VIRGINIA COASTAL RESILIENCE MASTER PLAN

Task 3: Coastal Flood Hazard Framework
Subtask 2: Future Conditions Modeling Approaches

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Dewberry

THE WATER INSTITUTE OF THE GULF

FINAL REPORT

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1. DOCUMENT PURPOSE

This document provides a proposed scope of work for quantifying state-wide existing and future conditions for purposes of subsequent iterations of the Virginia Coastal Resilience Master Plan (CRMP) to account for:

- Pluvial (rainfall-induced flooding) hazards;
- Fluvial (riverine flooding) hazards; and
- SLR-exacerbated landscape changes and their impact on flood hazards

A concise description of proposed activities and anticipated products are provided for each study task. Under separate cover, a rough-order-of-magnitude (ROM) cost estimate was provided to the Commonwealth to support the described activities. This estimate reflects estimated effort needed to accomplish the objectives in light of Commonwealth direction, team technical capabilities, known existing data limitations, and project geography (Virginia's eight coastal Planning District Commissions and/or Regional Commissions [PDCs/RCs]).

This document is organized into two sections:

1. Short-term recommendations for the 2022 iteration of the CRMP.
2. Mid-term recommendations for the 2026 iteration of the CRMP.

It is anticipated that the described approaches and specific activities may change due to increased understanding gained through the project progression.

2. BACKGROUND

The Commonwealth of Virginia undertook development of the first iteration of the CRMP between March and November 2021. The focus area of the first iteration was changes to coastal flood hazards with sea level rise (SLR), and their potential changing impacts to the Commonwealth. The Commonwealth received feedback from both the study Technical Advisory Committee (TAC) and study stakeholders that the hazard framework should be expanded to include consideration of coastal erosion, riverine, and rainfall-induced flooding. Further, challenges with increasing heavy rainfall were noted in almost of the workshop/charettes that were convened at the PDC/RCs and their respective stakeholders.

The initial CRMP was focused on a simple characterization of coastal flood hazards for both existing and future conditions. The approach incorporated approximation of dynamic changes to the coastal flood hazard by leveraging numerical modeling of future conditions and re-calculation of wave heights. Changes to the coastal landscape, and then cascading changes to the coastal flood hazard were not considered.

This approach was by design, and in response to the initial development schedule for the 2021 CRMP. The Commonwealth and Dewberry had discussed the potential need for further quantification of the hazard environment and identified this task as the means to address such needs as the CRMP progressed beyond the first iteration. This task was originally envisioned to include a numerical modeling effort to quantify dynamic changes to the coastal flood hazard in response to increasing sea level and the response in the coastal landscape. Key considerations for the effort were to be marsh loss and potentially barrier island overtopping and/or breaching. A presentation of approaches and options was provided to the Commonwealth on July 15, 2020, this document is provided as Appendix A.

Given feedback received, this document pivots from the originally identified scope. Options are presented to quantify the remaining flood hazards in the eight coastal PDCs/RCs, including:

- Riverine (fluvial) flood hazards
- Rainfall-runoff (stormwater, or pluvial) flood hazards
- Compound issues from co-occurrence of coastal, rainfall, and riverine flood hazards
- Future coastal landscape changes and cascading flood hazard impacts

Elements of these items are broken out for short-term and long-term progression. The short-term items focus on priorities identified by the Commonwealth, TAC, and stakeholders. These items involve foundational activities to enable further technical progression of the hazard factors between present and the next anticipated holistic update to the CRMP in 2026.

3. SHORT-TERM ACTIVITIES (2022)

TASK 1: PLUVIAL HAZARD

The 57-county coastal Virginia study area intersects catchments totaling about 16,000 square miles. In light of recent updates to the USACE HEC-RAS modeling system that support integration of spatially and time-varying precipitation and infiltration, Dewberry proposes to characterize pluvial hazards in the study area using the 2D modeling capability found in HEC RAS 6.0. The team recommends this approach to provide the Commonwealth with a documented, defendable, and reusable set of data to characterize pluvial hazards.

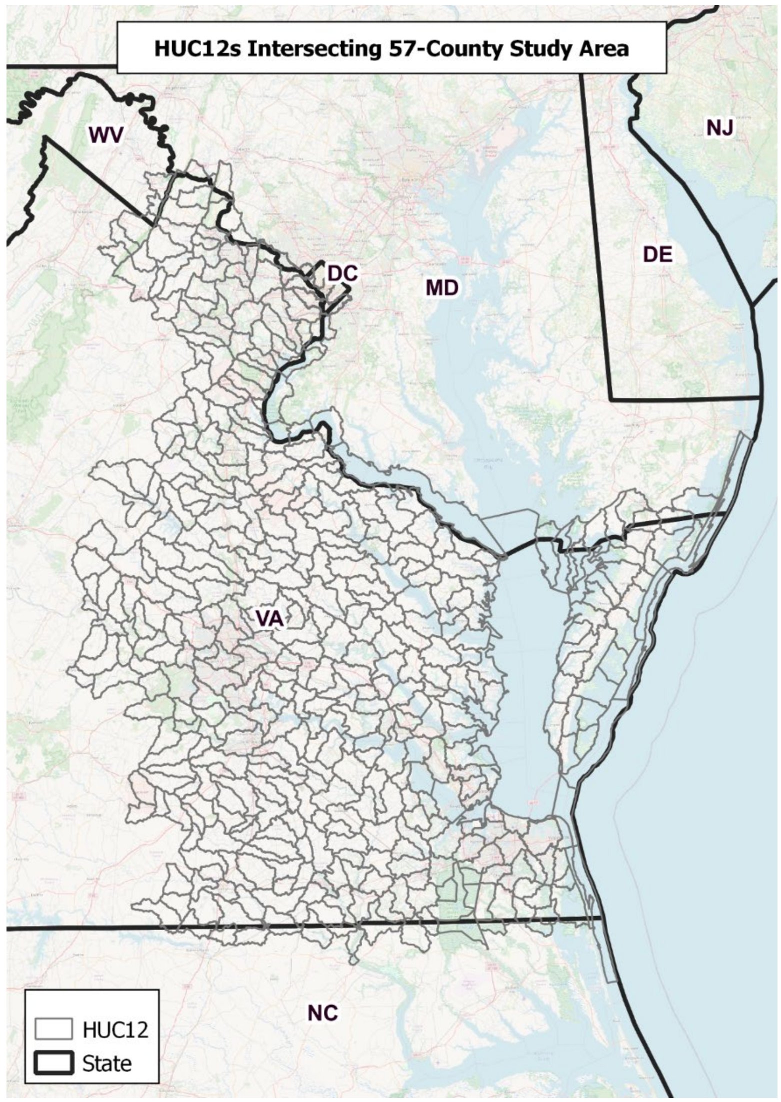


Figure 1: Overview of the 440 HUC 12s Cover the Study Area.

The proposed approach will subdivide the study areas into small basins (<10 sq mi) in which excess precipitation will be calculated and conveyed through the sub-basin, which will have been processed to account for critical topographic features like streams, roads, and large embankments. Any upstream sub-basin contributions will be considered associated with fluvial sources and excluded from the pluvial hazard analysis.

To further convey approach scale, using the USGS Hydrologic Unit Code (HUC) basin taxonomy, the study area spans 440 HUC 12s (Figure 1), which are, on average, over 30 sq. mi each. Our initial estimates are that we would develop between 2,600 and 3,300 individual basin models to represent the study area.

SUBTASK 1: DATA COLLECTION

Best available source for topographic data of the study area will be identified and documented at the inception of this task. In addition to the National Elevation Dataset, we will assess State and local sources, so that we can prioritize the highest quality dataset in the mosaicked terrain for the project area. Topographic data sets that meet USGS Quality Level 1 and 2 (QL1 and QL2) will be utilized. Wherever unavailable, QL3 datasets may be considered for use if that is deemed the best available data from all sources, including State and local repositories. If topographic data sources other than QL1 and QL2 are needed, Dewberry will document the request and submit to PM at VA DCR.

Other collection information will include relevant hydrologic and/or hydraulic model information, high resolution orthophotography, land use/land cover data, and publicly available stormwater infrastructure information.

SUBTASK 2: PLUVIAL BASIN DATA INPUT PROCESSING

- **Objective**:
  - Prepare physiographic data identified, collected, and sourced in Subtask 1 for model input.
- **Activities**:
  - Develop Digital Terrain Model (DTM) mosaic of best-available ground elevation datasets
  - Develop “burn line” features from combination of the National Hydrographic Dataset (NHD) High Resolution dataset and the Coordinated Needs Management Strategy (CNMS) S_Studies_Ln dataset, representing FEMA, with minor manual adjustments.
  - Develop hydraulic breakline features along major highways, dams, and levees.
  - Develop digital elevation model for modeling by modifying raw DTM with burn lines.
  - Develop pluvial model domains (basins) – aim for a median drainage area less than 10 square miles.
  - Develop land-cover-derived input rasters including roughness (Manning’s N), SCS Curve Number (CN), and Percent Imperviousness.

    - **Note:** The proposed analyses does not include projecting changes in land use that would affect the runoff estimates.

- **Products**:
    - Spatial features: raw DTM, H&H DEM, burn lines, breaklines, pluvial model domains (basins), land-cover-derived input datasets
    - Data Processing report providing contextual details on automation, assumptions, and source data.

SUBTASK 3: PLUVIAL FORCING DATA DEVELOPMENT

- **Objective**:
    - Develop current and future conditions pluvial hyetographs for input to pluvial hydraulic models.
- **Activities**:
    - Acquire or develop appropriate Intensity-Duration-Frequency (IDF) curves for current conditions
    - Use NOAA Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) Future Projected Intensity-Duration-Frequency Curves: Technical Report computed IDF change factors. May need Commonwealth support to secure MARISA back data or analyses.
    - Produce independent hyetographs for each pluvial model domain (basin)
- **Products**:
    - Spatially-static hyetographs for each pluvial model domain (basin)
        - Derived from NOAA Atlas 14
        - Durations – 2hr, 6hr, and 24hr
        - Recurrence Intervals – 2yr, 5yr, 10yr, 25yr, 50yr, 100yr, 500yr (50%, 20%, 10%, 4%, 2%, 1%, 0.2% Annual Exceedance Probabilities [AEPs]).
        - Climate Scenarios
            - Current conditions

        - Future conditions – RCP 8.5 (2020-2070)
        - Future conditions – RCP 8.5 (2050-2100)
    - Meteorology report

SUBTASK 4: PLUVIAL HYDRAULICS

- **Objective**:
    - Conduct HEC-RAS hydraulic analyses for each pluvial model domain.
- **Notes:**
    - Based on examination of the study area and Dewberry's experience characterizing pluvial hazards, we recommend using a set of small basins and higher resolution mesh representations to characterize the pluvial hazard. Basin to basin transfer flow will be segregated as fluvial risk as well as high flow rates, which are better handled by fluvial (riverine) modeling regimes.
    - Evaluate degree of urbanization and implement an abstraction approach to represent closed conduit stormwater infrastructure, using publicly available data to support parameterization of the abstraction technique.
- **Activities**:
    - Secure access from USACE to HEC RAS 6.0 in Linux or procure a Linux build for HEC RAS 6.0.
    - Initialize RAS "project" for each model domain.
    - Develop initial RAS 2D mesh geometry for each model domain.
        - Limited incorporation of breaklines to improve 2D mesh (will not necessarily incorporate every breakline developed earlier during preprocessing).
        - Limited incorporation of refinement regions to improve 2D mesh.
        - No structure data.
        - No survey data.

  - Incorporate precipitation boundary conditions (hyetographs developed in Subtask 3).
  - Develop and apply an automated outflow boundary condition (let the water leave the model anywhere along the perimeter of the domain).
  - Design efficient model running strategy.
  - Run and stabilize models.
  - Review initial results and flag anomalies spatially.
- **Products**:
  - Draft, unsteady-state, HEC-RAS 2D pluvial flood models.
    - Durations – 2hr, 6hr, 24hr.
    - Recurrence Intervals – 2yr, 5yr, 10yr, 25yr, 50yr, 100yr, 500yr (50%, 20%, 10%, 4%, 2%, 1%, 0.2% AEPs).
    - Climate scenarios.
      - Current conditions.
      - Future conditions – RCP 8.5 (2020-2070).
      - Future conditions – RCP 8.5 (2050-2100).
  - Pluvial hydraulics report.

SUBTASK 5: PLUVIAL HAZARD POST-PROCESSING AND DELIVERY

- **Objective**:
  - Extract and host meaningful results from pluvial models.
- **Activities**:
  - Evaluate and discuss options for pluvial results formats and hosting scenarios.
  - Extract and derive meaningful spatial layers from raw models.
  - Upload raw models and limited, meaningful results to AWS S3 bucket.

- Develop and stand up and host basic results viewer web service.

- **Products**:
  - Maximum water surface elevation and depth rasters for all modeled events (tiled mosaics).
  - Incorporate results into VACRMP web viewer.

TASK 2: PLUVIAL IMPACT ASSESSMENT

- **Objective**:
  - Evaluate pluvial hazard impacts to community resources and critical sectors using the CRMP V1.0 compiled asset dataset.
- **Activities**:
  - Produce hazard curves representing depth versus frequency for three time horizons (existing conditions, 2040s, 2060s, and 2080s).
  - Research peer-reviewed literature and Federal guidance document sources to inform quantification of the consequence of varying levels of pluvial hazard severity for the built environment. Select and assign the appropriate depth-damage curves for the hazard type and building stock.
  - Conduct quantitative or semi-quantitative pluvial risk assessment for community resources and critical sectors using the CRMP V1.0 compiled asset dataset.
- **Products**:
  - Quantitative and semi-quantitative pluvial impact metrics using the CRMP V1.0 compiled asset dataset.

TASK 3: FLUVIAL HAZARD NON-STATIONARITY ANALYSIS

Literature review indicates that the magnitude and intensity of precipitation events have increased in many areas world-wide [Kunkel et al., 2013]. However, translating precipitation changes into their resultant impacts to the magnitude and frequency of fluvial flood events can be difficult as floods are multidimensional processes and the 100-year rainfall seldom translates into the 100-year flood.

The idea that these hydrologic climate variables are varying with time contradicts a key assumption in water resources planning and design- namely that the statistical characteristics of hydrologic time series are constant, or stationary, over time.

An increasing body of evidence suggests that climate change and land use change are undermining the stationarity assumption, requiring evaluation and identification of a “non-stationary” signal in hydrologic observations in order to plan and design.

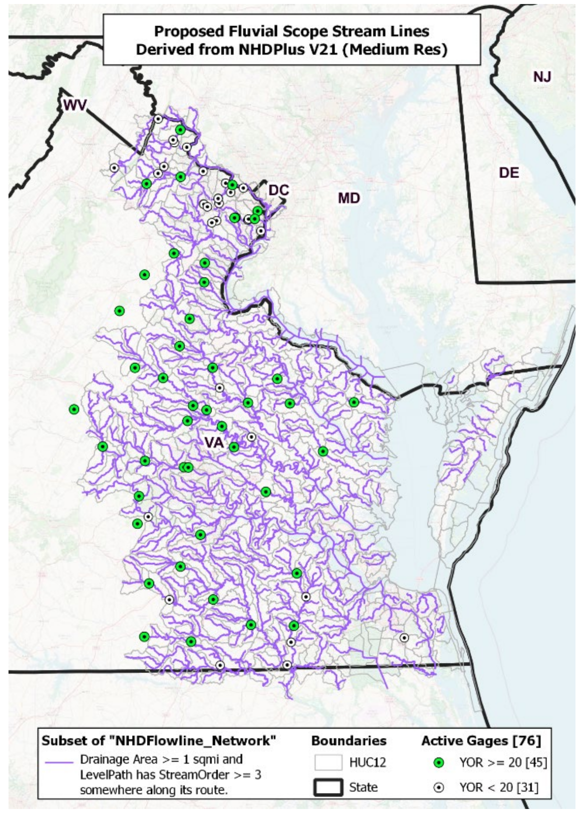


Figure 2: Active Gages and Record Length for the Study Area.

To support characterization of how fluvial hazards may change in the study area, Dewberry proposes to evaluate gage records in the study area with at least 20 years of record and apply non-stationarity detection techniques to identify whether a signal exists (Figure 2). Quantifying the magnitude of such a signal, especially at gages that have not seen significant changes in upstream land use, will offer broad value in assessing future fluvial risk. The evaluation will employ techniques from the USACE Engineering Technical Letter ETL1100-2-3, “Guidance for Detection of Non-stationarities in Annual Maximum Discharge” as well as a “Peaks Over Threshold” analysis, following the work of Villarini (2015) and Archfield et al (2016). Archfield’s work in particular has identified a strong positive signal in the peak flow trends for the study area’s region, as shown in Figure 3.

The analysis will thus lay the foundation to understanding fluvial flood hazard trends and will support scoping and prioritizing fluvial reaches for updated hydrologic and hydraulic analyses, as part of the longer term, 2026 efforts.

Trends (1940 to 2013): Peak Daily Streamflow of Flood Events
Ref: Archfield, S.A. et al (2016), "Fragmented patterns of flood change across the United States". https://doi.org/10.1002/2016GL070590.

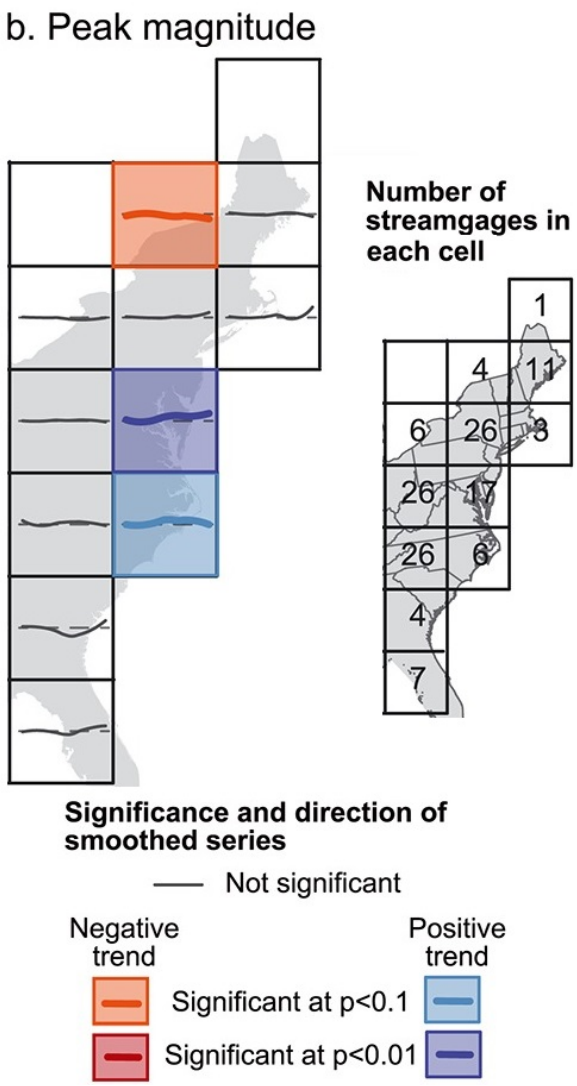


Figure 3: Peak Magnitude Trends in the Study Region as per Archfield et al. 2016.

SUBTASK 1: NON-STATIONARITY ANALYSIS

- **Objective**:
  - Secure Data and Apply Signal Detection Approach
- **Activities**:
  - Identify candidate USGS stream gages.
  - Evaluate gages for: quality of the data, historic changes in how data were collected (stream gage placement, etc.), natural phenomena that impact data reliability (backwater conditions, frozen apparatus, etc.), presence of gaps and missing data, and the frequency with which data are collected.
  - Explore data by plotting and reviewing raw data to identify presence of slowly varying or gradual changes, as well as spatial patterns when analyzing multiple time series.
  - Apply Appropriate Test Statistics- including parametric test (assuming underlying statistical distribution) and non-parametric tests (do not make distributional assumptions).
  - Formulate implications of results for fluvial hydrologic analyses to be completed as part of longer term efforts of the Commonwealth.
  - Develop report on needs, methods, and results.
- **Products**:
  - Non-stationarity evaluation report.

TASK 4: COMPOUND FLOODING POTENTIAL FROM COASTAL, FLUVIAL AND PLUVIAL HAZARDS

For coastal regions, a robust and holistic assessment of flood-risk must consider the potential compounding effects of coastal (tide and surge; no waves), fluvial (discharge) and pluvial (precipitation) flood hazards. There is growing evidence that climate change impacts will lead to increases in compound flooding hazards globally (Bevacqua et al., 2020). For the continental US, recent research has demonstrated that tropical cyclone climatology change greatly exacerbates joint rainfall-surge hazards, including a 30– to 195-fold increase in the frequency of exceeding joint historical 100-yr hazard levels by 2100 in the US northeast (Gori et al., 2021).

Not all geographical regions in the US are exposed to compound flood hazards at the same level, and in those that are, there can be further differences in the contributing factors of the individual flood hazards. The compound flood exposure of a particular region can also change with different future climatic conditions (Ghanbari et al. 2021). Further, even for a given condition and region, compound flooding exposure can vary across watersheds and by coastal reach (Jane et al., 2021). It is therefore important to first assess the dominant individual drivers and the compound flood hazard potential as locally as practically feasible.

In the 2022 iteration, a quantitative assessment of the potential of compounding effects from coastal, fluvial and pluvial hazards will be performed via pair-wise (precipitation-surge, surge-discharge, and precipitation-discharge) copula-based statistical modeling and analyses on observational (supported by reanalysis/hindcast as relevant) historical data for current conditions and downscaled climatic data for future conditions. This analysis will guide the level of detailed spatio-temporal compound flood hazard mapping that would need to be performed in the 2026 iteration and which will require a significantly larger effort. Due to the presently unknown nature of the compound flooding potential in terms of dominant contributing drivers as well as the importance level and geographic extent of compound flooding potential, the 2026 iteration analysis will be scoped in detail at a later date. Potential approaches and a ROM cost estimate for the 2026 interaction analysis are included.

The individual or marginal flood hazards for the 2022 iteration will include coastal, pluvial and fluvial contributors. Bivariate pair-wise copulas will be used to quantify the dependency/compound interactions; trivariate copulas are not anticipated to provide significantly more information. A maximum of eight (8) locations representative of the eight coastal PDCs/RCs (see Figure 4) will be used. Three conditions will be asessed – 1) Current conditions, 2) RCP 8.5 future condition (2020 – 2070), and 3) RCP 8.5 (2050 – 2100). For current conditions, the analysis will generally follow the methods described in Nasr et al. (2021). For current conditions, depending on data availability and quality constraints, observational data (primarily USGS and NOAA datasets; see Figure 4) may be supplemented by regional or global reanalysis/hindcast data (e.g. Muis et al., 2020; Harrigan et al., 2020). Data for future conditions – precipitation, discharge and storm surge – will be obtained from downscaled climatic models (e.g. Bevacqua et al., 2020; Naz et al., 2016, Gori et al. 2021). Climatic data for future conditions will likely be regional-scale but largely representative of local conditions.

For current conditions, the influence of seasonality, specifically tropical cylone and extra-/non-tropical events, on the compound dependency structures will be assessed by partitioning the analysis into two seasons – Tropical (June – Nov) and Extra-Tropical (Dec – May). Limited qualitative assessment of seasonality for future conditions will be performed. For both the individual and compound flood hazards, a maximum of six (6) AEPs (50%, 20%, 10%, 4%, 2%, 1%, 0.2%) will be quantified and compared. Finally, the eight (8) PDCs/RCs will be compared against each other with regard to individual flood hazards and compound flood hazard potential.

As relevant and to the extent feasible with the task schedule and budget constraints, results from other tasks to be executed in parallel and past related studies (e.g. Dewberry, 2018; MARISA - https://www.midatlanticrisa.org/; USACE, 2015; National Water Model hindcasts; Couasnon et al., 2020; Bates et al. 2021) will be used to inform and be potentially incorporated into the analysis (e.g. for bias corrections to reanalysis or downscaled climatic data).

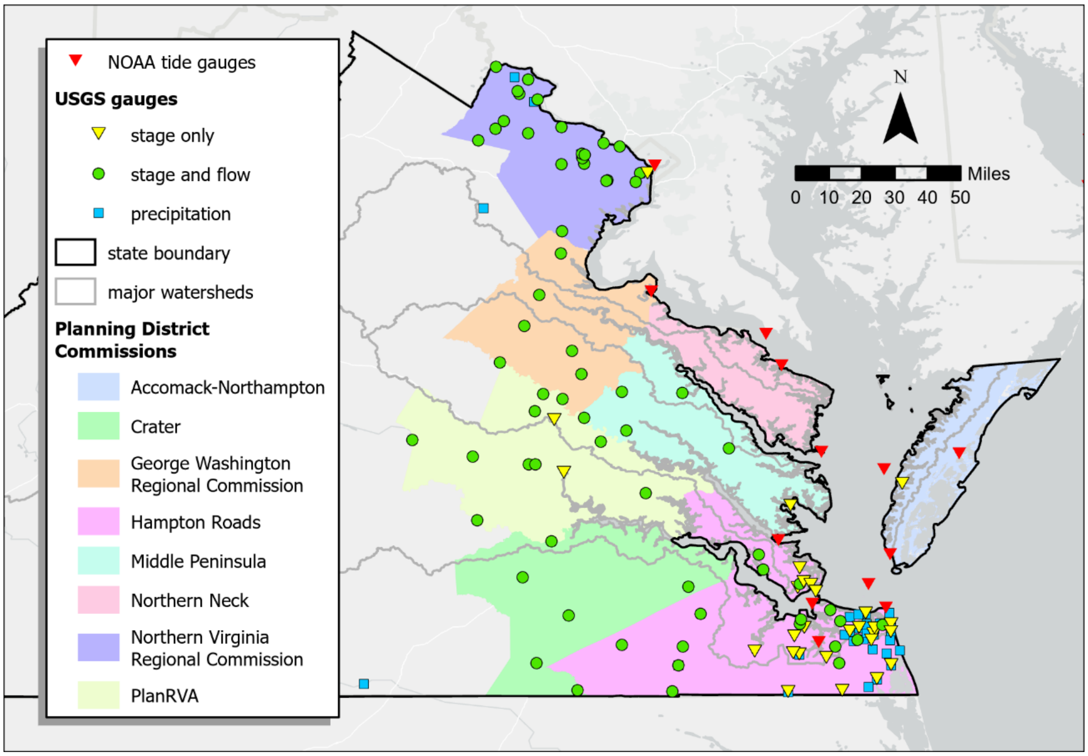


Figure 4: Coastal PDCs showing USGS and NOAA gages.

SUBTASK 1: DATA INVENTORY, REVIEW, AND PROCESSING

- **Objective**:
  - To collect, review and process coastal, hydrologic, and hydraulic data for subsequent use in statistical analyses.
- **Activities**:
  - Inventory and review historic (observational and including modeled reanalysis/hindcast as relevant) and downscaled (future) climatic (precipitation, discharge and coastal) data.

- For areas where sufficient data exists, process data for subsequent analysis.
- Identify data constraints and uncertainties.

- **Products**:
  - Raw and processed data for inputs into statistical (marginal and bivariate) analysis.

SUBTASK 2: MARGINAL ANALYSIS OF INDIVIDUAL FLOOD HAZARDS

- **Objective**:
  - Develop marginal distributions for each of the three flood hazards (precipitation, discharge and coastal) for current and future conditions.
- **Activities**:
  - Apply sampling (one-way, two-way, or using joint exceedances) using appropriate thresholds to identify relevant pairs of flood hazard values.
  - Test a range of commonly used distributions to identify most suitable distribution for each of the flood hazards using error statistics.
- **Products**:
  - Marginal distributions for each of the three hazards and associated AEPs (50%, 20%, 10%, 4%, 2%, 1%, 0.2%).

SUBTASK 3: BIVARIATE PAIR-WISE COMPOUND/DEPENDENCE ANALYSIS

- **Objective**:
  - Quantify the dependence (including seasonal – tropical and extra-/non-tropical) between each pair (precipitation-surge, surge-discharge, and precipitation-discharge) of flood hazards.
- **Activities**:
  - Use rank correlation coefficients to derive dependence between different flood hazards and associated uncertainties (for all data and separated into seasons).

- ○ Use tail dependence coefficients to derive dependence between different flood hazards and associated uncertainties (for all data and separated into seasons).

- **Products**:
    - ○ Pair-wise flood hazard dependency maps including seasonal dependence (see Figure 5 as an example).

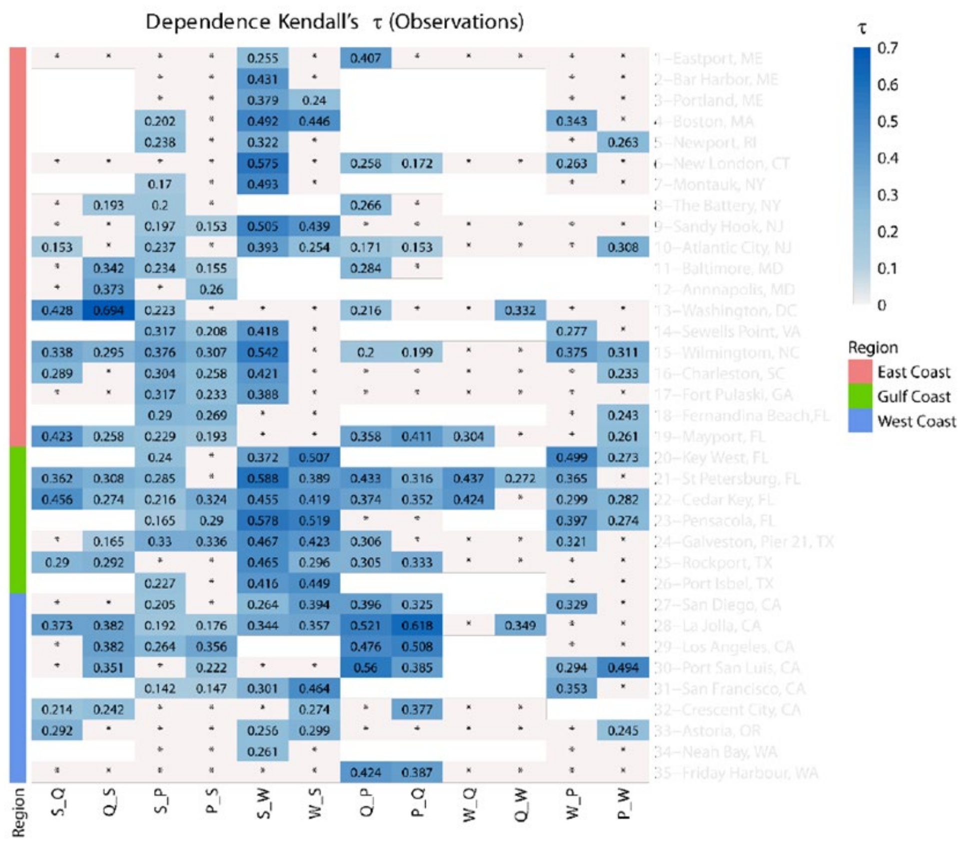


*Figure 5: Example dependence between different pairs of flooding drivers based on Kendall's τ and two-way sampling using annual maxima. Sites are grouped into East, Gulf, and West coast locations (see colors on the left and legend). The blue color bar denotes dependence strength, blank squares indicate that data for the particular pair didn't exist or that the number of overlapping years was less than 20 and squares with * indicate that correlation 330 is not significant; from Nasr et al. 2021.*

SUBTASK 4: COMPOUND FLOODING POTENTIAL

- **Objective**:
    - ○ Compare the individual flood hazards and compound flooding potential across the CRMP study area.

- **Activities**:
    - Identify suitable joint distribution functions (from a pool of ~40 copula functions) to model the (tail-) dependence between flood hazard combinations.
    - Derive joint AEPs for different pair-wise flood hazard combinations and compare to the joint AEPs under the independence (i.e., no dependency between the individual flood hazards) assumption.

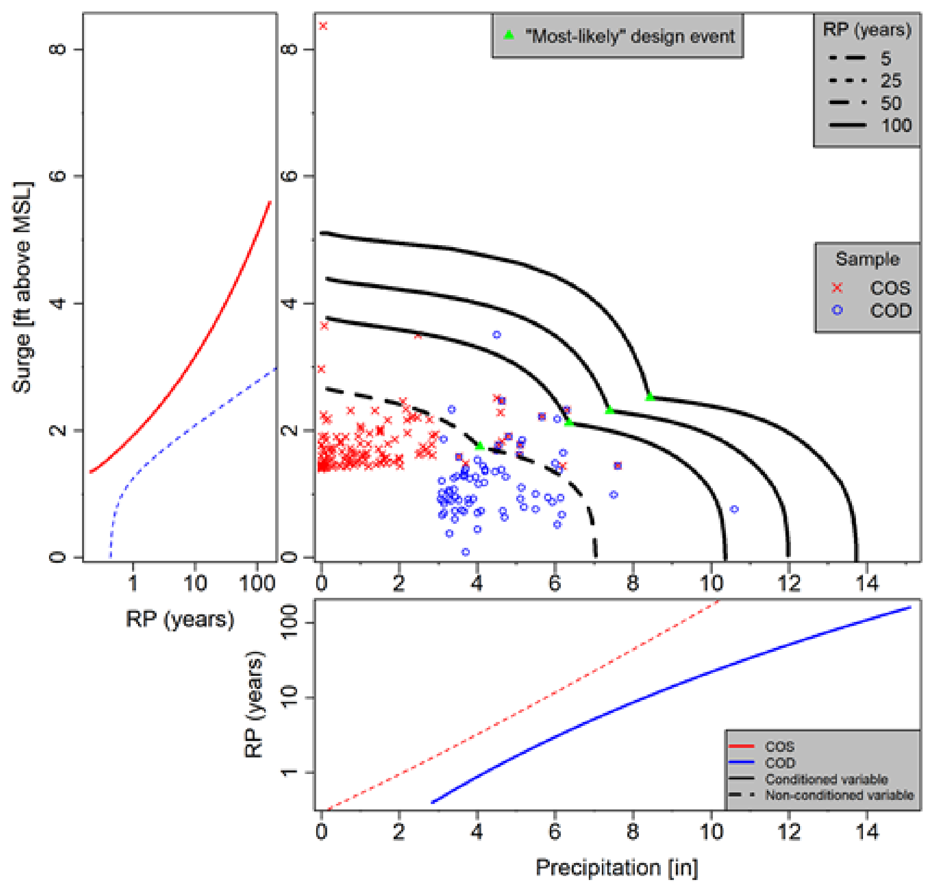


Figure 6: Example figure showing both joint and marginal AEPs. Top left panel: Probability isolines for different return periods from applying a two-way sampling approach (sample conditioned on discharge is shown in blue and sample conditioned on surge is shown in red); green triangles indicate the "most likely design points". Left panel: Marginal distributions for surge for the sample conditioned on surge (red) and the sample conditioned on discharge (blue). Bottom panel: same as left panel but for discharge.

- **Products**:
    - Compound flooding potential (pair-wise) compared across PDCs, including seasonal dependence.

SUBTASK 5: MEETINGS, PRESENTATIONS AND REPORTING

- **Objective**:
  - Provide periodic task updates via meetings.
- **Activities**:
  - Bi-weekly progress reporting
  - Virtual meetings (nine total).
  - Virtual PowerPoint presentations (3 total – including kick-off, interim, and final results).
  - No travel is included.
- **Products**:
  - Three (3) PowerPoint presentations.

TASK 5: SIMPLE COASTAL RETREAT MAPPING

It is well understood that an effect of higher sea levels will be increased erosion of unprotected coastlines throughout the world (e.g., Bruun, 1962; Zhang, Douglas and Leatherman, 2004). Assessment and mapping of projected changes can aid coastal communities in recognizing issues and initiating adaptation measures to reduce the consequences of this increased erosion. Task 5 effectively addresses marsh, marsh shoreline, and barrier island evolution but does not address Atlantic sandy shorelines (comprised of Virginia Beach), and interior shorelines of the Chesapeake Bay and tributaries.

In 1962, Per Bruun was the first to propose a model to describe the relationship between shoreline retreat and sea-level rise (P. Bruun, 1962). Not long afterwards, manual cartographic methods were used by Morton in the 1970s to map erosion trends for the entire state of Texas. Later, Leatherman and Everts used GIS methods to map erosion trends for a number of states beginning in the early 1980s. As the first means of projecting future shoreline change (and being relatively simple to use), cartographic methods as well as the “Bruun rule” were quickly adopted and remain in widespread use for projecting future shoreline change.

Since the advent of these early techniques, our understanding of coastal processes as well as our computational capabilities have greatly improved, and many additional methods have been developed for projecting future shoreline change with and without sea level rise. Despite the introduction of these various other models, the Bruun rule and historical trend extrapolation remain the two most widely used methods to project shoreline change. In 1990, Leatherman described the following four distinct types of models used to predict shoreline change due to sea level rise, each of which is discussed in further detail in the following text:

- The Bruun Rule
- Historical trend analysis
- Sediment budget approaches
- Dynamic equilibrium models

In addition to the four model types described by Leatherman in 1990, there are also newer types of models in active development thanks to advances in computer science, basic coastal science, statistics, and a heightened awareness of the potential impacts of future sea levels. These include, and are discussed in Task 6:

- Process-based models
- Probabilistic models
- Bayesian networks
- Monte Carlo simulations
- Integrated coastal systems models

The state of Virginia has over 5,000 miles of coastal shoreline along the Atlantic Ocean, Chesapeake Bay, and estuarine tributaries. At present, historical shoreline rates have been calculated for much of this shoreline by the Virginia Institute of Marine Science (VIMS) (Hardaway et al. 2017). This analysis provides for long-term shoreline change rates from the 1930s to 2009 for most of Virginia's coast, with much smaller areas available from the 1930s to 2017, and/or 1949. At present, some areas have been updated to 2017 (counties with bay side shorelines), with additional work noted as "in progress" (Hardaway et al. 2017).

It is noted that these rates represent End-Point rates. End-Point rates are calculated from two end-member shoreline positions and do not consider any intermediate shoreline data or any intermediate variations of shoreline position. Such rates represent the most common form of shoreline change analysis but may misrepresent change rates if the end-member shorelines are influenced by intermediate storm conditions or coastal management activities such as beach nourishment. More robust rates are derived from linear-regression analysis of a series of two end-member and several intermediate shoreline positions. Use of this approach allows insight into the consistency of the trend over time. Where the quality of the linear regression fit is high, the rate determined by this method would match the end-point rate.

At this time, we recommend that the state consider methods based on extrapolation of historical rates, or the Bruun Rule, considering the potential approaches, available data, and potential costs of more sophisticated methods, in the context of the overall uncertainty of the projections. Extrapolation of historical rates is the simplest most cost-effective approach. For this, the future projected shoreline is simply estimated based on the base shoreline condition (present-day or most recent shoreline) and the historic shoreline change rate. An example from Puerto Rico is shown in Figure 7.

For Virginia, this approach would be partially compromised by reliance on historical shoreline data. Available data is from the historical epoch of the 1930s to 2009, or 2017. The historical shoreline change rate reflects coastal dynamics from this period – including natural sediment process, anthropogenic interventions, and the historical rate of sea level rise. Despite these limitations, this approach could cost-effectively provide basic information that would help inform long-term risks and adaptation responses to sea level rise.

Figure 7: Example of future shoreline erosion areas created as an advisory product by FEMA to inform the resilient recover of Puerto Rico after Hurricane Maria.

Another option would be the application of the Bruun Rule. The Bruun Rule approach can be described as a two-dimensional mass balance approach based on the notion that as sea level rises and sand erodes from the beach-face and dune, an equal amount of sediment is deposited at the beach slope toe offshore. In 2004, Cooper and Pilkey noted the following (Cooper and Pilkey 2004): “In its simplest form, as it is actually applied, the

Bruun Rule states that shoreline erosion caused by sea-level rise is a function of the average slope of the shore-face, which is typically the steepest part of the near-shore profile."

While the Bruun Rule has been widely used, it has also been widely criticized. The Bruun rule also requires additional data beyond historic shoreline change rates, including near-shore slope, berm heights, and the depth of closure. Gathering and development of this information takes additional time and resources. In many cases, nearshore slopes are difficult to estimate due to the quality and/or age of the nearshore bathymetry. Additionally, depth of close must be estimated from either wave height information or a time-series of beach profiles. Such data may take significant time to develop for Virginia's shorelines. Even so, returned values should be considered estimates, and it is noted that the output of the Bruun Rule is sensitive to this value – for example, percent error in the projected shoreline for a 1.5 ft SLR scenario due to depth and distance to closure inputs was estimated to be about +/- 20% (Batten et al. 2020). The Bruun Rule is also subject to the limitations of the source epoch of the historical shoreline change rates, as mentioned in previously. Methods, such as those employed by Ashton et al. (2011) have sought to overcome that limitation by adjusting the rate using a factor based on the historical and future rates of sea level rise.

For 2022, it is recommended to complete a pilot study effort to further inform broader application of either approach. Ultimately, it may be beneficial to engage state academic partners on this problem and direct research and development funding to support a determination of the most suitable approach and needed data development. Coordination with stakeholders to identify the best path forward for such products, in consideration of existing data, planned improvements, and overall Commonwealth agency needs is essential.

SUBTASK 1: PILOT APPLICATION OF EXTRAPOLATED HISTORICAL RATES

- **Objective**:
    - Provide future shoreline change products based on simplistic extrapolation methods to socialize with stakeholders.
- **Activities**:
    - Select a mostly contiguous reach of coast, up to 50-miles in length, in the Chesapeake Bay or tributaries for the pilot application.
    - Retrieve historic shoreline change rates and modern shoreline vector shoreline from VIMS.

    - Create geospatial product of projected shoreline change for two future epochs. We recommend to 2040 and 2060, as longer epochs have greater uncertainty.

- **Products**:
    - ESRI-compatible geodatabase with vector polygons for the two future shoreline retreat hazard areas.
    - Technical Memorandum describing approach and limitations.
    - Estimated cost for state-wide application.

SUBTASK 2: ASSESSMENT OF DATA RESOURCES FOR BRUUN-RULE BASED APPLICATION

- **Objective**:
    - Determine data development needs and costs for potential state-wide application of the Bruun Rule-based Approach.

- **Activities**:
    - Conduct literature review for potential sources of information, such as depth of closure.
    - Evaluation of existing seamless terrain topo-bathymetric datasets for the purpose of evaluating potential sources of slope information and their associated quality.
    - Assess approaches for estimating parameters at needed state-wide scale.
    - Summarize findings, and present potential costs of data development and method application for potential state-wide application in Technical Memorandum.

- **Products**:
    - Technical Memorandum describing findings and potential costs.

TASK 6: COASTAL LANDSCAPE CHANGE AND FLOOD HAZARDS

A thorough examination of future coastal flood hazards will include a coastal numerical modeling effort that considers future changes to the barrier islands and marshes that make up the coastal landscape. Degradation of the marshes or barrier islands may allow water to flow more freely into populated areas, resulting in non-linear changes to storm surge and generally exacerbated flood conditions that must be considered in an assessment of future coastal hazards.

Cascading changes can happen as the coast degrades in response to SLR as shown in Figure 8 through Figure 11. For example, marshes may shrink or drown, and allow floodwaters to move more freely. Marshes can also migrate into upland areas or be prevented from growing into the upland areas by urbanization and land use decisions. Barrier islands may be overtopped, be breached, or drown. The retreat of barriers exposes marshes and communities to marine conditions and can trigger non-linear and widespread degradation of marshes.

The level of complexity and the number of dynamic processes that must be considered call for a robust probabilistic analysis framework that is organized around the output of physics-based or empirically well-founded models of coastal hydrodynamics, marsh evolution, and barrier island change.

The eventual modeling framework that is developed for the 2026 iteration will consist of three elements. These are:

1. A hydrodynamic model that will be used to simulate water levels, currents, and waves on a regional grid throughout the study area (both for the bay, and for Coastal Virginia Eastern Shore)

2. Simple models of marsh evolution or barrier island evolution and attendant processes that take input from the hydro model and are used to simulate complex processes based on empirical observations.

3. A probabilistic analysis framework.

The four subtasks described in the 2022 iteration are designed to provide a strong foundation for the future work through 2026, and in particular to inform choices about model development that will need to be made as the 2026 iteration begins. Additional information on the approach can be found in Appendix A.

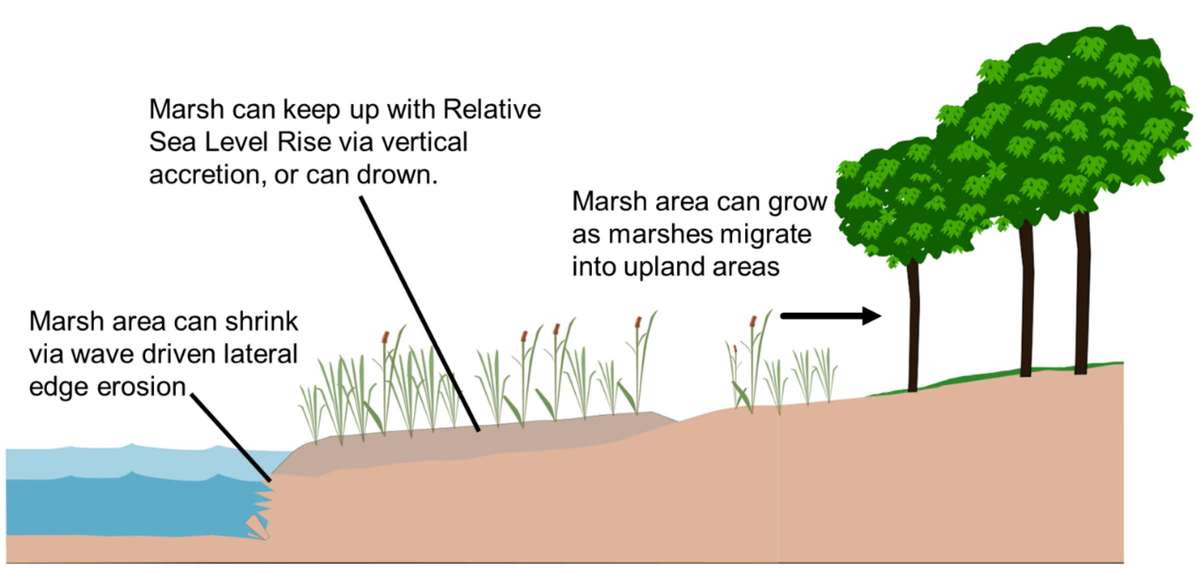


Figure 8: Dynamic marsh evolution processes. After Kirwan et al. 2016.

Figure 9: Dynamic marsh evolution processes.

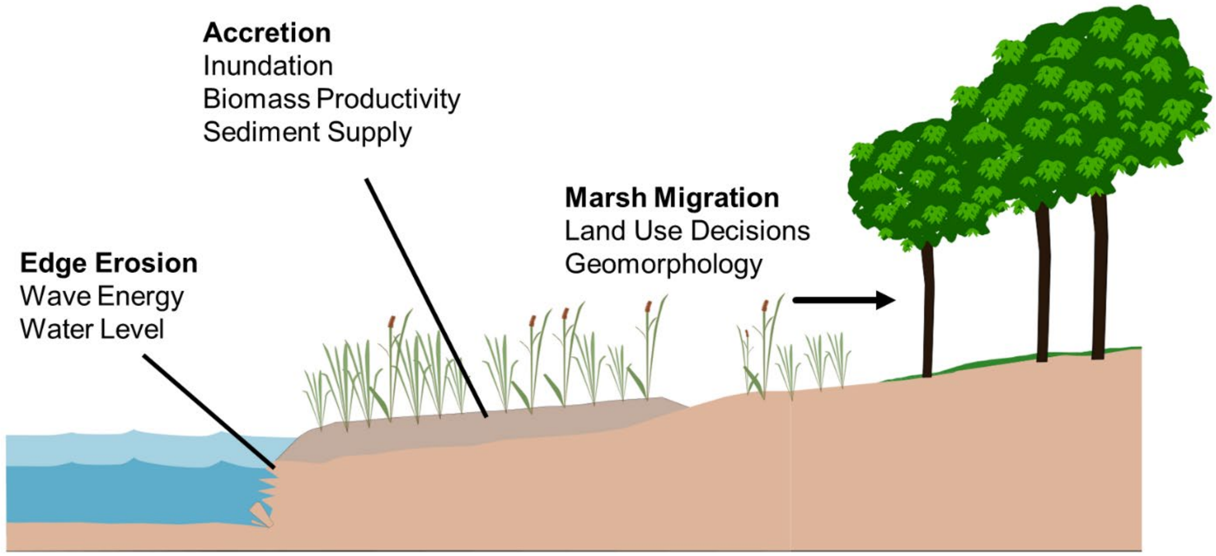


Figure 10: Processes that must be accounted for to dynamically evaluate coastal landscape changes.

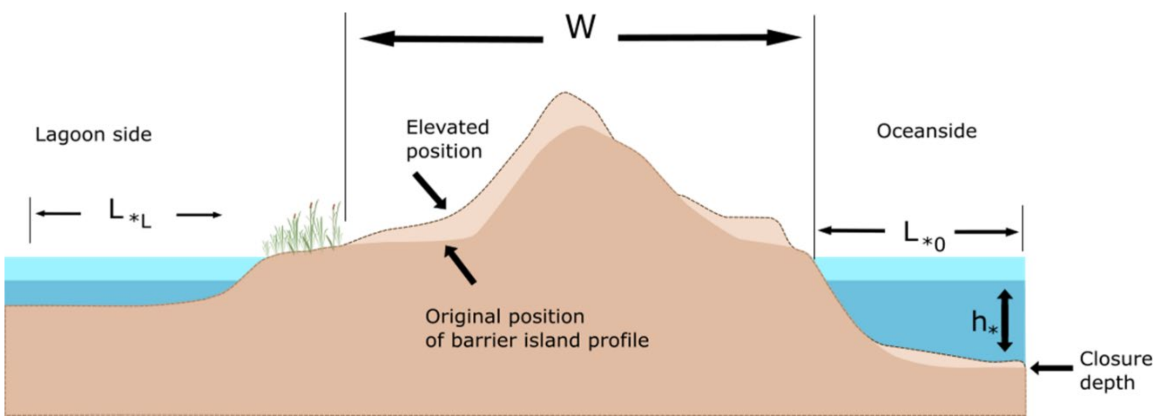


Figure 11: Barrier island dynamics modeling.

SUBTASK 1: HYDRO MODEL SELECTION

- **Objective**:
  - To provide guidance on the most appropriate hydro model to use in the 2026 iteration, in terms of technical capabilities and usability.
- **Activities**:
  - Inventory and review existing model options (low and high complexity).

- Interact with model developers to assess each model based on scalability, availability within an open source framework, spatial coverage, model performance history, and accessibility of the model developers.
- Identify additional coverage needed or links between spatially distinct hydro models. There are many functioning models of the Virginia coast, especially of the Chesapeake side, so some will likely be combined in this activity.

- **Products**:
  - Guidance on the most appropriate hydro model, and the tradeoffs among relevant models.

SUBTASK 2: DATA REVIEW AND COMPILATION

- **Objective**:
  - Catalog and compile input and calibration data from relevant reports, published data, and State guidance documents.
- **Activities**:
  - Catalog available DEMs, leveraging information collected for the initial CRMP Hazard Framework and other activities described herein. Specific attention will be given to coverage, quality, and potential for correction techniques in the context of the proposed application.
  - Compile a database of Accretion and Edge Erosion historical measurements and ongoing studies.
  - Compile a database of Barrier Island historical morphology
  - Conduct gap analysis. Where will additional data be helpful as the model comes online, and is run through future conditions?
- **Products**:
  - Guidance document on the quality and availability of data to develop, and calibrate the 2026 models, and the gaps in the available data set that are expected to be important to fill in support of the 2026 process. Particular attention will be paid to DEM quality, which is very variable, and a major contributor to wetland and barrier island model performance.

SUBTASK 3: MODEL WORKFLOW DIAGRAMING

- **Objective**:
  - Develop model linkages and workflows between model components.
- **Activities**:
  - Code and testbed models to demonstrate functional linkages between model components (i.e. hydro, wetlands, barrier islands).
  - Develop conceptual figures of the workflows and physical/ecological processes involved.
- **Products**:
  - A flow chart describing how the anticipated 2026 model components will work together, and sample output demonstrating that the anticipated links work.

SUBTASK 4: PROBABILISTIC ANALYSIS FRAMEWORK

- **Objective**:
  - Develop a probabilistic analysis framework to provide a foundation for the 2026 desired outcomes.
- **Activities**:
  - Conduct literature review on similar efforts.
  - Develop conceptual diagrams and workflows.
  - Use analysis framework and results of testing in Subtask 1 to identify limitations in computational resources and time.
- **Products**:
  - A report describing how model output in the 2026 plan will be assessed against available data, and how the 2026 model process will incorporate uncertainty.

4. LONG-TERM ACTIVITIES (THROUGH 2026)

TASK 1: FLUVIAL HAZARD

In preparation for building on the non-stationarity analysis proposed for the 2022 iteration of the CRMP, Dewberry evaluated the fluvial landscape in the 57-county coastal Virginia study area. Using the National Hydrographic Dataset, we identified ~20,000 miles of stream in the area, with ~5,600 miles of fluvial reaches that drain more than a square mile and have a stream order of 3 or higher (Figure 5). These criteria helped the team identify, from a fluvial perspective, those reaches that are more likely to pose a fluvial flood threat, as opposed to pluvial hazard threat.

From, there, the team used FEMA's hazard data inventory information, in the form of the Coordinated Needs Management Strategy (CNMS) dataset, to understand FEMA's existing model inventory for this area. Out of ~10,500 miles of streams analyzed and depicted on FEMA Flood Insurance Rate Maps, ~5,400 miles have been identified as "unverified"- meaning there are documented reasons why the existing analyses do not accurately represent the flood hazard, and those streams are targeted for restudies.

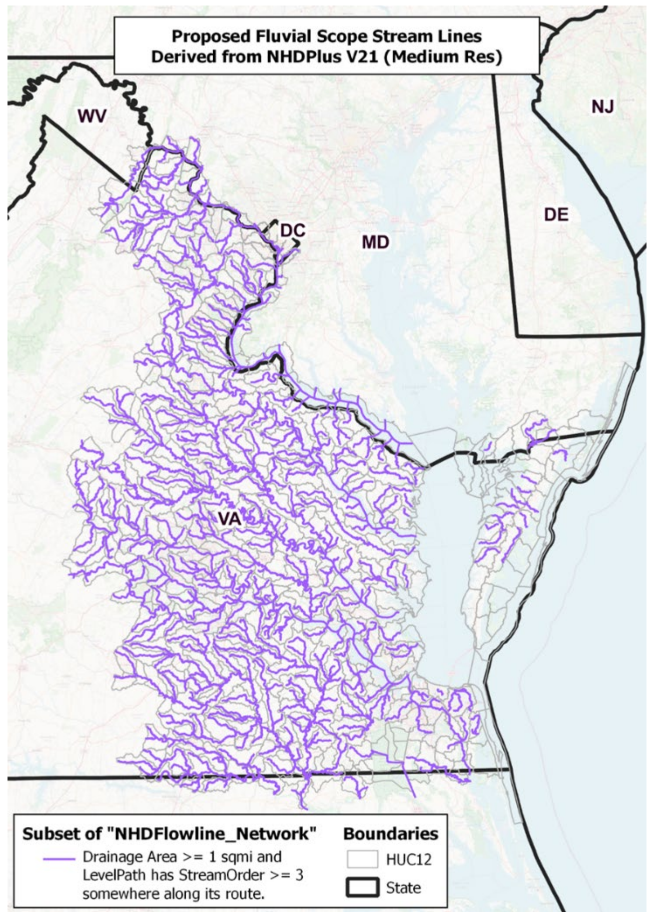


Figure 12: Using NHD, ~20,000 miles of stream were identified in the study area with ~5,600 miles draining more than 1 sq. mi and a stream order of 3 or higher.

We further filtered the “valid” portion of the inventory based on:

- date of the hydrologic analyses (more recent than 2000);
- date of the hydraulic analyses (more recent than 2000);
- use of LiDAR data; and
- use of HEC-RAS versions 4, 5, or 6.

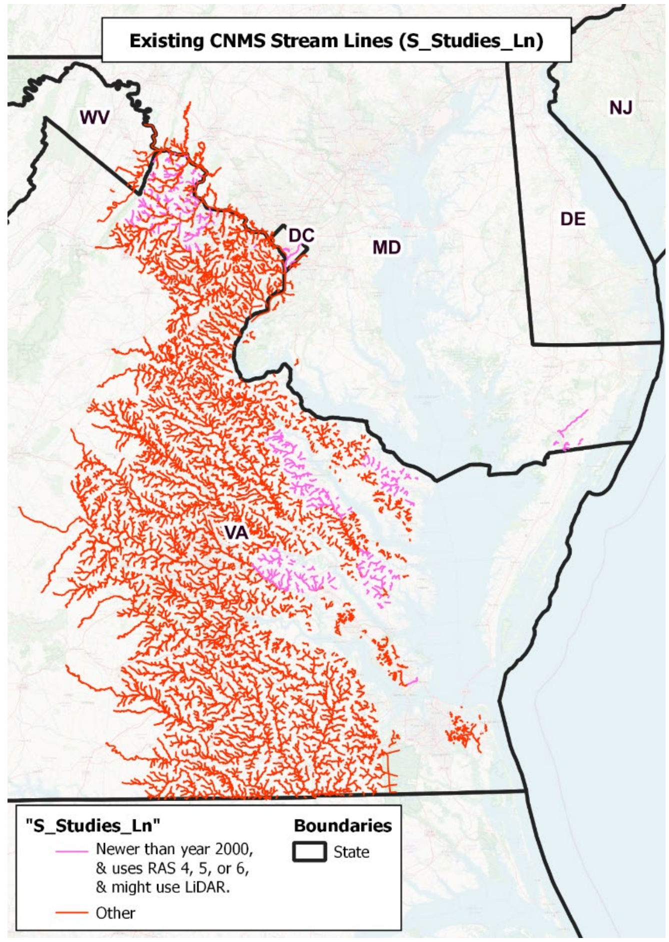


Figure 13: Approximately ~670 (~5%) miles in the study area have modern and potentially reusable fluvial flood hazard analyses.

This yielded ~670 miles that have modern, and potentially reusable, fluvial flood hazard analyses. And for the remaining 95% of the fluvial flooding sources in the study area, new hydraulic analyses would be needed to estimate future fluvial hazards. Thus given the small portion of likely useful, existing data, and the efficiency dividend in applying a consistent set of methods for the analyses, in the subtasks presented below, It is recommended to prioritize fluvial reaches for analyses through a scoping process and developing new hydraulic models to estimate future fluvial hazards.

SUBTASK 1: FLUVIAL SCOPING

- **Objective**:
  - Determine prioritize reaches for fluvial model development.
- **Activities**:
  - Evaluate existing stream centerline data from NHD and CNMS and develop composite dataset for scoping and prioritization.
  - Determine scoping criteria- use multi-criteria weighting to prioritize watersheds and fluvial reaches for study. Factors may include current

100-year extent structure counts, population counts, population growth, non-stationarity signal, etc.

- **Products**:
  - Feature class of prioritized stream reaches for fluvial model development.

SUBTASK 2: FLUVIAL BASIN DATA INPUT PRE-PROCESSING

- **Objective**:
  - Prepare physiographic input data for fluvial hazard characterization.
- **Activities**:
  - Develop Digital Terrain Model (DTM) mosaic of best-available ground elevation datasets.
  - Develop hydraulic stream centerline features from combination of NHD High Resolution and CNMS S_Studies_Ln, with minor manual adjustments.
  - Develop hydraulic breakline features along major highways, dams, and levees.
  - Develop digital elevation model (DEM) by modifying raw DTM with hydraulic stream centerlines (burn lines).
  - Develop model domains (basins) – primarily HUC12.
  - Develop land-cover-derived input rasters including roughness (Manning's N), SCS Curve Number (CN), and Percent Imperviousness.
- **Products**:
  - Spatial layers: raw DTM, H&H DEM, stream centerlines, breaklines, model domains, land-cover-derived input datasets.
  - Data Processing report.

SUBTASK 3: FLUVIAL HYDROLOGY

- **Objective**:
    - Develop fluvial hydrologic input datasets.
- **Activities**:
    - Evaluate approaches for estimating riverine flow rates.
        - Option 1 – Use non-stationarity analysis conducted in short term scope to adjust flow estimations for future estimates of the 5yr, 10yr, 25yr, 50yr, 100yr, and 500yr recurrence intervals (20%, 10%, 4%, 2%, 1%, 0.2%), using analysis described in this article from Dr. Stacey Archfield in AGU Geophysical Research Letter "Fragmented patterns of flood change across the United States" (S. A. Archfield, 2016). *Note: according to this publication, peak flows in coastal Virginia have increased significantly since 1940. Trends were developed from stream gages where changes in Land Use / Land Cover have been minimal.*
        - Option 2 – Develop current-conditions HMS models, then increase the HMS precipitation for future conditions using the MARISA future IDF curves. Use the HMS output (at the future rain rates) as future condition inflow hydrographs.
        - Option 3 – Mix of approaches listed above, depending on basin characteristics.
    - Design and execute workflow producing inflow hydrographs.
- **Products**:
    - Inflow hydrographs for each modeled reach:
        - Recurrence Intervals – 2yr, 5yr, 10yr, 25yr, 50yr, 100yr, 500yr (50%, 20%, 10%, 4%, 2%, 1%, 0.2% AEPs).
        - Epochs – current conditions, RCP 8.5 2020-2070, RCP 8.5 2050-2100
    - Fluvial hydrology report

SUBTASK 4: FLUVIAL HYDRAULICS

- **Objective**:
  - Develop unsteady-state, HEC-RAS 2D fluvial flood models for each fluvial model domain.
- **Activities**:
  - Coordinate with USACE to obtain RAS 6 Linux.
  - Initialize RAS "project" for each model domain.
  - Develop first-cut RAS 2D mesh geometry for each model domain.
    - Limited incorporation of breaklines to improve 2D mesh (will not necessarily incorporate every breakline developed earlier during Preprocessing).
    - Limited incorporation of Refinement Regions to improve 2D mesh.
    - Limited incorporation of existing H&H model data (Note: this would be used only where there is potential to speed up workflow – it is expected that the vast majority of existing models will not be useful in this context).
    - No structure data.
    - No survey data.
  - Incorporate inflow hydrographs (developed in hydrology task).
  - Design efficient model running strategy.
  - Run and stabilize models.
  - Cursorily review results – flag anomalies spatially, without resolving.
- **Products**:
  - First-cut, unsteady-state, HEC-RAS 2D fluvial flood models.
    - Recurrence Intervals – 2yr, 5yr, 10yr, 25yr, 50yr, 100yr, 500yr (50%, 20%, 10%, 4%, 2%, 1%, 0.2% AEPs).
    - Epochs – current conditions, RCP 8.5 2020-2070, RCP 8.5 2050-2100.

- Fluvial hydraulics report.

SUBTASK 5: FLUVIAL POSTPROCESSING AND DELIVERY

- **Objective**:
    - Extract and host meaningful results from fluvial models.
- **Activities**:
    - Evaluate and discuss options for fluvial results formats and hosting scenarios.
    - Extract and derive limited, meaningful spatial layers from raw models.
    - Upload raw models and limited, meaningful results to AWS S3 bucket.
    - Stand up and host basic results viewer web service.
- **Products**:
    - Maximum WSE and Depth rasters (tiled mosaics).
    - Basic results viewer web service.

TASK 2: IMPROVEMENTS TO PLUVIAL ANALYSIS

- **Objective**:
    - Enhance the 2022 pluvial models and derived products.
- **Note**:
    - When enhancing earlier pluvial models, review the results anomalies that had been flagged earlier, and consider resolving underlying causes.
- **Activities**:
    - (If necessary) update DTM and DEM with latest-available at the time.
    - Additional storm durations and future climate scenarios.
    - Improve precipitation forcing data (hyetographs) to be spatially-variable.
    - Enhanced precipitation statistics – stochastic storm transposition.

  - Incorporate new features into RAS pluvial models:
    - Spatially-variable hyetographs
    - Infiltration and evapotranspiration
    - Additional breaklines
    - Additional mesh refinement regions
    - Tidal and surge boundary conditions
    - Hydraulic structures (with or without survey)
    - Develop and implement method of estimating effects of urban storm sewer systems
  - Develop prioritization and focus efforts along critical routes – emergency evacuation routes, military bases, hospitals, etc.
  - Build more sophisticated custom applications for interacting with results.
- **Products**:
  - Same results classes as 2022 iteration (but with improved models).
  - New results classes, such as timeseries data, velocity, etc.
  - New and/or improved applications / websites / services for results interaction.

TASK 3: COMBINED COASTAL, FLUVIAL AND PLUVIAL FLOODING

As noted earlier in the description of Compound Flooding Task in the 2022 iteration analysis, there is inadequate information presently to provide a detailed and definitive scope, schedule, or budget for the detailed 2026 iteration for combined flood hazard analysis and mapping. There are a variety of options to perform detailed spatio-temporal compound flooding analysis each with its own challenges and benefits ranging across levels of complexity, computational costs, fidelity, and accuracy. However, there are several related initiatives that are ongoing in state-wide studies of compound flooding in the states of Louisiana (https://www.watershed.la.gov/) and Texas (https://www.glo.texas.gov/the-glo/news/press-releases/2019/december/cmr-george-p-bush-announces-texas-glo-seeking-experts-to-develop-river-basin-flood-study.html) , and which are expected to produce "best-practice" guidance in the selection of one or more of these options towards application in state-wide studies as would be desired for present application.

For the purposes of providing a ROM cost estimate for the 2026 iteration, a medium-high approach in terms of complexity, fidelity and accuracy is proposed (see Figure 14 through Figure 17), and which will be revisited at a later date when substantial results of the 2022 iteration analysis are available. With the present uncertainty, only high-level and broad descriptions and ROM cost estimates are provided for each sub-task.

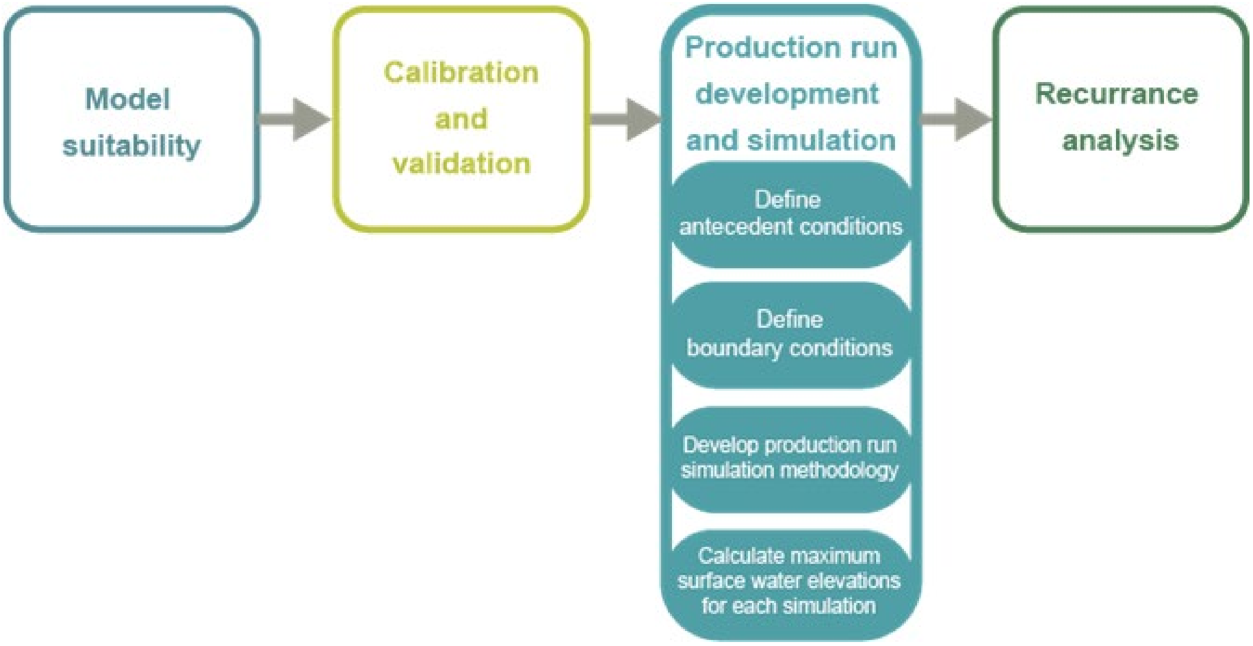


Figure 14: Parameterization of antecedent and boundary conditions for each individual simulation.

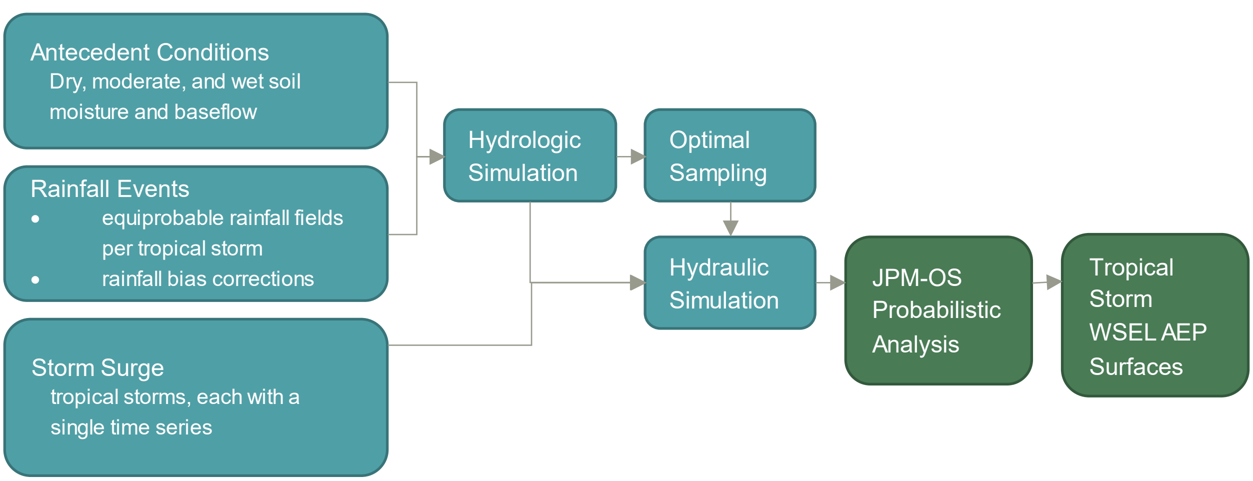


Figure 15: Workflow of synthetic storm boundary and initial conditions development, numerical simulations, and statistical analyses for tropical storms.

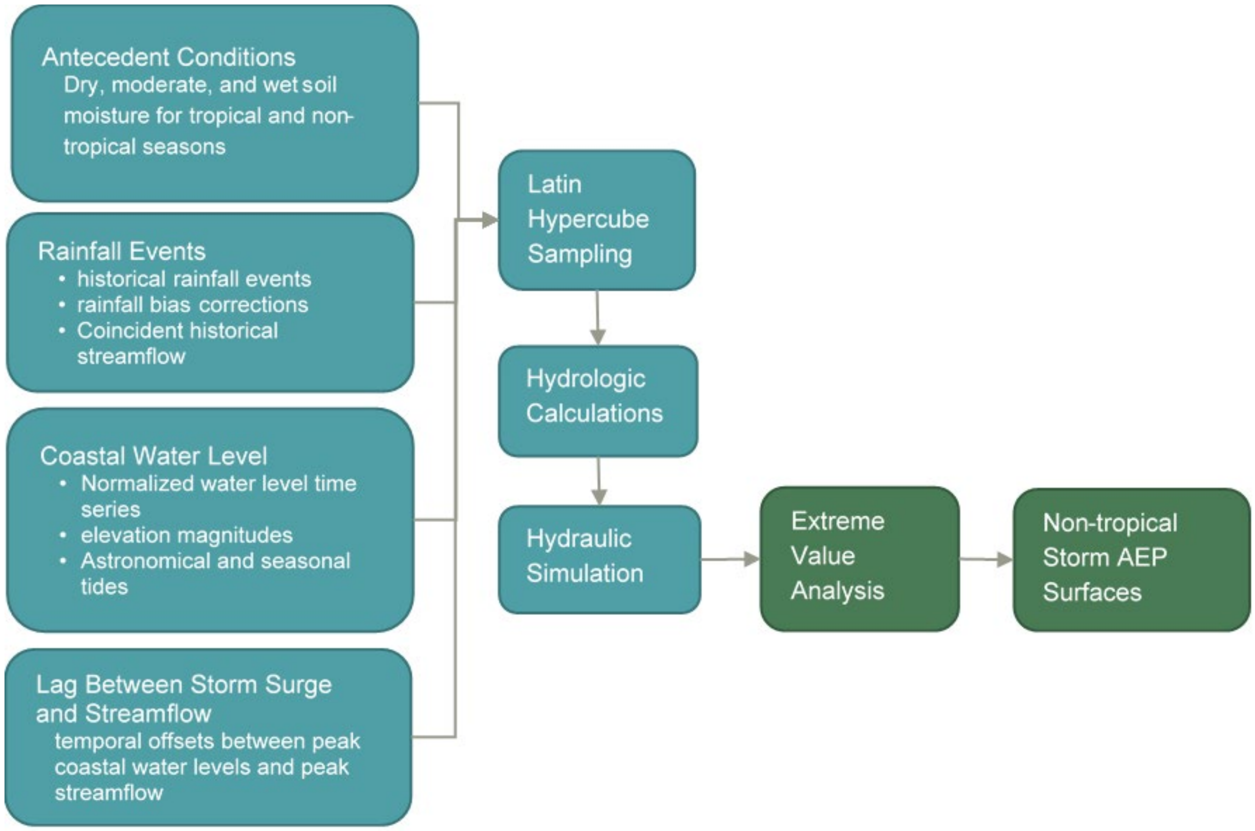


Figure 16: Workflow of non-tropical storm boundary and initial conditions development, numerical simulations, and statistical analyses.

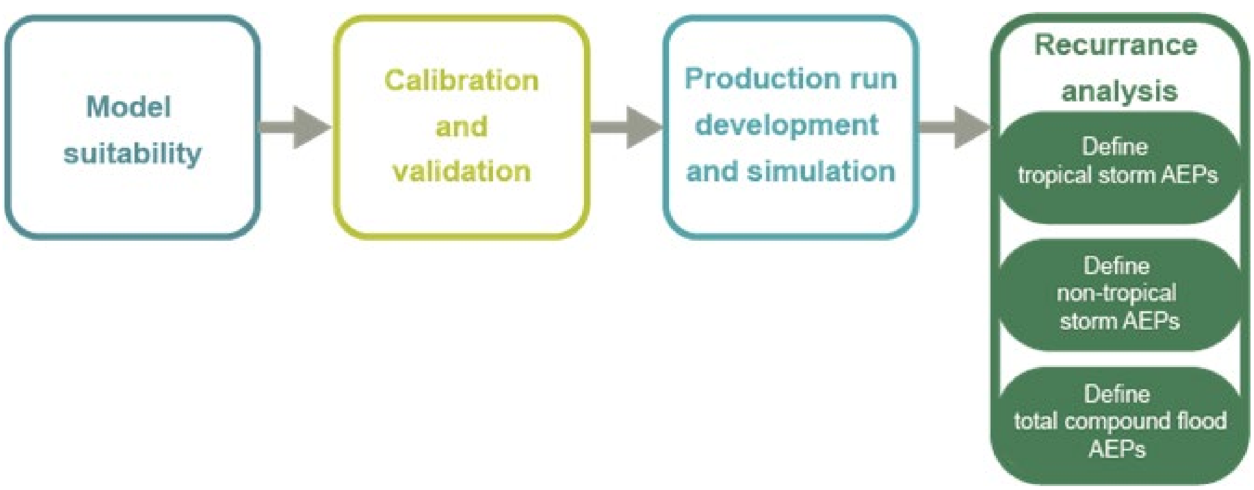


Figure 17: Diagram of elements of recurrence analysis component of the study methodology.

The overall deliverable for compound flooding hazard analysis in the 2026 iteration will be flood hazard grids with their associated marginal and joint AEPs, respectively. These gridded products may be used in addition to or in place of existing flood hazards data developed in the pluvial, fluvial, and coastal analysis in applicable areas.

SUBTASK 1: ANTECEDENT CONDITIONS DATA ANALYSIS

- **Objective**: Determine antecedent conditions (e.g., soil moisture, riverine baseflow) to be used as initial conditions for simulations.
- **Activities**: For both tropical and extra-tropical seasons, analyze historical observations or models (e.g. NASA soil moisture model) to parameterize antecedent conditions into ordinal categories (e.g., wet, moderate, and dry).
- **Products**: Equiprobable value sets of antecedent conditions, based on observed datasets, that define ordinal categories.

SUBTASK 2: TROPICAL CYCLONE RAINFALL GENERATION

The overall workflow for rainfall generation is shown in Figure 18.

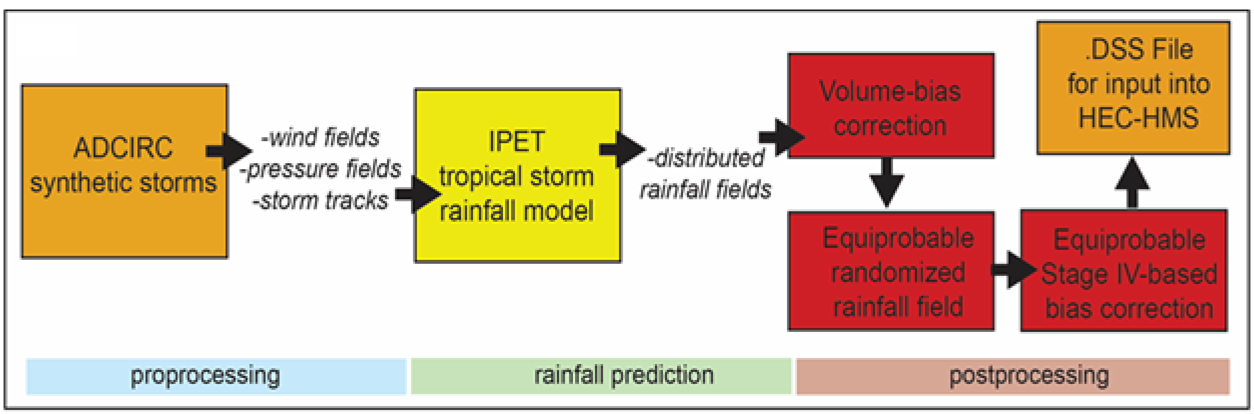


Figure 18: Workflow of the synthetic rainfall generation methodology, including a preprocess step that creates input parameters for the IPET parametric rainfall model and a postprocess step that improves the predictive ability of the IPET model for use in the study area.

- **Objective**:
  - Develop spatio-temporal rainfall grids consistent with the probabilistic storm suite for forcing pluvial models.

- **Activities**:
  - Generate rainfall grids to support development of hazard products consistent with the individual modeling outputs.
- **Products**:
  - Spatio-temporal rainfall grids for production simulations.

SUBTASK 3: JOINT-PROBABILITY METHOD WITH OPTIMAL SAMPLING UPDATE

- **Objective**:
  - Update JPM-OS storm suite to account for variability in (joint) rainfall from tropical events and antecedent baseflows and soil moisture.
- **Activities**:
  - Perform statistical analysis (e.g. principal components analysis and k-means clustering) to produce an optimal sample of discharge conditions associated with storm surge events.
- **Products**:
  - Optimal suite of events that captures joint pluvial, fluvial, and coastal hazards.

SUBTASK 4: NON-TROPICAL STORM ASSESSMENT AND SELECTION

- **Objective**:
  - Develop optimal set of non-tropical storms.
- **Activities**:
  - Perform extreme value analysis on observational data (and modeled results) for fluvial, pluvial, and coastal hazards to determine a set of optimal non-tropical storms.
- **Products**:
  - Rainfall, streamflow, and coastal water level boundary conditions for each non-tropical storm event.

SUBTASK 5: PRODUCTION SIMULATIONS (TROPICAL AND NON-TROPICAL) FOR CURRENT CONDITIONS

- **Objective**:
    - Develop and execute model simulations to create hazard products describing the combined flood hazards in identified locations.
- **Activities**:
    - Simulate combined fluvial, pluvial, and coastal scenarios in identified areas.
- **Products**:
    - Depth grids for each of the joint AEPs.

SUBTASK 6: PRODUCTION SIMULATIONS (TROPICAL AND NON-TROPICAL) FOR FUTURE CONDITIONS

- **Objective**:
    - Prepare and execute model simulations to create hazard products describing the combined flood hazards in identified locations for future conditions.
- **Activities**:
    - Update the models from Subtask 5 with forcing reflecting future conditions.
    - Simulate combined fluvial, pluvial, and coastal scenarios in all areas modeled in Subtask 5.
- **Products**:
    - Depth grids for AEPs for future conditions.

SUBTASK 7: JOINT/COMPOUND FLOODING RECURRENCE ANALYSIS

- **Objective**:
    - Develop compound flooding hazards with associated AEPs.

- **Activities**:
  - Combine flood hazard AEPs for tropical and non-tropical events into a single joint/compound AEP.
- **Products**:
  - Annualized depth exceedance (and non-exceedance) AEPs considering both compound/joint and independent flood hazards.

SUBTASK 8: QUALITY ASSURANCE AND COORDINATION

- **Objective**:
  - Ensure quality products fully integrated with and informed by other tasks in project.
- **Activities**:
  - Perform quality assurance of processes and products and keep stakeholders informed of progress and products.
- **Products**:
  - Draft and final PowerPoint presentations and reports for products.

TASK 4: COASTAL LANDSCAPE CHANGE AND FLOOD HAZARDS

SUBTASK 1: CORE MODEL DEVELOPMENT

- **Objective**:
  - Develop Hydrodynamic Model and Model Integration Framework.
- **Activities**:
  - Working with the hydrodynamic model(s) that were chosen in the Hydro Model selection process of the 2022 iteration, develop a hydrodynamic model that can represent conditions (water level, water velocity, salinity, wave energy) at a resolution that is sufficient to drive barrier island evolution and coastal wetland evolution.
  - Calibrate the model using data from selected historical time periods.

- Develop boundary condition timeseries and parameterizations that can be used to represent the expected range of future conditions.

- **Products**:
  - A working hydrodynamic model that can represent conditions throughout the Virginia coastal zone.

SUBTASK 2: DEVELOP WETLAND EVOLUTION MODEL

- **Objective**:
  - Develop an empirical model of coastal wetland evolution that can be driven by the output of the hydro model.
- **Activities**:
  - Based on the historical marsh accretion and edge erosion data sets that are compiled during the 2022 iteration, develop empirical relationships that define wetland vertical accretion and wetland edge erosion as functions of inundation and incoming wave power, respectively.
  - Quantify the confidence bounds on these relationships, and the sources of uncertainty.
  - Prepare codes to couple the hydro model (Subtask 1) with the wetland evolution model.
- **Products**:
  - A model of wetland accretion and edge erosion that can be coupled to the hydro model that is developed in Subtask 1.

SUBTASK 3: DEVELOP BARRIER ISLAND MODEL

- **Objective**:
  - Develop an empirical model of barrier island evolution that can be driven by the output of the hydro model and able to respond to environmental and climate drivers.

- **Activities**:
    - Following the historical projections of barrier shoreline compiled during the 2022 iteration, develop a robust framework of cross-shore transects that employ shoreface, inlet migration, interaction with back barrier bays, and account for most dominant shoreline response to long-term forcing such as sea level rise, as well as functioning probabilistic framework for assessing storm impacts and/or restoration.
    - Quantify the confidence bounds on these relationships and predictions, document the sources of uncertainty, and incorporate final uncertainty in the predictions.
    - Prepare codes to couple the hydro model (Subtask 1) with the barrier island evolution model, as well as the wetland evolution model where necessary.
- **Products**:
    - A model of barrier island evolution that can be coupled to the hydro model that is developed in Subtask 1 and communicate with the wetland evolution model in the Virginia Eastern Shore.

SUBTASK 4: MODEL PRODUCTION RUNS

- **Objective/Activities**:
    - Perform production runs of the hydro model coupled to the Barrier Island and Wetland Morphology models for a range of potential future conditions scenarios. The results will be assessed in Subtask 5 to provide a range of potential responses in coastal morphology and flooding.
- **Products**:
    - Suite of model output showing the range of likely responses to future environmental conditions.
- **Note:** This element is not included in the cost estimate. Additional information is needed from antecedent activities to cost appropriately.

SUBTASK 5: ANALYSIS AND REPORTING

- **Objective/Activities**:
  - Compile the results of the Production Runs (Subtask 4) and analyze them using the probabilistic analysis framework developed during the 2022 iteration.
- **Products**:
  - A report detailing the results of the modeling runs and probabilistic analysis in terms of flooding throughout coastal Virginia.

APPENDIX A.

The following includes a technical presentation of options provided to the Commonwealth CRMP Team on July 15, 2021.

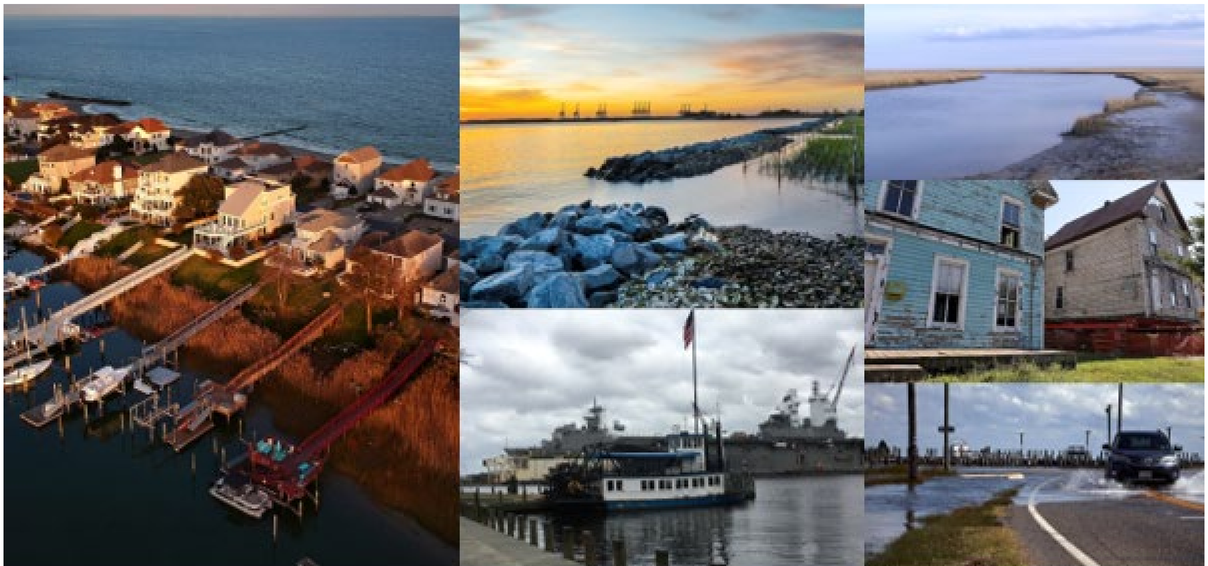


Photo Credits: Virginia Sea Grant, Dewberry

Virginia Coastal Resilience Master Plan

Dynamic Future Conditions Modeling Options | 7/15/2021

Dewberry

Objective

- Identify approaches for quantifying state-wide existing and future conditions for the purposes of the CRMP for:
  - pluvial (rainfall-induced flooding) hazards, and
  - fluvial (riverine flooding) hazards.

- Conceive and articulate a detailed approach to account for SLR-exacerbated landscape changes and their impact on flood hazards through numerical modeling.

1 | Dynamic Future Conditions Modeling Options | 7/15/2021 Dewberry

Activities

- Literature/Case Study Review
- Determine Options
- Discuss Options with Commonwealth
- Engage TAC
- Develop modeling approach document

1 Dynamic Future Conditions Modeling Options | 7/15/2021 Dewberry

Schedule

- **Final Deliverable:** July 30
- **Milestone Dates:**
  - Presentation of case study review of methodological inputs: July 15
  - Initial draft of modeling approach document: July 30

1 Dynamic Future Conditions Modeling Options | 7/15/2021 Dewberry

Priorities Identified During 6/9 Meeting

Inland Hazards

1. Future rainfall (pluvial flooding)
2. Riverine (fluvial flooding)

Coastal Hazards

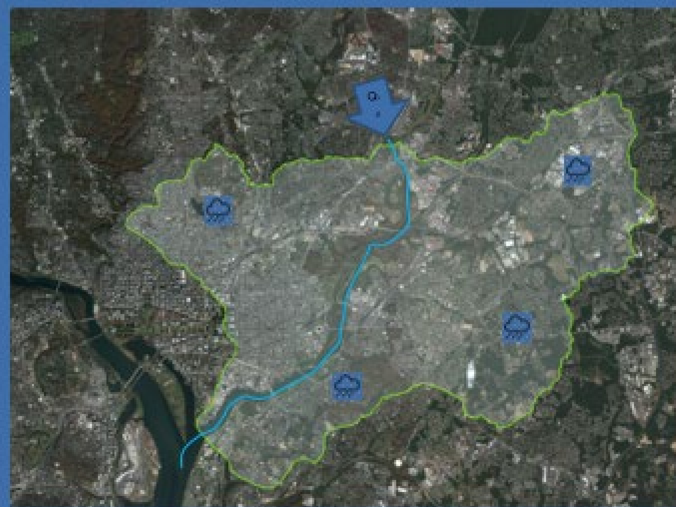
3. Shoreline erosion inside the bay
4. Barrier island dynamics
5. Marsh migration

Inland Hazards

1. Future rainfall (pluvial flooding)
2. Riverine (fluvial flooding)

Inland Hazards Task Elements

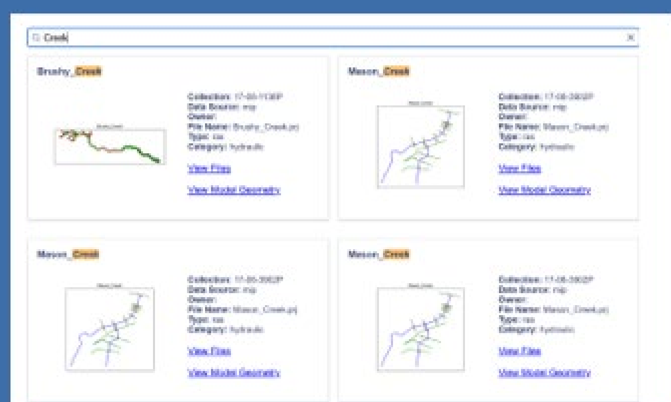
- Objectives
- Approaches
- Constraints
- Decision Support



Inland Hydraulics

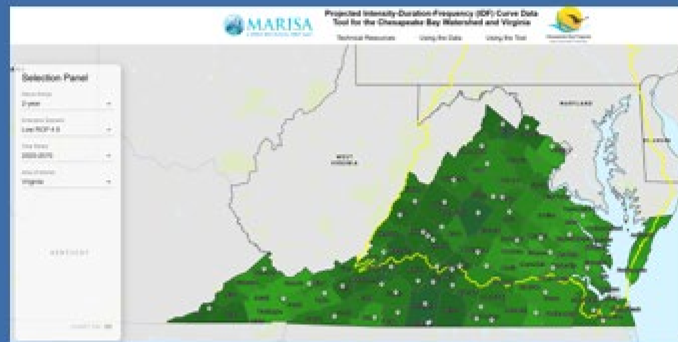
Model Options:

- HEC-RAS 2-D
  - Preferred
  - Model Inventory tools available
- TELEMAC
  - Secondary option
- Alternatives
  - SCHISM
  - Delft3D
  - MIKE
  - ADH



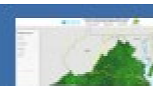
Pluvial Forcing: Hydro-Meteorology

- Atlas 14
  - RCP Options
    - 4.5
    - 8.5
  - Future Conditions
    - 2020-2070
    - 2050-2100
- Stochastic Storm Transposition
  - Experimental approach for creating and using a "Storm Catalog"
  - No Future Conditions capability that we know of



https://midatlantic-idf.rcc-acis.org

Pluvial Event Selection

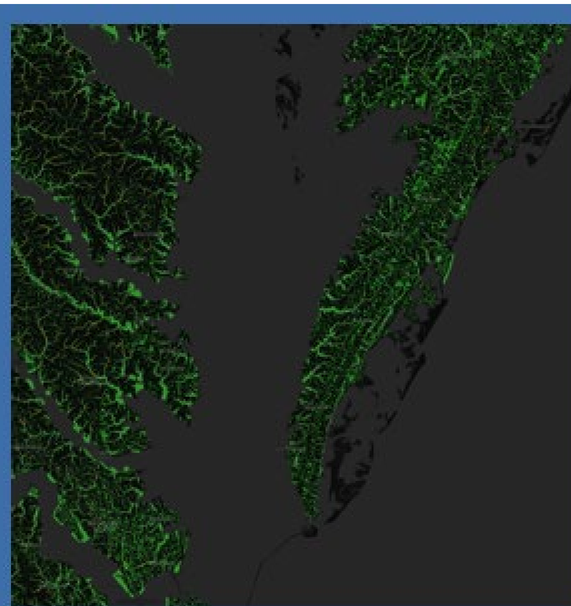


- Which storm durations are most significant for various stakeholders?

Pluvial Modeling

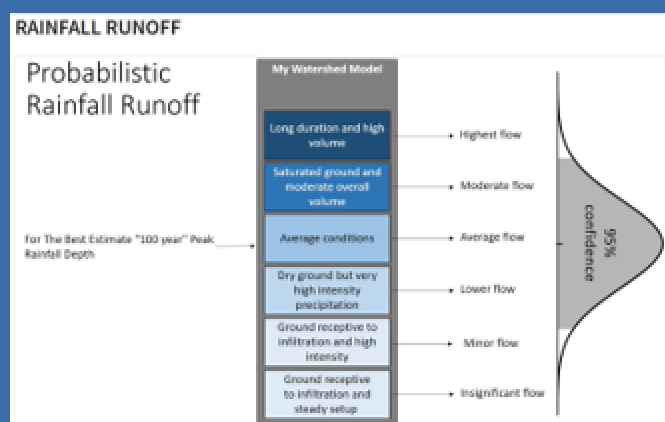
Basin Size Considerations

- HUC 12s (~40 mi^2) generally too large for Pluvial Approaches
- Early work suggests partitioning HUC 12's into sub watersheds from 5-7mi^2
- Sensitivity needed to understand basin-basin interaction



Pluvial Event Selection

- Full Monte Carlo
  - Includes uncertainty and variability
  - Thousands of events
  - Computationally expensive
- Analytical Approach
  - Includes uncertainty and variability
  - Select discrete frequencies
  - Fewer hydraulic results
- Tidal Analysis
  - Boundary condition options
  - MLW, MHW
  - Future conditions



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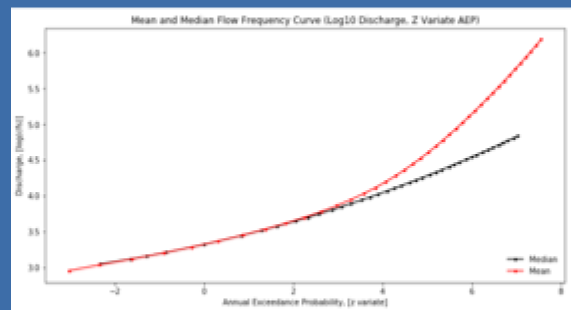
Fluvial Event Selection

- Modeling Framework
  - 1D vs 2D
  - USACE Mean Curve approach
  - Bulletin B vs C
- Tidal Analysis
  - Boundary condition options
  - MLW, MHW
  - Future conditions
- Alignment with Pluvial
  - Frequencies aligned with Pluvial?
  - Model use/reuse?
  - Managing areas of combined pluvial/fluvial risk?



Inland Hydraulics

Considerations

- Level of detail on model geometry
  - Burn culverts into DTM?
  - Bridge inclusion/Detail?
  - Mesh break lines
    - All major roads and railroad lines?
    - Top-of-dam lines?
- Area of Interest Prioritization
  - Emergency evac routes
  - Routes to/from military bases
  - Routes to/from hospitals

Inland Hydraulic Considerations

Requirements

- Just results data?
- Results data + editable models?
- Results data + editable models + applications?
  - Web products
  - Public or govt-only access?
- Delivering intermediary H&H inputs as products ("forcing data")?
- Managing areas of combined pluvial/fluvial risk?

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Pluvial Recommendations

Short Term

- Identify storm durations that provide coverage for the most common types of meteorological systems that cause inland flooding
- Model discrete scenarios using joint probability method (precipitation and soil moisture)
- For future conditions, model the 4.5 scenarios from MARISA
- Conduct sensitivity analysis to identify appropriate basin size and basin-basin interaction
- Impose a minimum standard for drainage area to define model domains
- Impose a maximum standard based on fluvial limits

Long Term

- Incorporate additional durations, uncertainty, and variability in select locations
- For future conditions, model the 8.5 scenarios from MARISA
- Calibrate model parameters based on events
- Inventory models using Model Content Analysis Tools

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Fluvial Recommendations

Short Term

- Establish Drainage Area constraints to guide where fluvial models are needed
- Create a framework for identifying which fluvial sources should be modeled using1D vs 2D methods.
- Evaluate appropriate boundary conditions for tidal and surge events by location
- Model only gaged locations with sufficient period of record
- Use HEC products where possible

Long Term

- Incorporate detailed hydraulic structures data where feasible/reasonable
- Calibrate model parameters based on events
- Inventory models using Model Content Analysis Tools
- Incorporate storm sewer conveyance methods into hydraulic model using approximate methods
- Conduct literature review to identify approaches for applying future conditions to fluvial frequencies

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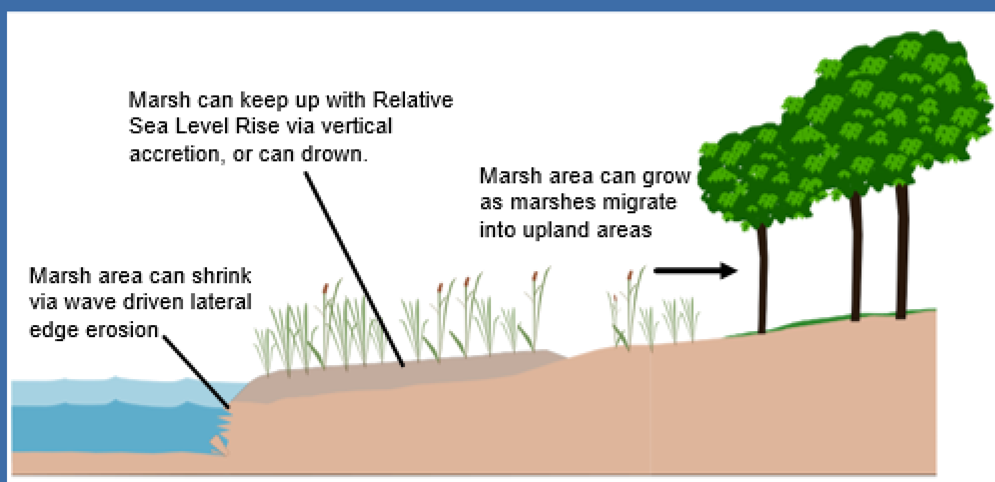
Coastal Hazards

3. Shoreline erosion inside the bay
4. Barrier island dynamics
5. Marsh migration

Importance of considering coastal hazards

- (3) Shoreline erosion inside the bay
  - Critical to determine marsh loss, and local-to-regional impacts to aquatic-to-terrestrial habitat changes
- (4) Barrier island dynamics
  - Barriers regulate water, nutrient, surge, and wave energy exchange with their back bay environments. The retreat of barriers exposes marshes and communities to more erosion, and could trigger non-linear and widespread degradation of marshes
- (5) Marsh migration
  - Critical to determine landscape evolution, and conversion of coastal forests to marshes, with dynamic feedbacks to systemwide evolution, important for land use prediction, and better prediction of flood risk or exposure

Processes that must be modeled for items 3 and 5



After Kirwan et al., 2016

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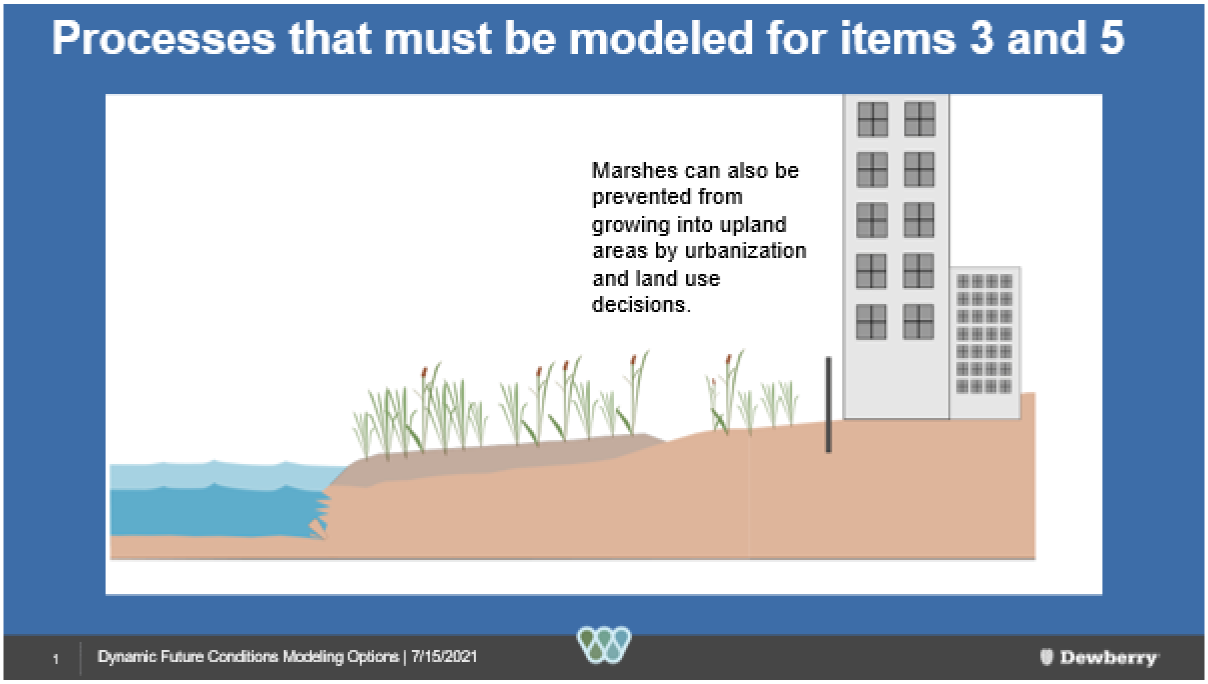
Processes that must be modeled for items 3 and 5
Marshes can also be prevented from growing into upland areas by urbanization and land use decisions.
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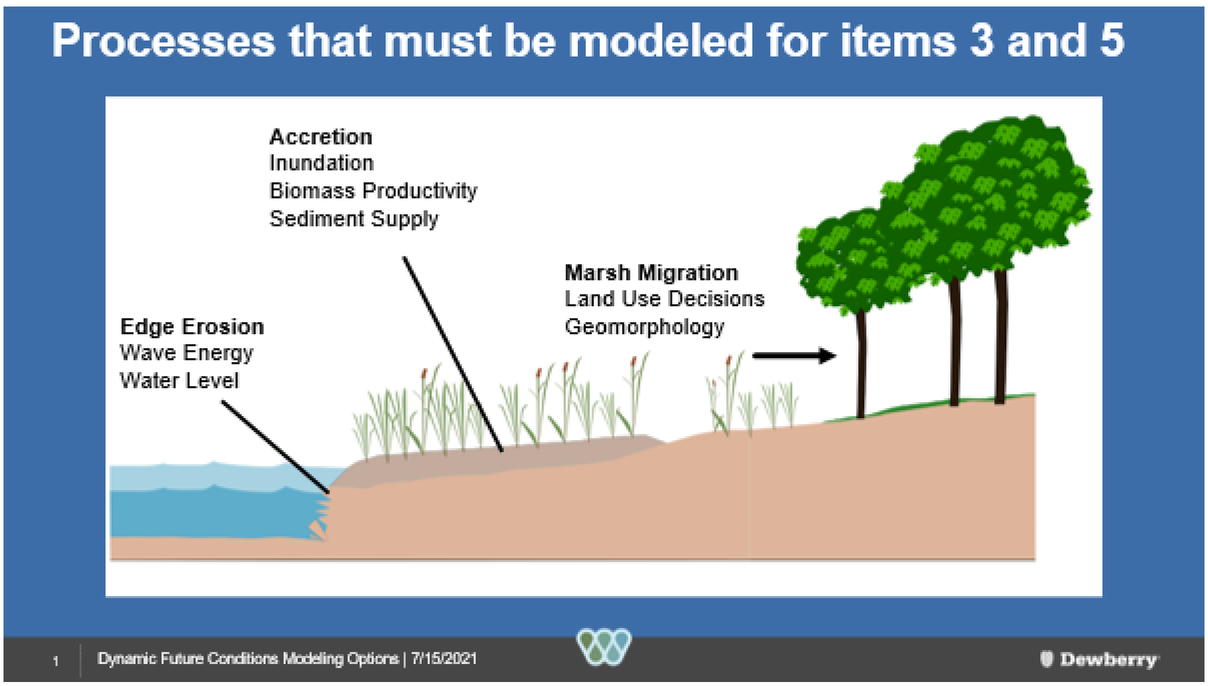
Processes that must be modeled for items 3 and 5
Accretion
Inundation
Biomass Productivity
Sediment Supply
Marsh Migration
Land Use Decisions
Geomorphology
Edge Erosion
Wave Energy
Water Level
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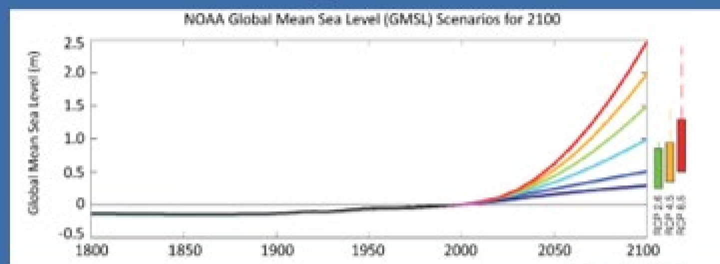
To date, marsh losses have mostly been due to edge erosion

Deaton et al. (2017)

As sea level continues to rise the rate of drowning will increase and accretion will become more important.



Swift et al. (2017)

Marsh Modeling Options

Lower Complexity

- SLAMM (Clough 2016)
- Sea Level Over Proportional Elevation (SLOPE)
- Integrated Compartment Model (ICM)
- NOAA SLR Viewer
- Kirwan and Guntenspergen (2010)
- Mariotti and Canestrelli (2017)

Higher Complexity

- Hydro-MEM (Alizad et al., 2016)
- Tidal Marsh Model (via SCHISM)
- Delft3D with marsh model add-on

Marsh Modeling Options – Lower Complexity

Lower Complexity

- Marsh Vertical Accretion is a function of inundation
- May or may not include edge erosion.
- Will not dynamically model the physics of water, sediment, or waves. Inundation is calculated via tidal datums (MLLW, etc.)
- Generally simple to impose land use projections conditions.

Typical Input Data Requirements

- DEM
- National Wetlands Inventory maps
- Wind Rose
- Accretion calibration constants (preferably from local data)
- Historical edge erosion rates
- Tidal datums

Marsh Modeling Options – Higher Complexity

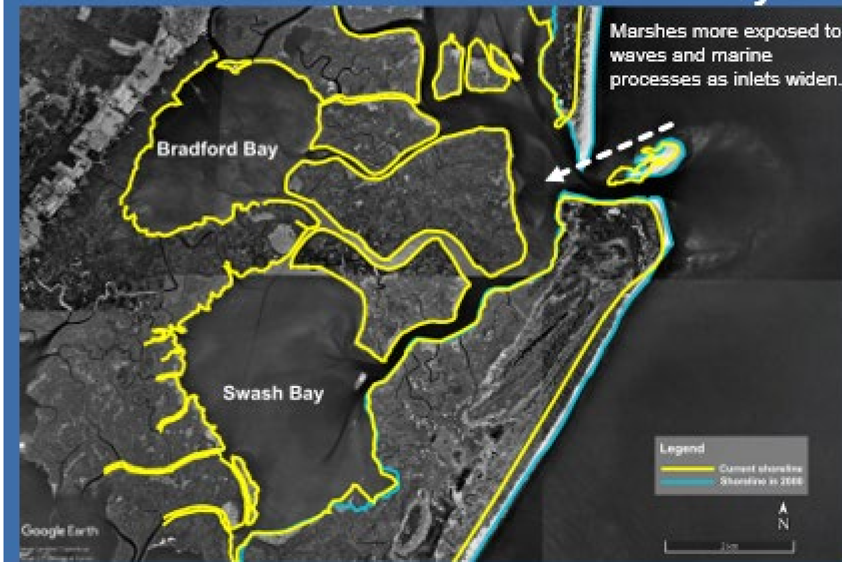
Higher Complexity

- Marsh Vertical Accretion is a function of a cell's duration of inundation, similar in scheme to the lower complexity models. But inundation is calculated via a dynamic run of the ADCIRC model.
- Edge erosion may or may not be included.
- Sediment transport may or may not be included.

Typical Input Data Requirements

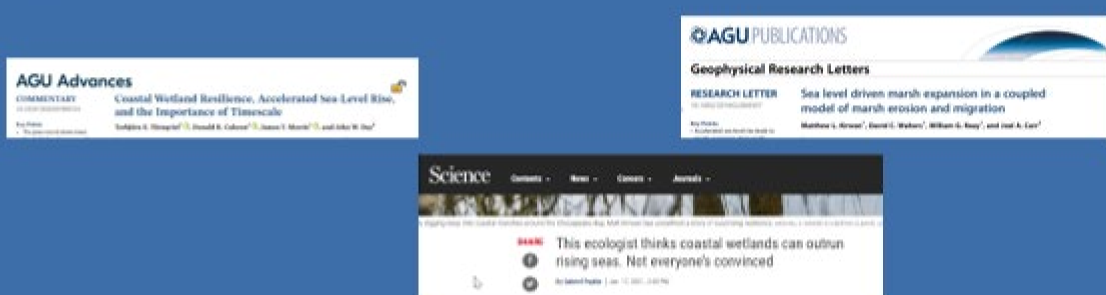
- DEM
- Computational grids
- Water level and wave calibration data
- Accretion and biomass calibration constants (preferably from local data)
- Historical edge erosion data

Marshes and Barrier Islands are Closely Connected



- Wave impacts and water levels in the marshes are determined by the barrier island evolution, and the storage of sand in shoals.
- A modeling framework that predicts marsh evolution must also include tools for barrier islands.

NOTE: The relevant questions are not all settled in the scientific literature. It is important early on to develop a clearly articulated framework that includes uncertainty analysis and a decision processes that adapts to new data.



Recommendations (items 3 and 5)

Short Term

- Assessment of DEM coverage and quality throughout the coastal zone, including literature review of the control points and correction techniques.
- Assessment of accretion and edge erosion calibration data.
- Assessment of existing grid availability.
- Review and data mine from all relevant reports (including those specified in State documents); address data gaps through field data collection
- Lay the foundation for the analysis framework, uncertainty scheme, and collaborative process to include evolving data and opinions.

Long Term

- Preliminary suggestion is to use a full physics hydro model with an added marsh component.
- This could facilitate a probabilistic framework if done careful.
- SCHISM/TMM are candidate models but are not yet developed enough.
- SLAMM is likely too simple.
- Hydro-MEM relies on ADCIRC grid, which is not designed for morphology.
- To meet all the needs of the resiliency effort some combining of existing modeling products will be needed.

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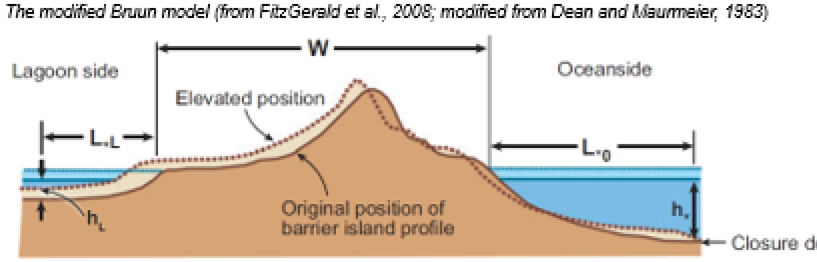
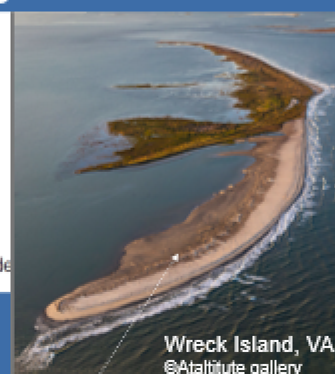
Barrier Island Dynamics modeling

The modified Bruun model (from FitzGerald et al., 2008; modified from Dean and Maurmeier, 1983)





- The Brunn rule (model), developed for beaches originally, and modified for barriers later, doesn't have universal applicability
- Most barriers do not translate entirely in this way, except if they are comprised of sand only
- Barrier evolution is asymmetric and not as depicted here
- Some modified treatment is necessary

The sandy part of Wreck island likely follows Bruun Response, but the rest of the island doesn't

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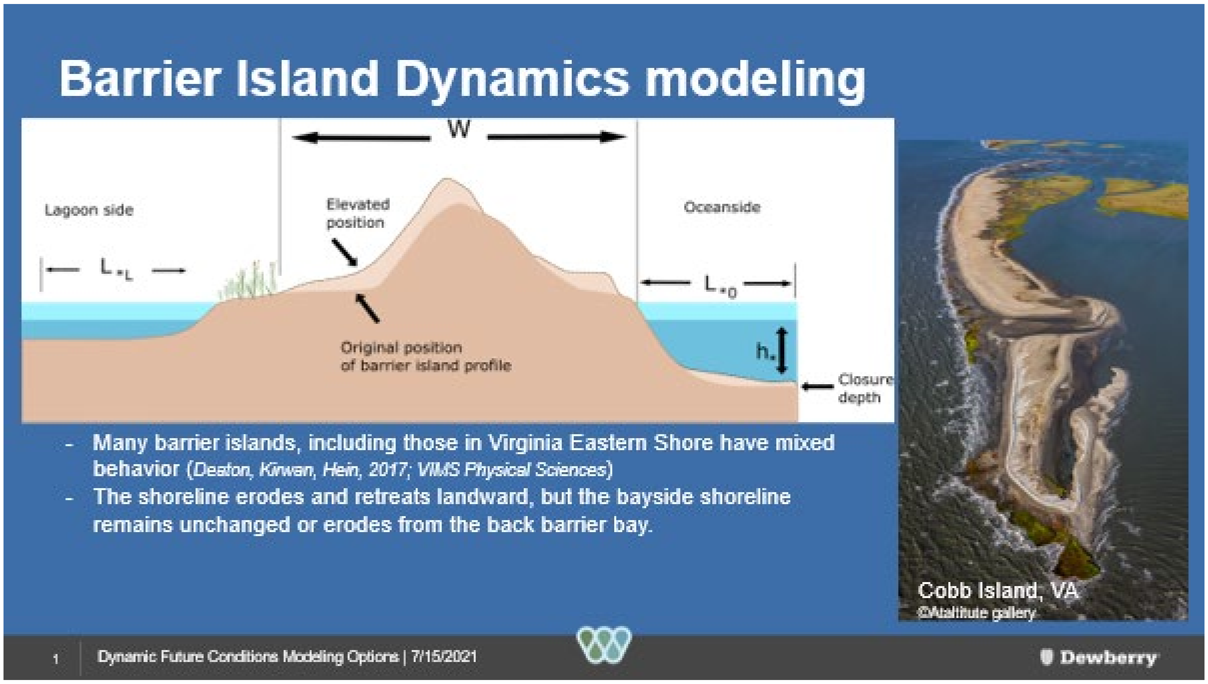
Barrier Island Dynamics modeling
W
Lagoon side
Elevated position
Oceanside
L*L
L*0
Original position of barrier island profile
h*
Closure depth
- Many barrier islands, including those in Virginia Eastern Shore have mixed behavior (Deaton, Kirwan, Hein, 2017; VIMS Physical Sciences)
- The shoreline erodes and retreats landward, but the bayside shoreline remains unchanged or erodes from the back barrier bay.
Cobb Island, VA
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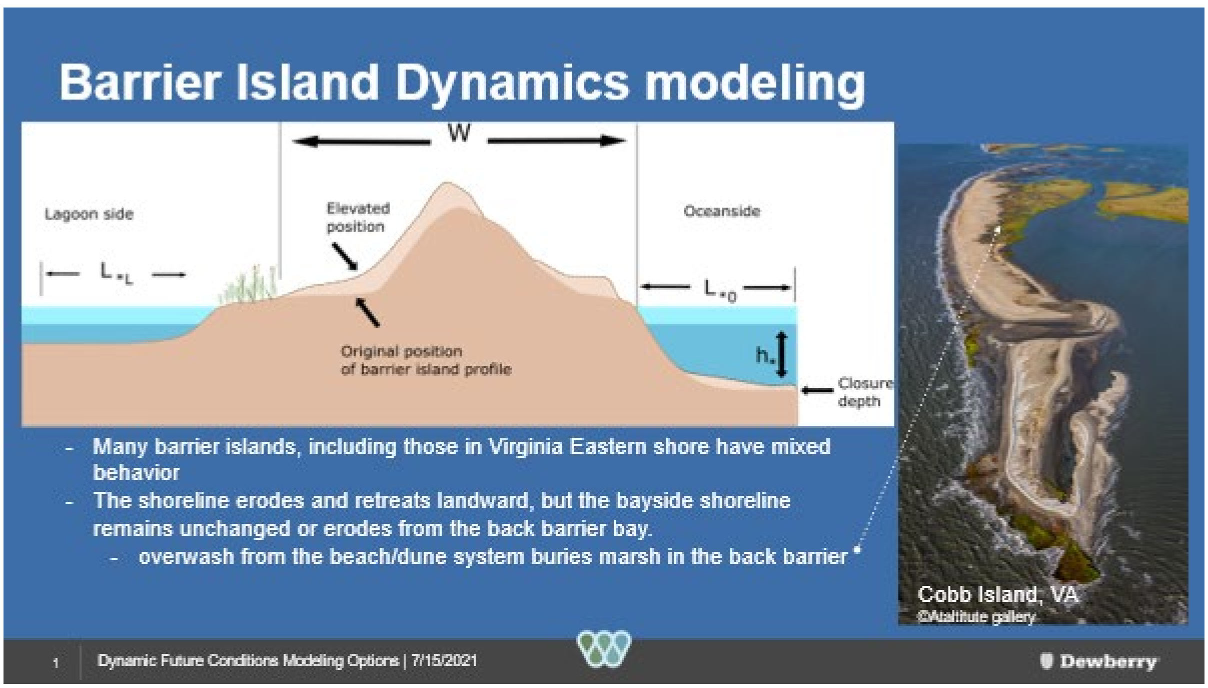
Barrier Island Dynamics modeling
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Original position of barrier island profile
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Closure depth
- Many barrier islands, including those in Virginia Eastern shore have mixed behavior
- The shoreline erodes and retreats landward, but the bayside shoreline remains unchanged or erodes from the back barrier bay.
- overwash from the beach/dune system buries marsh in the back barrier
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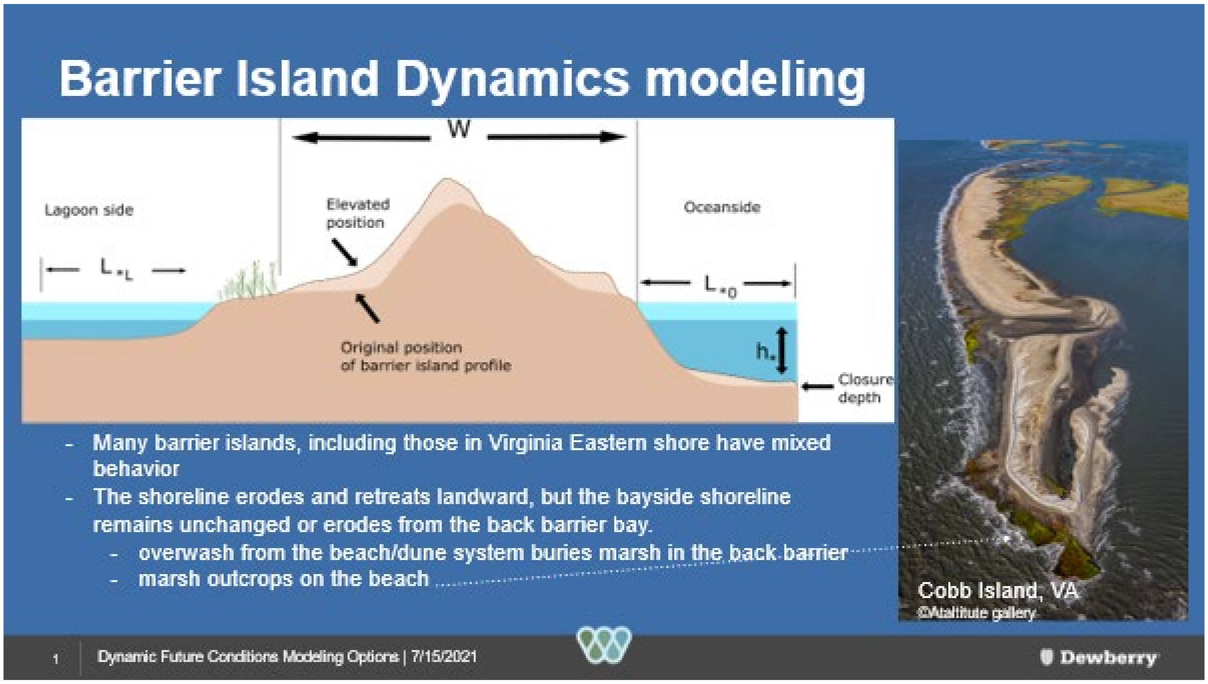

Barrier Island Dynamics modeling
W
Lagoon side
Elevated position
Oceanside
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h_*
Original position of barrier island profile
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- The shoreline erodes and retreats landward, but the bayside shoreline remains unchanged or erodes from the back barrier bay.
  - overwash from the beach/dune system buries marsh in the back barrier
  - marsh outcrops on the beach
Cobb Island, VA
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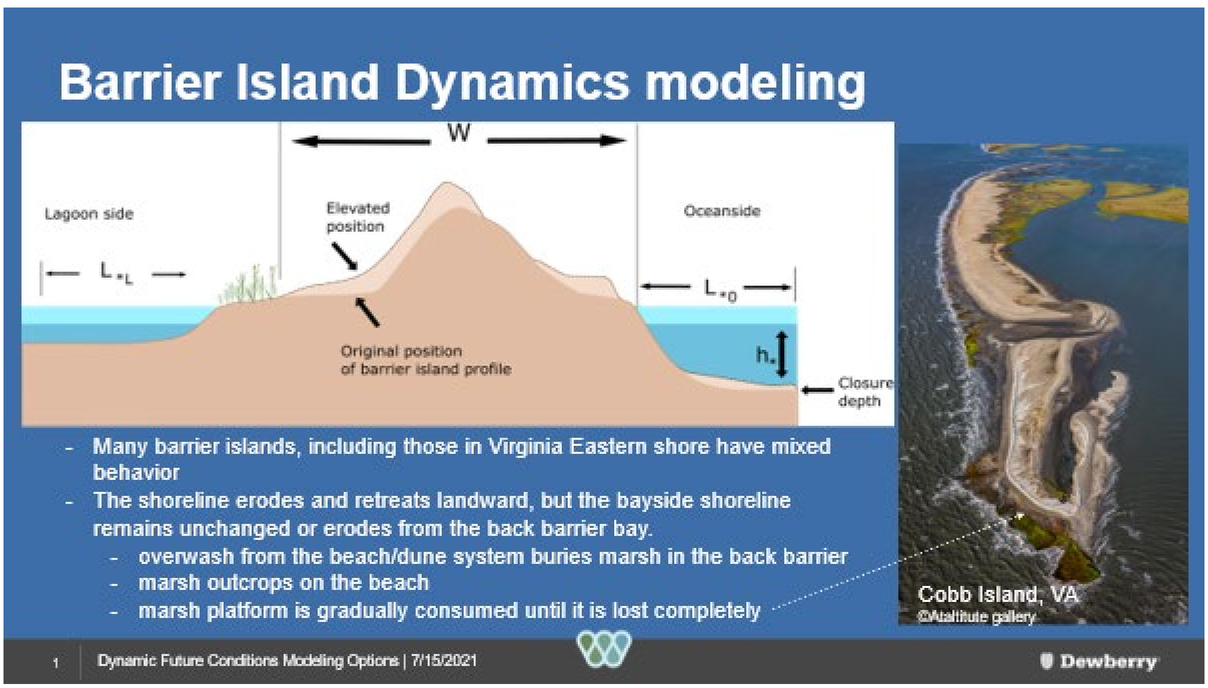

Barrier Island Dynamics modeling
W
Lagoon side
Elevated position
Oceanside
L_{*L}
L_{*0}
h_*
Original position of barrier island profile
Closure depth
- Many barrier islands, including those in Virginia Eastern shore have mixed behavior
- The shoreline erodes and retreats landward, but the bayside shoreline remains unchanged or erodes from the back barrier bay.
  - overwash from the beach/dune system buries marsh in the back barrier
  - marsh outcrops on the beach
  - marsh platform is gradually consumed until it is lost completely
Cobb Island, VA
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Processes associated with modeling for items 4. Barrier islands

- Constructive and Destructive processes
  - Destructive is easier than constructive
- Timescale
  - Interest in capturing specific response to storms?
  - Recovery from storms
  - Overall barrier response
    - Multidecadal or centennial.
- Processes of interest influence model selection

Processes that must be modeled for items 4. Barrier islands

- Water level variation and waves from the ocean fronting barriers
- Sediment transport processes associated with incoming wave energy and currents
  - Both in the alongshore and cross shore dimensions
- Aeolian processes
  - Dune destruction and dune building processes (with related ecogeomorphic interactions)
- Inlet processes (tidal inlets interrupt barrier shorelines, the size of which influences sand bypassing)

Barrier Modeling Options

Lower Complexity

- Shoreline Retreat models (leverage previous and ongoing VIMS Coastal geology)
- Semi-empirical Models (Komar, 1998, Kamphuis, 1990, Cowell et al., 2003a,b)
- Barrier Island and Inlet Environment (BRIE) Model (Nienhuis and Lorenzo-Trueba, 2019)
- Coastal Evolution Model (CEM) (Ashton and Murray, 2001)
- LTA Model (Lorenzo-Trueba and Ashton, 2014; leverage VIMS Shawler et al., 2018)
- GEOMBEST (Stolper et al., 2005; Moore et al., 2010 – LTER efforts, Walters et al., 2014)

Higher Complexity

- XBEACH (Roelvink et al., 2010)
  - Ongoing VIMS efforts (Hein et al., at Cedar Island, VA)
- Delft3D (Lesser et al., 2004)
  - Ongoing efforts at Chincoteague Inlet (Parramore to Ocean city inlet; VIMS/WI Hein/Georgiou)
- CROSMOR (Leo van Rijn)
- UNIBEST-CL or LT (Bosboom et al., 1997)
- C2SHORE (Johnson et al., 2012)

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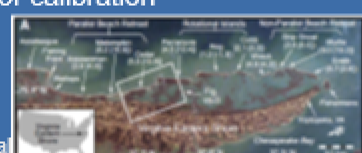
Barrier Modeling Options

Empirical or historical Shoreline Retreat Models

- Simple shoreline evolution model, or line model
- Replies on incident wave energy to estimate longshore sediment transport
- Uses simple mass balance to predict shoreline movement
- Requires calibration to historic shorelines
- Ignores cross-shore processes, subaerial processes, indirectly addresses storm impacts

Input Data Requirements

- DEM or simple bathymetry defining the barrier cross-shore profile
- Wave Rose, or wind rose to calculate waves using wave models
- Historical barrier shoreline retreat rates for calibration



Deaton, Kirwan et al

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Barrier Modeling Options

Barrier Island and Inlet Environment (BRIE) Model

- Very simple and schematized (conceptual basin) line model that accounts for simple sediment bypassing across inlets and sea level rise
- Replies on simple wave energy to estimate longshore sediment transport
- Uses a simple cross shore model (LTA) to estimate shoreface flux
- Uses simple mass balance to predict shoreline movement
- Good for several centennial or millennial timescales
- Has not be applied to non-uniform coastlines or any real applications

Input Data Requirements

- Simple topography and bathymetry, and simple shoreface slope and depth of closure
- Simplistic offshore wave rose
- Sediment median grain diameter

(Nienhuis and Lorentzo-Trueba, 2019)

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Barrier Modeling Options

Coastal Evolution Model (CEM)

- Very simple shoreline configuration line model that accounts for simple alongshore and cross shore sediment transport processes
- Replies on simple wave energy to estimate longshore sediment transport
- Uses a simple cross shore model (LTA) to estimate shoreface flux
- Uses simple mass balance to predict shoreline movement
- Good for several centennial or millennial timescales
- Although it can handle non-uniform coastlines, real world applications are lacking

Input Data Requirements

- Simple bathymetry, and simple shoreface slope and depth of closure
- Simplistic offshore wave rose
- Sediment median grain diameter

Ashton et al., 2001

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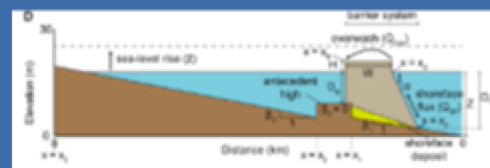
Barrier Modeling Options

Lorenzo-Trueba Ashton (LTA) Model

- Simple cross shore model that accounts only for cross shore processes
- Replies on simple wave energy and sea level rise to estimate sediment transport
- Uses simple mass balance to predict barrier retreat, but only accounts for shoreline movement at one location
- Good for several centennial or millennial timescales
- Model does not resolve alongshore

Input Data Requirements

- Simple bathymetry, and simple shoreface slope and depth of closure
- Simplistic offshore wave rose
- Sediment median grain diameter
- Sea level rise rate



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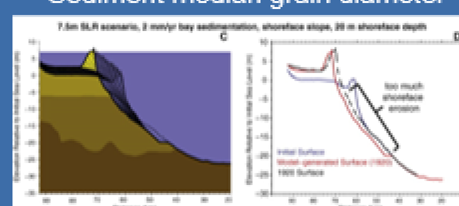
Barrier Modeling Options

GEOMBEST

- Simple cross shore model that translates a profile due to sea level rise and longshore sediment flux gradient
- Replies on sea level rise and geologic framework to predict profile position
- Uses simple mass balance to predict barrier retreat, but only accounts for shoreline movement at one location
- Good for millennial timescales
- Model does not resolve alongshore variation

Input Data Requirements

- Simple bathymetry, and simple geologic framework/stratigraphy
- Sea level record, longshore sediment transport gradient
- Sediment median grain diameter



Moore et al., 2010

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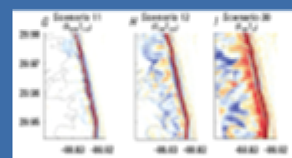
Barrier Modeling Options

XBEACH or Delft3D

- Flexible for real world applications
- Replies on water level and waves to drive multidimensional sediment fluxes
- Reasonable to good shoreline prediction
- Good for several days (XBEACH) to several years or a decade or so (Delft3D) of simulation
- Many applications exist in the literature

Input Data Requirements

- DEM or detailed topography and bathymetry
- Full wave climate, water levels, storm surge (as needed)
- Sediment median grain diameter and other sediment properties including composition and distribution



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Barrier Modeling Options

CROSMOR, C2SHORE, UNIBEST

- Robust cross shore models that are flexible for real world applications
- Replies on water level and offshore waves to drive sediment fluxes
- Accurate shoreline position prediction
- Good for several days to several years or a decade of simulation
- Many applications exist in the literature

Input Data Requirements

- DEM or detailed topography and bathymetry
- Full wave climate, water levels, storm surge (as needed)
- Sediment median grain diameter and other sediment properties including composition and distribution

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Recommendations (item 4)

Short Term

- Assessment of DEM coverage and quality throughout the coastal zone.
- Assessment of good quality and both long-term and short-term database of shoreline surveys
  - *(for use in model development, or calibration; leverage VIMS efforts; Deaton et al., 2017; Raff et al., 2018; Mahina et al, in prep)*
- Suggest using a simple shoreline retreat model or a hybrid semi-empirical-retreat model with sediment mass balance
- Assess response to sea level rise scenarios using a cross shore model (*e.g. Georgiou et al., 2019; Dalyander et al., 2020*)
  - (e.g. LTA; *leverage VIMS Physical Sciences work, e.g. Shawler et al., 2020; Ciarletta et al., 2019; Hein et al., 2019)*

Long Term

- Expand sediment/coring data to broaden existing conditions, sediment size, and possible sediment model parameters, for long-term
  - *(leverage and built on. Fenster et al, 2016 - RMC; Shawler et al., 2020; Hein et al., 2019; VIMS)*
- Consider a tighter coupling between a combination of models (cross shore and alongshore) with more robust sediment balance *(e.g. modified Cowell et al., 2003)*
- Consider developing regional coastal morphology models
  - (Delft3D based; leverage LTER models; and Chincoteague Inlet Modeling Study – VIMS/WI Parramore to Ocean City)
- Develop methods for storm impacts and recovery
  - *(XBEACH; Dune response/recovery; leverage VIMS efforts at Cedar island – Hein et al, and approaches to nourishment/restoration; LTER efforts, Reeves et al., 2021)*

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