLW	H10034	1982
ATLANTIC OCEAN, MYTLE ISL. TO COBB ISLAND	NAD83	MLLW	H09969	1981
ATLANTIC OCEAN, COBB ISLAND TO HOG ISLAND	NAD83	MLW	H09980	1981
ATLANTIC OCEAN, SMITH ISLAND INLET TO LITTLE INLET	NAD83	MLLW	H09961	1981
ATLANTIC OCEAN, ALONGSHORE - SANDBRIDGE BEACH	NAD83	MLW	H09948	1981
CHESAPEAKE BAY ENTRANCE, LYNNHAVEN ROADS	NAD83	MLW	H09814	1980
CHESAPEAKE BAY, LITTLE CREEK HARBOR	NAD83	MLLW	H09923	1980

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
CHESAPEAKE BAY ENTRANCE, OFFSHORE CAPE HENRY	NAD83	MLW	H09905	1980
CHESAPEAKE BAY, CRUMP'S BANK	NAD83	MLW	H09910	1980
ATLANTIC OCEAN, CAPE HENRY TO DAM NECK	NAD83	MLLW	H09922	1980
CHESAPEAKE BAY ENTRANCE, CHESAPEAKE CHANNEL	NAD83	MLW	H09880	1980
POTOMAC RV. & WASH. CHAN., HAINES POINT TO ROOSEVELT ISLAND	NAD83	MLW	H09478	1977
CHESAPEAKE BAY ENTRANCE, NAUTILUS SHOAL	NAD83	MLW	H09693	1977
VIRGINIA BEACH, RUDEE INLET	NAD83	MLW	H09701	1977
POTOMAC RIVER, ROOSEVELT I. TO CHANIN BRIDGE	NAD83	MLW	H09488	1976
POTOMAC RIVER, HAINS PT. TO WOODROW WILSON BRIDGE	NAD83	MLW	H09477	1974
POTOMAC RIVER, FERRY	NAD83	MLW	H09479	1974

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
POINT TO JONES POINT				
POTOMAC RIVER, MASON NECK	NAD83	MLW	H09349	1974
POTOMAC RIVER, OCCOQUAN BAY	NAD83	MLW	H09292	1973
POTOMAC RIVER, COCKPIT POINT TO INDIAN HEAD	NAD83	MLW	H09324	1973
POTOMAC RIVER, MARYLAND PT. TO BRENT PT.	NAD83	MLW	H09301	1972
POTOMAC RIVER, AQUIA CREEK, VA. AND SMITH POINT, MD.	NAD83	MLW	H09321	1972
POTOMAC RIVERE, VICINITY OF QUANTICO	NAD83	MLW	H09322	1972
HAMPTON ROADS, HAMPTON FLATS	NAD83	MLW	H08878	1966
LYNNHAVEN INLET, LYNNHAVEN, BROAD, LINKHORN BAY & RUDEE INLET	NAD83	MLW	H08724	1963
POTOMAC RIVER, DAHLGREN VICINITY	NAD83	MLW	H08703	1962
POTOMAC RIVER, LOWER	NAD83	MLW	H08704	1962

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
CEDAR JPOINT TO MATHIAS POINT				
POTOMAC RIVER, RIVERSIDE - SMOOT'S PIER	NAD83	MLW	H08706	1962
POTOMAC RIVER, PORT TOBACCO RIVER & NANJEMOY CREEK	NAD83	MLW	H08705	1962
POTOMAC RIVER, YEOCOMICO RIVER & APPROACHES	NAD83	MLW	H08549	1961
POTOMAC RIVER, VICINITY OF KETTLE BOTTOM SHOALS	NAD83	MLW	H08611	1961
POTOMAC RIVER, RAGGED POINT TO NOMINI BAY	NAD83	MLW	H08610	1961
POTOMAC RIVER, COLONIAL BEACH VICINITY	NAD83	MLW	H08614	1961
POTOMAC RIVER	NAD83	MLW	H08550	1961
CHESAPEAKE BAY, ONANCOCK CREEK TO SANDY POINT	NAD83	MLW	H08446	1961
POTOMAC RIVER, LOWER MACHODAOC	NAD83	MLW	H08612	1961

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
& MOMINI CREEK				
POTOMAC RIVER, TRAVIS POINT & COAN RIVER, VA.	NAD83	MLW	H08495	1959
POTOMAC RIVER, SOUTH SIDE OF POTOMAC RIVER BELOW TRAVIS PT.	NAD83	MLW	H08494	1959
CHESAPEAKE BAY - E. SHORE, HUNGER CREEK, MATTAWOMAN CREEK & OFFSHORE	NAD83	MLW	H08506	1959
CHESAPEAKE BAY, NASSAWADOX CREEK & OFFSHORE	NAD83	MLW	H08505	1959
CHESAPEAKE BAY, OCCOHANNOCK CREEK TO NASSAWADOX CREEK	NAD83	MLW	H08507	1959
CHESAPEAKE BAY, ONANCOCK CREEK TO BUTCHER CREEK	NAD83	MLW	H08445	1958
CHESAPEAKE BAY, EAST OF WOLF TRAP LIGHTHOUSE	NAD83	MLW	H08448	1958
CHESAPEAKE BAY, SANDY POINT TO	NAD83	MLW	H08447	1958

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
OCCOHANNOCK CREEK				
CHESAPEAKE BAY, POCOMOKE SOUND	NAD83	MLW	H08405	1957
CHESAPEAKE BAY, POCOMOKE SOUND	NAD83	MLW	H08408	1957
CHESAPEAKE BAY, POCOMOKE SOUND, VICINITY OF CHESCONESSEX CR.	NAD83	MLW	H08406	1957
CHESAPEAKE BAY, SOUTH OF TANGIER ISLAND	NAD83	MLW	H08407	1957
CHESAPEAKE BAY, SMITH POINT TO POINT NO POINT	NAD83	MLW	H08283	1956
CHES.BAY, POCOMOKE SOUND, BEASLEY BAY TO DEEP CREEK	NAD83	MLW	H08347	1956
CHESAPEAKE BAY, SMITH POINT TO HOLLAND ISLAND BAR	NAD83	MLW	H08435	1956
CHESAPEAKE BAY, SMITH POINT TO HULL NECK, POTOMAC RIVER	NAD83	MLW	H08278	1955
CHESAPEAKE BAY,	NAD83	MLW	H08191	1955

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
STINGRAY POINT TO GREAT WICOMICO RIVER				
GREAT WICOMICO RIVER, HAYNIE POINT TO CRAWLEY CREEK	NAD83	MLW	H08276	1955
CHESAPEAKE BAY, GREAT WICOMICO RIVER TO SMITH POINT (OFFSHORE AREA)	NAD83	MLW	H08280	1955
CHESAPEAKE BAY, GREAT WICOMICO RIVER TO SMITH POINT	NAD83	MLW	H08277	1955
CHESAPEAKE BAY, GREAT WICOMICO RIVER	NAD83	MLW	H08190	1955
CHESAPEAKE BAY, FLEETS BAY AND VICINITY	NAD83	MLW	H08188	1954
CHESAPEAKE BAY, RAPPAHANNOCK RIVER ENTRANCE	NAD83	MLW	H08082	1954
CHESAPEAKE BAY, DIVIDING CREEK TO GREAT WICOMICO RIVER	NAD83	MLW	H08189	1954
CHES.BAY - RAPPAHANNOCK R., GREY'S	NAD83	MLW	H08185	1954

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
POINT AND RAPPAHANNOCK RIVER				
ATL.OCEAN & CHESAPEAKE BAY, ENTRANCE TO CHESAPEAKE BAY	NAD83	MLW	H08218	1954
RAPPAHANNOCK R., CHES. BAY, CORROTOMAN RIVER	NAD83	MLW	H08187	1954
CHESAPEAKE BAY, RAPPAHANNOCK RIVER & CARROTOMAN RIVER	NAD83	MLW	H08186	1954
CAPE CHARLES, FISHERMAN'S ISLAND	NAD83	MLW	H08217	1954
CHOPTANK RIVER, CAMBRIDGE TO CABIN CR., INCL.BOLINGBROKE & CABIN CRS	NAD83	MLW	H07911	1954
CHESAPEAKE BAY, YORK RIVER - POQUOSON RIVER	NAD83	MLW	H07954	1953
YORK RIVER, YORKTOWN	NAD83	MLW	H07952	1953
CHESAPEAKE BAY, UPPER PIANKATANK RIVER	NAD83	MLW	H08081	1953
YORK RIVER, YORKTOWN TO TUE	NAD83	MLW	H07953	1953

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
MARSH LIGHTHOUSE				
CHESAPEAKE BAY, HORN HARBOR TO STINGRAY POINT	NAD83	MLW	H08083	1953
CHESAPEAKE BAY, VICINITY OF HORN HARBOR	NAD83	MLW	H08078	1953
CHESAPEAKE BAY, ENTRANCE TO THE PIANKATANK RIVER	NAD83	MLW	H08080	1953
CHESAPEAKE BAY, VICINITY OF MILFORD HAVEN	NAD83	MLW	H08079	1953
CHESAPEAKE BAY, MOBJACK BAY, NORTH & EAST RIVERS	NAD83	MLW	H07957	1952
CHESAPEAKE BAY, MOBJACK BAY, VICINITY OF NEW POINT COMFORT	NAD83	MLW	H07958	1952
CHESAPEAKE BAY, UPPER WARE RIVER & NORTH RIVER	NAD83	MLW	H07956	1952
CHESAPEAKE BAY, BACK RIVER	NAD83	MLW	H07959	1952
CHESAPEAKE BAY, SEVERN RIVER	NAD83	MLW	H07955	1952

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
LOWER CHESAPEAKE BAY, OFF CAPE CHARLES	NAD83	MLW	H08012	1952
CHESAPEAKE BAY, ENTRANCE TO YORK RIVER & MOBJACK	NAD83	MLW	H07960	1952
CHESAPEAKE BAY, TANGIER SOUND	NAD83	MLW	H07944	1951
CHESAPEAKE BAY, POCOMOKE SOUND AND POCOMOKE RIVER	NAD83	MLW	H07946	1951
CHESAPEAKE BAY, POCOMOKE SOUND	NAD83	MLW	H07945	1951
CHESAPEAKE BAY, TANGIER SOUND	NAD83	MLW	H07942	1951
CHESAPEAKE BAY, WEST OF SMITH STRAIT	NAD83	MLW	H08069	1951
CHESAPEAKE BAY, SMITH ISLAND	NAD83	MLW	H07943	1951
HAMPTON ROADS, NEWPORT NEWS MIDDLE GROUND ANCHORAGE	NAD83	MLW	H07894	1951
Lower Chesapeake Bay, Off Cape Charles	NAD83	MLW	H07910	1950
CHESAPEAKE BAY, LOWER	NAD83	MLW	H07750	1950

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
CHESAPEAKE BAY				
LOWER CHESAPEAKE BAY, FORT WOOL TO BUCKROE BEACH	NAD83	MLW	H07824	1950
LOWER CHESAPEAKE BAY, BUCKROE BEACH TO GRANDVIEW	NAD83	MLW	H07823	1950
LOWER CHESAPEAKE BAY, VICINITY OF FISHERMAN ISLAND	NAD83	MLW	H07791	1949
E.SHORE, CHESAPEAKE BAY, NANDOA CREEK	NAD83	MLW	H07680	1949
LOWER CHESAPEAKE BAY, LITTLE CREEK TO FORT WOOL	NAD83	MLW	H07783	1949
JAMES RIVER, ALAREMONT TO STORGEON PT.	NAD83	MLW	H07610	1948
JAMES RIVER, COGGINS POINT TO BERMUDA HUNDRED	NAD83	MLW	H07612	1948
ATLANTIC OCEAN, VIRGINIA BEACH	NAD83	MLW	H07703	1948

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
JAMES RIVER, WESTOF MULBERRY I.	NAD83	MLW	H07174	1948
JAMES RIVER, SWAN POINT TO DANCING POINT	NAD83	MLW	H07642	1948
JAMES RIVER, HOG POINT TO SWAN POINT	NAD83	MLW	H07641	1948
JAMES RIVER, WINDMILL POINT	NAD83	MLW	H07611	1948
JAMES RIVER, BURWELL BAY	NAD83	MLW	H07160	1947
MACHIPANCO INLET, UPSHUR BAY	NAD83	MLW	H07184	1947
YORK RIVER, CLAYBANK VA. AND ABERDEEN CREEK	NAD83	MLW	H07181	1947
CHICKAHOMINY RIVER, SHIELDS PT. TO BIG MARSH PT.	NAD83	MLW	H07714	1947
JAMES RIVER, PAGAN RIVER	NAD83	MLW	H07162	1947
CHESAPEAKE BAY, BACK RIVER AND ENTRANCE	NAD83	MLW	H07185	1947
MOBJACK BAY, BROWNS BAY AND ENTRANCE	NAD83	MLW	H07175	1947
HAMPTON RODADS, HAMPTON BAR TO SEWALL PT. SPIT,	NAD83	MLW	H07171	1947

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
N.E.WILLOUGHBY BANK				
JAMES RIVER, VICINITY OF HOG ISLAND	NAD83	MLW	H07087	1946
JAMES RIVER, BERMUDA HUNDRED TO WESTERN ENT. DUTCH GAP CUT OFF	NAD83	MLW	H07083	1946
JAMES RIVER, FORT EUSTIS	NAD83	MLW	H07025	1945
YORK RIVER, VICINITY OF CHEATHAM ANNEX NAVAL SUPPLY DEPOT	NAD83	MLW	H07022	1945
JAMES RIVER, CHICKAHOMINY RIVER	NAD83	MLW	H07021	1944
NEWPORT NEWS, VIRGINIA, JAMES RIVER	NAD83	MLW	H06928	1944
WILLOUGHBY SPIT, HAMPTON ROADS	NAD83	MLW	H06930	1944
NORFOLK, VIRGINIA, SOUTH OF NAVAL OPERATING BASE - MUNICIPAL PIERS	NAD83	MLW	H06815	1943
NORFOLK, WILLOUGHBY BAY	NAD83	MLW	H06832	1943
JAMES RIVER, NEWPORT NEWS	NAD83	MLW	H06812	1943

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
NORFOLK, NAVAL OPERATING BASE DOCKS	NAD83	MLW	H06833	1943
JAMES RIVER, ENTRANCE TO NANSEMOND RIVER	NAD83	MLW	H06729	1942
VIRGINIA CAPES, CHESAPEAKE BAY ENTRANCE	NAD83	MLW	H06595	1940
OFFSHORE VIRGINIA COAST, NORTH OF PARRAMORE BANKS	NAD83	MLW	H05715	1934
NANSEMOND RIVER, TOWN PT. TO WESTERN BRANCH	NAD83	MLW	H05969	1934
EASTERN SHORE, CHINCOTEAG UE TO WACHAPREA GUE INLETS	NAD83	MLW	H05703	1934
HOG AND COBB ISLANDS, LITTLE MACHIPONG O & GREAT MACHIPONG O INLET	NAD83	MLW	H05704	1934
PARRAMORE ISLAND, WACHAPREA GUE INLET TO MACHIPONG O INLET	NAD83	MLW	H05674	1934

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
OFFSHORE VIRGINIA COAST, WACHAPREAGUE TO GREAT MACHIPONGO INLETS	NAD83	MLW	H05770	1934
MOUTH OF NANSEMOND RIVER	NAD83	MLW	H05968	1934
NORFOLK, CRANEY I. CHANNEL AND W. BRANCH ELIZABETH R.	NAD83	MLW	H04962	1930
COAST OF VIRGINIA, LAT. 36`30' TO VIRGINIA BEACH	NAD83	MLW	H04286	1922
MATTAPONI RIVER, WEST POINT TO MUDDY PT.	NAD83	MLW	H04019	1918
YORK & MATTAPONI RIVERS, TERRAPIN PT. TO WEST POINT	NAD83	MLW	H04018	1918
PAMMKEY RIVER, WHITE HOUSE TO WORMLY FERRY	NAD83	MLW	H03425	1913
MATTAPONI RIVER, MATTAPONI RIVER - WEST POINT TO SANDY POINT	NAD83	MLW	H03369	1912
YORK RIVER, MT. FOLBY TO	NAD83	MLW	H03343	1912

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
WESTPOINT AND VICINITY				
PAMMKEY RIVER, WESTPOINT TO WHITE HOUS	NAD83	MLW	H03424	1912
MATTAPONI RIVER, SCOTLAND LANDING TO DUNKIRK	NAD83	MLW	H03375	1912
YORK RIVER, CLAY BANK TO POROPOTAULS CREEK	NAD83	MLW	H03311	1911
RAPPAHANNOCK RIVER	NAD83	MLW	H03003C	1910
RAPPAHANNOCK RIVER	NAD83	MLW	H03003B	1910
RAPPAHANNOCK RIVER, OCCUPACIA CR. TO LEEDSTOWN, HYDROG/TOPO.	NAD83	MLW	H03029	1910
RAPPAHANNOCK RIVER, JONES PT. TO WARES WHARF, TOPO./HYDROG.	NAD83	MLW	H03009	1910
CAT POINT CR.	NAD83	MLW	H03011A	1910
RAPPAHANNOCK RIVER, TAPP.TO OCCUPACIA CR., TOPO/HYDROGRAPHY RAPPAHANNOCK RIVER,	NAD83	MLW	H03011	1910

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
TAPP.TO OCCUPACIA CR., TOPO/HYDROGRAPHY RAPPAHANNOCK RIVER, TAPP.TO OCCUPACIA CR., TOPO/HYDROGRAPHY				
RAPPAHANNOCK RIVER, WARES WARF TO TAPPAHANNOCK, TOPO/HYDROG	NAD83	MLW	H03010	1910
RAPPAHANNOCK RIVER	NAD83	MLW	H03003E	1910
PICATAWAY CR	NAD83	MLW	H03010A	1910
RAPPAHANNOCK RIVER, URBANA TO LA GRANGE CREEK	NAD83	MLW	H03003	1909
RAPPAHANNOCK RIVER, GREENLAWS WHARF-MILLBANK CRK,HYDROG./TOPO.	NAD83	MLW	H03035	1909
RAPP.R., MILLBANK CREEK TO SKINKERS CRK, HYDROG/TOPO	NAD83	MLW	H03036	1909

Topo Coverage	Horizontal Projection	Vertical Datum	Project Name	Year Acquired
RAPPAHANNOCK RIVER, SKINKERS CRK.TO BELVEDERE, HYDROG. & TOPOG.	NAD83	MLW	H03038	1909
RAPPAHANNOCK RIVER, LEEDSTOWN TO GREENLAWS WHARF, HYDROG/TOPOG.	NAD83	MLW	H03030	1909
RAPPAHANNOCK RIVER	NAD83	MLW	H03003A	1909