Virginia Coastal Resilience Master Plan, Phase II

Pluvial Model Use Case Guide

Virginia Department of Conservation & Recreation

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Acronyms and Abbreviations

1-D: One-dimensional

2-D: Two-dimensional

AAL: Average Annualized Losses

AEP: Annual Exceedance Probability

AWS: Amazon Web Services

CN: Curve Number

CRMP: Coastal Resilience Master Plan

DCR: Virginia Department of Conservation and Recreation

DDF: Depth Damage Function

EAP: Emergency Action Plan

FAST: Flood Assessment Structure Tool

FEMA: Federal Emergency Management Agency

FIRM: Flood Insurance Rate Map

GIS: Geographic Information Systems

HEC-RAS: Hydrologic Engineering Center-River Analysis System

HUC: Hydrologic Unit Code

MARISA: Mid-Atlantic Regional Integrated Sciences and Assessments

NHD: National Hydrographic Dataset

NLCD: National Land Cover Dataset

NOAA: National Oceanic and Atmospheric Administration

RCP: Representative Concentration Pathway

VGIN: Virginia Geographic Information Network

A. Introduction

This Pluvial Model Use Case Guide provides an overview of pluvial (rainfall) flood models developed in 2024 for coastal Virginia and various use cases that highlight valuable applications of the models. The rain-on-grid pluvial flood models and associated data can support informed decision-making for flood resilience planning and implementation. Using this public resource, users can reduce the costs associated with model development and data collection and enhance flood resilience.

The Virginia Department of Conservation (DCR) contracted Dewberry to develop these models to support the development of the Virginia Coastal Resilience Master Plan (CRMP). The models provide pluvial data for the CRMP planning area, which includes approximately 16,600 square miles and 57 counties.

The content within this Guide is intended for a broad audience of stakeholders engaged in flood resilience planning across the Commonwealth of Virginia, including local, regional, and state government, stormwater engineers, public utility managers, floodplain administrators, and state agency program managers.

B. Data Products

B.1 PRODUCT OVERVIEW

The CRMP Phase II pluvial production effort sub-divided coastal Virginia's HUC-12 watersheds into 1,830 smaller sub-catchments. Each sub-catchment has an area ranging between 3 and 10 square miles to make the models more manageable and support uniform precipitation.

These models were created using the United States Army Corps of Engineers (USACE) HEC-RAS version 6.1 software. The scale of this project required the creation and use of a semi-automated cloud-based system to complete about 300,000 simulations of current and future-condition rainfall events in urban, rural, and suburban communities in coastal Virginia.

Each pluvial flood model required foundational input data, which includes topographic data, hydraulic friction values, surface water infiltration values, and precipitation depths. Key model data sources are summarized in Table 1. Complete documentation of data sources and treatment for model application is provided in the technical memorandum.[1]

[1] Dewberry Engineers, Inc. Virginia Coastal Resilience Master Plan, CO-8A: Pluvial Modeling Final Report. June 14, 2024. https://vadcr-frp.s3.amazonaws.com/Pluvial_CRMP/VACRMP_PluvialModelingReport_Final_20240614.pdf.

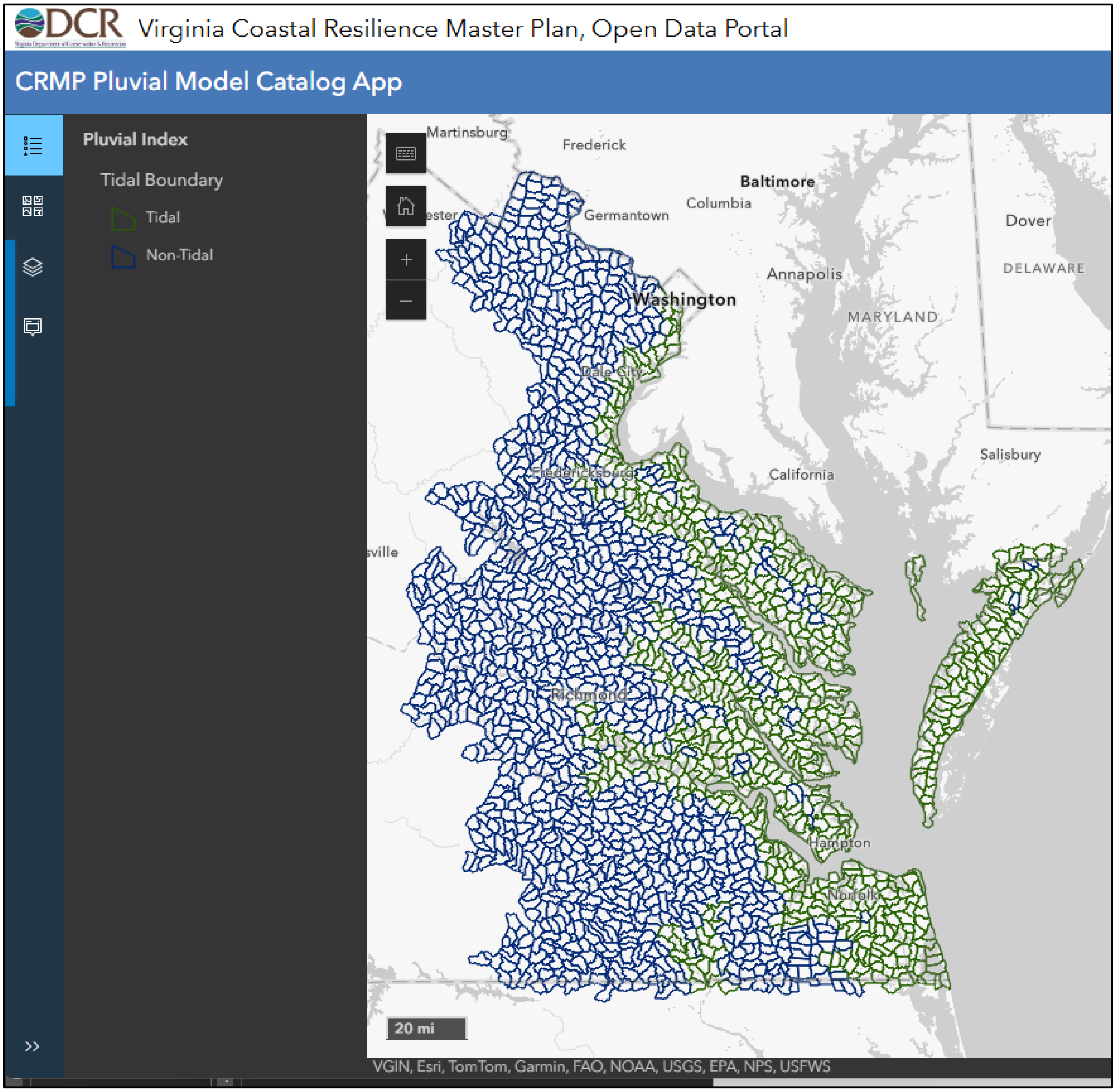

Figure 1: Model sub-basins across CRMP study area[2]

[2] Shown as available in the [DCR CRMP Pluvial Model Catalog App]

Table 1: Essential datasets included in the pluvial models

Dataset	Model Use	Source
Topography	Terrain	CRMP Phase I, updated with more recent publicly available data in the National Elevation Dataset
Land Cover	Friction (Manning's n)	2019 National Land Cover Dataset[3]
Soil Type	Infiltration	U.S Department of Agriculture, Soil Survey Geographic Database (SSURGO)
Land Cover	Infiltration, first priority	2022 Chesapeake Land Use and Land Cover (LULC) Database
	Infiltration, second priority	2016 Virginia State Land Cover Dataset
	Infiltration, third priority	2021 National Land Cover Database

The model simulations include a wide range of precipitation scenarios to cover the current and future conditions due to the projected increase in precipitation intensity-duration-frequency. In contrast to more traditional approaches that rely on volume estimates selected from Atlas 14[4] at selected frequencies, this study instead developed a pre-defined range of volumes using Atlas 14 at the lower end and Atlas 14 adjusted using climate factors from the MARISA[5] study at the upper end for each modeled storm duration (i.e., 2-hour, 6-hour, and 24-hour). The low end of each duration was taken as the lowest 2-year precipitation for current conditions. In contrast, the high end of each duration was taken as the highest extrapolated 500-year precipitation for future conditions when considering the MARISA 90% percentile of Representative Concentration Pathway (RCP) 8.5 in the 2050 to 2100 time period.

[3] The 2019 National Land Cover Dataset was used to develop the friction grid; the friction grid was created prior to the availability of the 2021 dataset.
[4] National Oceanic and Atmospheric Administration. Precipitation Frequency Data Server. Hydrometeorological Design Studies Center. https://hdsc.nws.noaa.gov/pfds/.
[5] Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) Program. Projected Intensity-Duration-Frequency Curve Data Tool for the Chesapeake Bay Watershed and Virginia. https://midatlantic-idf.rcc-acis.org/.

As shown in Table 2 below, each delivered HEC-RAS model contains 63 pluvial plans that reflect the range of precipitation values. If a model included tidal waters, where Mean High Water (MHW) serves as a boundary condition, additional models were generated to account for increasing tailwater conditions for rising sea level projections out to 2100. In these situations, five sets of simulations totaling 315 RAS plans, represent MHW in years 2020, 2040, 2060, 2080, and 2100 according to NOAA's 2017 Intermediate-High Relative Sea Level Rise scenarios, which can be viewed using the USACE Sea Level Tracker.[6]

Table 2: Fixed-interval approach range of precipitation totals

Storm Duration	Starting Rainfall Total (inch)	Ending Rainfall Total (inch)	Depth Interval Between RAS Plans (inch)	Number of RAS Plans
2 hours	1.0	12.0	0.5	23
6 hours	1.0	17.0	1.0	17
24 hours	2.0	24.0	1.0	23
			Total RAS Plans	**63**

B.2 DATA PRODUCTS AND ACCESS

Two groups of products are available: rainfall-interval-based and the scenario-based products used in the Coastal Resilience Master Plan. An overview of each product type and access location is provided below. Additional data products such as flow velocity or flood durations can be produced with the HEC-RAS models to support various use cases; however, these products were not created for this effort.

B.2.i Rainfall Interval-based Products

The specific rainfall interval-based products include the HEC-RAS pluvial models, input data, and depth grid outputs.

Depth Grids: Depth of flooding for each discreet recurrence interval as a raster in TIFF format. The rainfall interval-based depth grids have a ten-foot resolution and do not have a depth threshold applied.

HEC-RAS Pluvial Models: HEC-RAS model packages that include model inputs, RAS plans, and outputs.

B.2.ii Scenario-based Products

The scenario-based products are derivatives of the rainfall interval-based products. Phase II of the CRMP has adopted a planning framework encompassing five scenarios, including present (current conditions) and short-and long-term time horizons with moderate and low-

[6] United States Army Corps of Engineers. Sea Level Analysis Tool. https://climate.sec.usace.army.mil/slat/.

risk tolerance variations. For each scenario, cross-referencing related the rainfall intervals to 2-, 5-, 10-, 25-, 50-, 100-, and 500-year recurrence intervals for each rainfall duration.

Depth Grids: Depth of flooding for each discreet recurrence interval as a raster in TIFF format. A threshold removing any depths less than six inches was applied to the depth grid model outputs. The depth grids represent the maximum flooding depth from the three modeled rainfall durations (2-, 6-, and 24-hr durations).

Storm Duration of Maximum Depth: The rainfall duration (2-, 6-, or 24-hr) associated with the maximum depth of flooding for each rainfall recurrence interval as a raster in TIFF format.

Graduated Flood Extents: A combined flood extent depicting the most frequent rainfall recurrence interval of the rainfall interval that floods the local topography (2-, 5-, 10-, 25-, 50-, 100-, and 500-year recurrence interval pluvial floods) for each scenario.

B.2.iii Access Overview

All data outputs for the project are publicly accessible through DCR's Virginia Coast Resilience Master Plan Open Data Portal. DCR will publish ESRI Map Services for select data outputs. For additional technical support for data access, please email flood.resilience@dcr.virginia.gov.

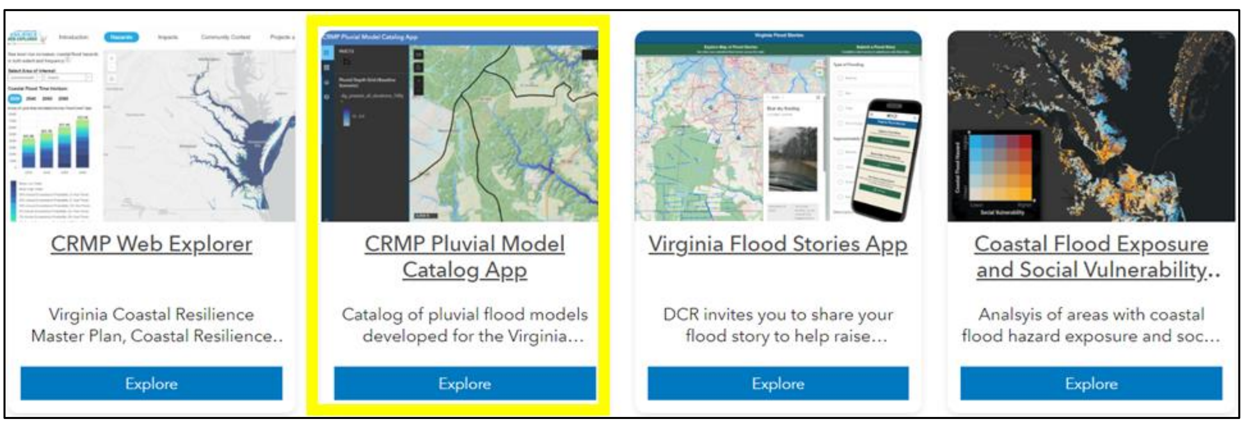

Figure 2: Location of Pluvial Model Catalog App[7]

The rainfall interval-based products are best accessed through DCR's Pluvial Model Catalog App (Figure 2). The CRMP Pluvial Model Catalog Application allows users to search for specific subbasins of interest through an interactive map application. Subbasins can be selected to view and download available models and products.

[7] Available through the DCR Open Data Portal (https://crmp-vdcr.hub.arcgis.com/)

The workflow for the catalog application is demonstrated in Figure 3 and described as follows.

1) Using the STAC catalog, users can see available model basins, and
2) zoom to and select the basin of interest. Where relevant, select the tidal boundary condition of interest.
3) Users can browse the available rainfall simulations by duration and select the desired data for download. The depth grid viewer is accessed at the bottom of the page, and
4) the depth grid viewer allows the user to quickly view and/or download simulation-specific depth grids.

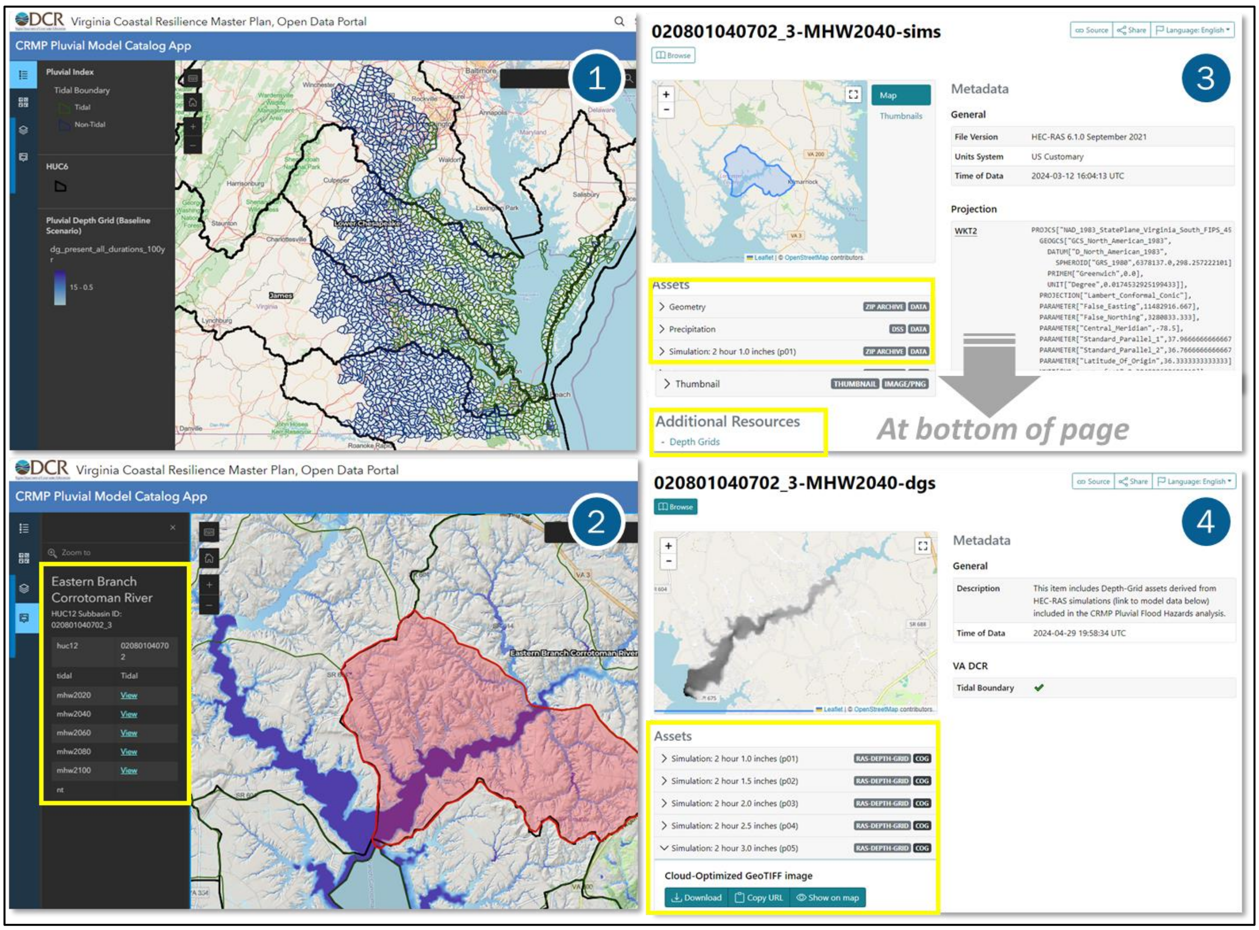

Figure 3: Process for accessing pluvial models and data

The scenario-based products are best accessed through the AWS Open Data Portal S3 Bucket (Figure 4). Additional details on the folder structures are provided in ReadMe.txt files within the folders.

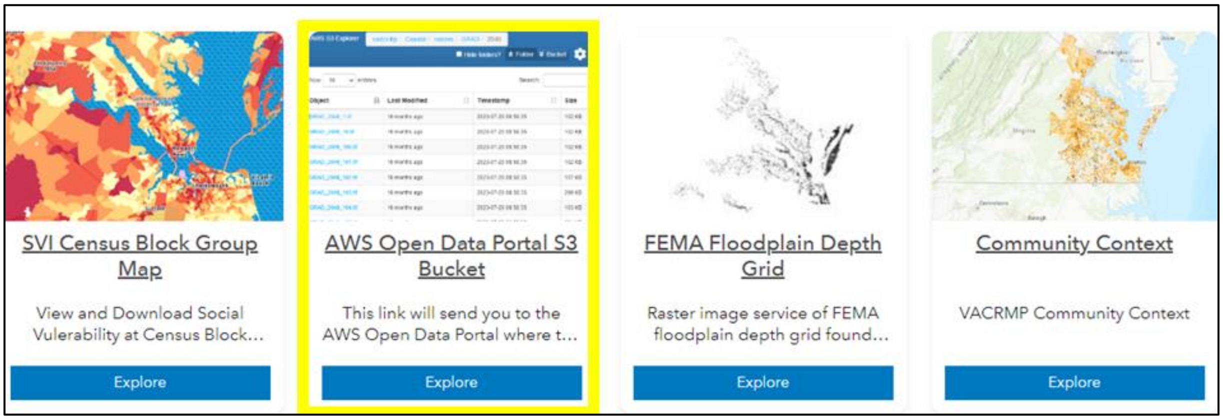

Figure 4: Location of AWS Open Data Portal S3 Bucket[8]

C. Model Benefits and Limitations

The pluvial models are an effective tool for understanding inundation from rainfall events in the Commonwealth under various storm scenarios. However, like any model, they are developed for a specific purpose and are best used within those constraints. Users can benefit from the models by understanding their benefits and limitations.

C.1 PRODUCT BENEFITS

The CRMP pluvial models provide users with complete, ready-to-use models that contain all the data necessary for running rain-on-grid simulations without the need to collect, generate, and process data from scratch. In addition, HEC-RAS software provides various options to display results graphically—primarily flow depth, velocity, and direction—allowing users to present results tailored to a specific audience, including individuals unfamiliar with flood modeling. Users can also export results to GIS and create maps for various planning purposes. Section D. Use Cases highlights examples of these benefits when using the models.

C.1.i Wide Range of Return Period Storms

The rainfall depths associated with the models cover a wide range of return period storms. Using rainfall not tied to a specific return period makes model results more accessible and easier to understand. Further, they are more practical for analytical purposes such as emergency planning. For example, knowing that 7 inches of rain in 24 hours may flood a facility or overtop a specific road is a more intuitive method for describing the simulation inputs rather than stating that flooding may result from a 25-year, 12-hour storm event. As a result, the models make it easier for users to assess and present results to a broader audience.

[8] Available through the DCR Open Data Portal (https://crmp-vdcr.hub.arcgis.com/)

C.1.ii Simulation of Extreme Rainfall Events

HEC-RAS 2-D overland flow models are well-suited for simulating extreme rainfall events. Storm sewer systems are typically designed for 10-year rainfall depths, while roadway culverts may be designed to accommodate the 50-year rainfall depth, depending on the road classification. However, during extreme events such as the 100- or 500-year storms, pipe systems and culverts become overwhelmed and cannot convey the runoff generated. Rain-on-grid models excel at simulating flood conditions during such events (i.e., when overland flow bypasses stormwater inlets and overtops roadways). The pluvial models enable users to quickly generate, compare, and present results for extreme rainfall depths with little or no modifications.

C.1.iii Results for Small Rainfall Events

The models provide users with valuable information for less severe rainfall events without making modifications or edits to the model. Blocked stormwater pipes or culverts often contribute to recurrent or nuisance flooding in urban areas, and the models can help assess and visualize these situations. For example, results from models using rainfall depths that approximate 2- or 5-year storms can be used to evaluate flood potential in specific areas if maintenance is neglected or if the inlets or pipes become blocked. Flood depths and inundation areas can also be assessed and mapped for low-lying areas within a watershed where stormwater infrastructure may not exist, such as greenspaces or rural areas.

C.1.iv Map Tidal Flooding

Users can readily map tidal flooding for various water surface elevations by editing the boundary condition and changing the elevation used for the tidal tailwater. The models will then show the tidal inundation at the start of the simulation. Users can readily create and compare inundation maps for future sea-level rise scenarios in HEC-RAS or export the results for use in GIS mapping.

C.1.v Model Refinements for Further Analysis

The models also provide an excellent base or starting point for more detailed modeling in a watershed. As described by FEMA in its *HEC-RAS Recommended Practices*, "Given the upgradable nature of 2-D watershed model meshes, it is possible to use them as the base for a library of national flood models to provide probabilistic flood risk information, capture future conditions, forecast inundation, and support other example use cases."[9] These analyses can be supported by leveraging the existing library of pluvial base data and models.

Users familiar with HEC-RAS can readily edit and refine portions of the model, such as the terrain or the 2-D computational mesh for a specific area of interest, without requiring refinements to the entire model. Typical one-dimensional HEC-RAS features such as culverts, weirs, and lateral and in-line structures can also be added to specific locations in the model. The terrain modification tools in HEC-RAS allow users to add roadway

[9] FEMA. (2021). 2-D Watershed Modeling in HEC-RAS Recommended Practices. https://webapps.usgs.gov/infrm/pubs/211203_HUC8_2D_Watershed_Modeling_Recommendations.pdf.

embankments, levees, proposed grading, or channels to the models to evaluate potential impacts or benefits such structures may provide.

C.2 PRODUCT LIMITATIONS

Although the models are well suited for simulating and generating inundation maps for extreme rainfall events, users must understand their limitations to apply them appropriately.

C.2.i Lack of 1-D Model Elements

The models are strictly rain-on-grid and do not contain the typical 1-D HEC-RAS model elements such as river reaches, cross sections, and structure geometries (i.e., bridges and culverts) that are found in FEMA's 1-D HEC-RAS models used for regulatory floodplain mapping. While water surface elevations and profiles can be compared to those from 1-D FEMA models or elevations on Flood Insurance Rate Maps (FIRMs), such comparisons require an understanding and appreciation of the differences in methodology and assumptions.

C.2.ii Applicable Scale

The models provide high-level results showing inundation and flooding over a large watershed area. The results are not recommended to be interpreted at a specific location (e.g., parcel level) scale. However, with refinements by qualified staff, the models may be appropriate for more site-specific purposes, such as informing preliminary alternatives analysis.

Virginia's HUC-12 watersheds were broken into smaller sub-catchments to make the models more manageable and to support the use of uniform precipitation applied across the domains. The modeled areas range between 3 and 10 square miles on average. Several model limitations are related to the resolution of the input data necessary to keep the models manageable.

The terrain data is at a 10-foot by 10-foot resolution to optimize file size storage requirements. While this topographic resolution can accurately model larger conveyances, the 10 ft DEM grid is too coarse to pick up small terrain features such as curbs and gutters and may not accurately depict small swales and ditches. Similarly, the RAS 2D computational mesh grid size is approximately 100 feet by 100 feet. This size is appropriate for large-scale runoff modeling and reduces model run times. However a mesh cell may span terrain features and allow water to cross small berms, levees, or minor roadway embankments that, in reality, would impede flow. Further discussion is provided in Section D.4 Model Modifications to address these limitations for localized use cases.

C.2.iii Stormwater Infrastructure Considerations

Users should be careful when analyzing and presenting results for small storm events because the current version of HEC-RAS does not incorporate underground pipe networks and drainage systems (although it does support modeling large culverts and bridge crossings). Model results for rainfall depths less than typical storm sewer design standards may show flooding in areas where stormwater pipes would likely have the capacity to convey the runoff.

Likewise, the models do not contain all roadway culverts and may show flooding for minor storms upstream of roadway embankments. Identifying the locations of culverts within a large watershed can be challenging. Therefore, utilizing external culvert datasets (e.g., sourced from VDOT) in addition to high-resolution imagery and terrain data is recommended. Modifications in the form of burn lines through embankments were made at many selected locations to simulate passage of flows by larger culverts from upstream to downstream without getting artificially trapped.

This approach is common practice with rain-on-grid modeling. Still, it can mask upstream flooding from small storm events caused by undersized culverts. Where culvert information is available, users can add culverts, add burn lines, or modify existing burn line geometry to improve results in the area of interest.

C.2.iv Influence of Upstream Inflows

The models are stand-alone and do not include upstream inflows (basin transfer) from other watersheds. They are optimal for headwater streams and creeks, where the entire drainage area is contained within a single rain-on-grid model. Users should be aware of the relative locations of the modeled sub-catchments within the larger HUC-12 watershed. Adjacent watershed models can be run, and the runoff hydrographs for an upstream area can be included as a boundary condition in a downstream model.

While this is a straightforward solution when only one upstream model is involved, including flows from multiple models can be challenging for several reasons, such as the timing of peak flows along the waterway. Where stream gauge information is available, flows from large streams and rivers can be added to the models as an inflow boundary condition.

C.2.v File Sizes

Model file sizes are large, and while users may easily edit and refine the models, those refinements can increase the file sizes significantly. Refining the size of the 2-D mesh requires an appropriate reduction in the model time step. When first downloaded, model run times are typically a few minutes (for example, with a 10-second timestep). However, run times can substantially increase to several hours depending on the extent of refinements, minimum cell sizes, and the timesteps used.

D. Use Cases

This section describes nine examples of using the pluvial models for stormwater management, regional resilience planning, emergency management, and public safety. The section also describes four examples of model modifications. DCR used feedback from stakeholders across the Commonwealth to inform the use cases included in this Guide. Stakeholders attended a series of virtual workshops in summer 2024 to discuss the new models and how they could be most helpful.

Table 3: Summary of use cases

Category	Use Case	Requires Model Modification	Use Case Complexity	Related Datasets
Stormwater Management	Pre and Post Development Hydrology	Yes	Medium	LandCover
	Overland Flow Relief	Yes	Medium to High	Terrain
	Alternatives Identification	Yes	Medium to High	Terrain / LandCover
Regional Resilience Planning	Pluvial Flood Exposure Assessment	No	Low to Medium	Asset Data
	Pluvial Flood Loss Estimations	No	High	Building Datasets, Depth Damage Functions
	Compound Flooding/ Tidal Boundaries	Depends	Low	Forcing
Emergency Management/ Public Safety	Evaluation of Hazards By Potential Loss of Life	No	Medium	Multiple
	Changing Design Storms	Yes	Low	Forcing
	Dam Failure Scenarios	Depends	Medium to High	Multiple

D.1 STORMWATER MANAGEMENT

The models may be used in various stormwater management applications, such as analyzing differences in pre- and post-development hydrology, overland flow, and alternatives identification for stormwater management.

D.1.i Pre- and Post-Development Hydrology

As developed for the CRMP, the rain-on-grid pluvial models allow you to calculate peak runoff and the timing of overland flow across the site. This data helps design stormwater management systems, ensuring that detention basins or other solutions are sized appropriately for managing runoff during design storms.

An example of a hydrologic analysis that can be performed is to modify the infiltration layer used in the models to reflect planned changes to the landscape. Users can readily drawing infiltration “calibration region” polygons in RAS Mapper for specific areas of interest. Existing GIS shapefiles can also be imported and used for the calibration regions. The model will apply user-entered override values instead of the base layer parameters within the calibration polygons. In this way, users can simulate changes in land cover or imperviousness and compare the resulting runoff between scenarios at specific locations downstream.

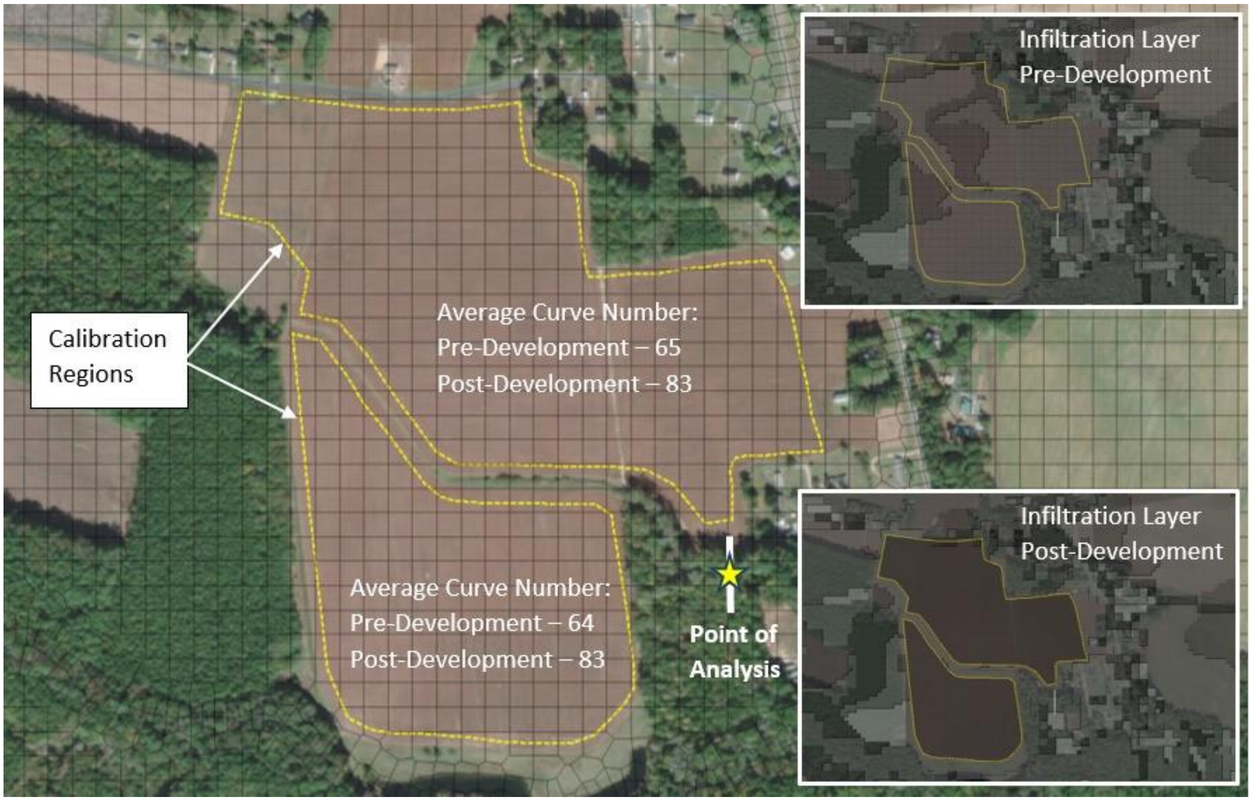

Figure 5: Comparison of peak runoff values under simulated conditions

Figure 5 shows an example hydrologic analysis comparing peak runoff values in a channel before and after making curve number modifications to the model's infiltration layer. In the example, approximately 86 acres of agricultural field—the "pre-development" condition—are assumed to be converted to a single-family residential development, with lots averaging one-quarter acre. The two agricultural fields are divided by a small channel, and the analysis point was located along this channel just downstream from the assumed development.

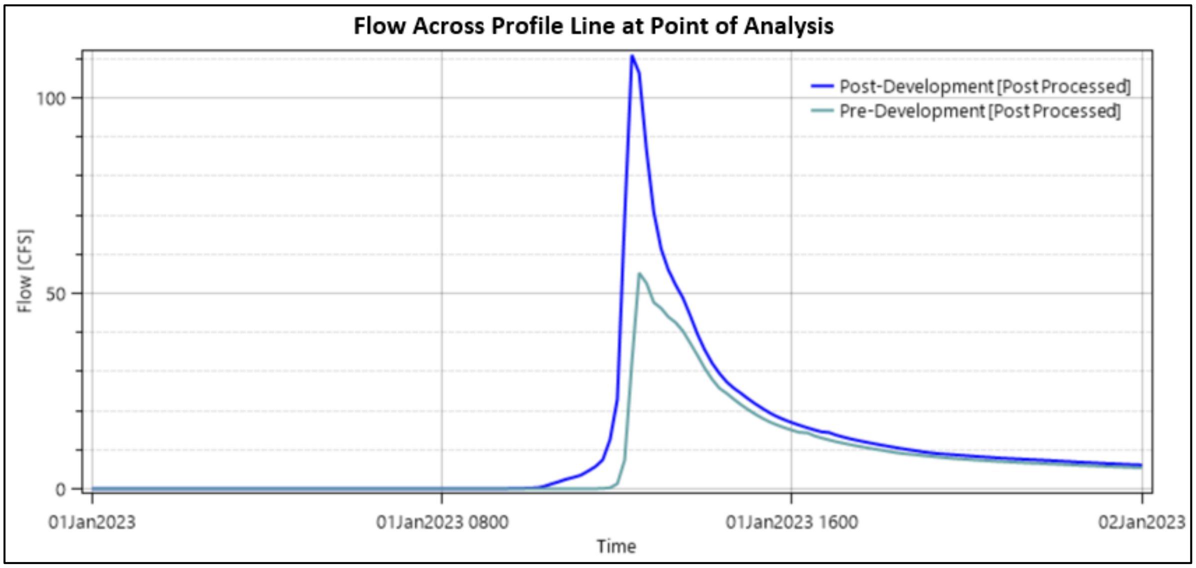

Figure 6: Differences in peak flow for pre- and post-development scenarios

Two calibration regions were drawn around the agricultural fields, and the table of infiltration parameters was edited by adding override values for each of the two calibration regions. The average curve numbers for the calibration areas in the original pre-development scenario were 65 and 64 for the north and south calibration regions, respectively. A post-development curve number of 83 was used as the override value for both calibration areas, assuming approximately 38% imperviousness and quarter-acre residential lots. The differences in the peak flow for the two scenarios taken at a profile line drawn across the channel at the point of interest can be seen in Figure 6. Manning's n values can be modified similarly to account for seasonal changes in vegetation along a channel or future development.

D.1.ii Overland Flow Relief

Rain-on-grid pluvial simulations help identify and model overland flow paths across urban or rural landscapes. These are crucial in stormwater planning to ensure that excess runoff can be directed through appropriate relief pathways to help prevent flooding. Engineers can simulate how water will move across the terrain in various rainfall events, helping design drainage systems to manage extreme weather events.

Figure 7 and 8 show an area that is subject to flooding due to a lack of overland flow relief and the subsequent reduction in flooding by modifying the model to simulate construction of a dry swale.

Figure 7 shows a low area in the topography where water enters an existing drainage system and fills up during the model simulation. Model results for a storm producing approximately 4 inches of rain in 12 hours show flooding around several structures due to high ground and the lack of an overland relief flow path. Regrading the open green space between the low area and the outfall would provide overland relief before structural flooding occurs.

Figure 8 shows the reduction in flooding provided by an overland relief flow channel. After refining the mesh, a channel for overland flow was added to the terrain.

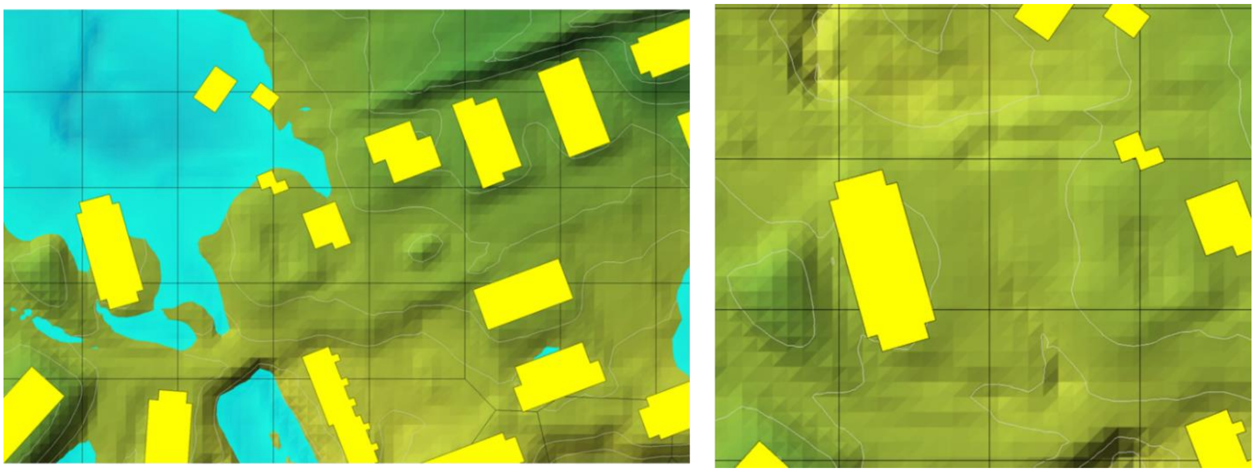

Figure 7: Flooding at a location due to lack of overland flood relief

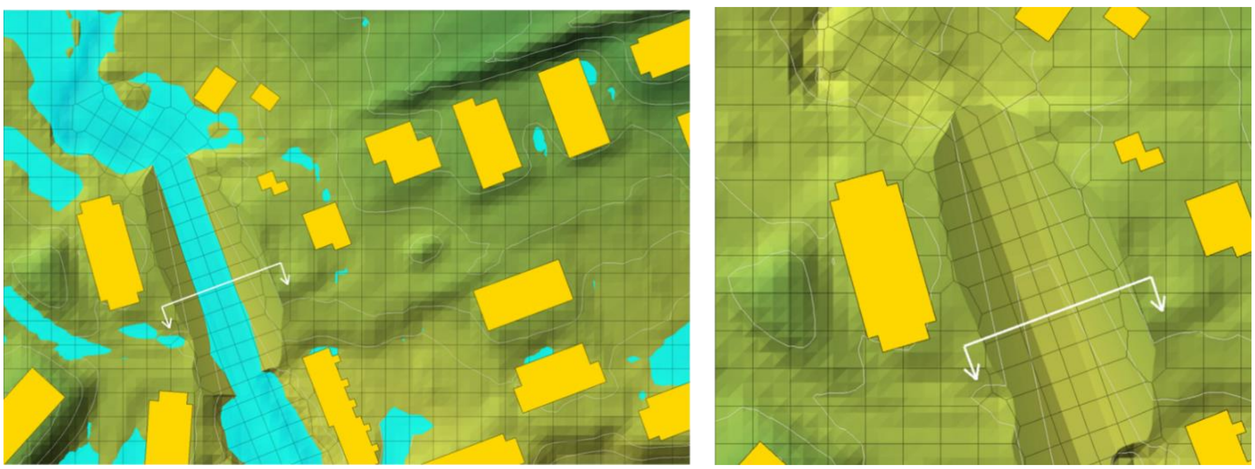

Figure 8: Flood water conveyance via a simulated relief flow channel

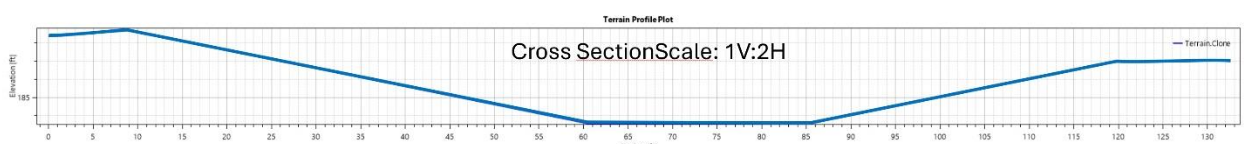

Figure 9: Cross-section depicting the grading of the overflow relief channel

The tools in RAS Mapper allow users to modify channel geometries, including defining various bottom widths, side slopes, and inverts. Users can also see how channel grading fits into the terrain and the flood reductions provided by various channel layouts. In this example, a trapezoidal channel representing a grass swale was modeled with a bottom width of 25 feet and side slopes equal to 10H:1V, intending to provide overland relief when needed without altering the usability of the green space.

For more details on model modifications, including terrain modifications like the relief channel shown in Figure 9, see Section D.4.

D.1.iii Alternatives Identification

The models can highlight areas where surface water exceeds natural or engineered drainage capacities. Such applications can help determine which areas need intervention (e.g., additional culverts, berms, or storage ponds) and serve as a baseline to compare alternatives.

After running a baseline simulation, alternatives such as detention ponds or modifications to the terrain (e.g., regrading or levees) can be simulated. Each alternative's impact on reducing overland flow or mitigating flooding can be assessed to determine the most effective solution. Figure 10 and 11 show an example of using one of the models to support an alternatives analysis that involves a floodplain modification intended to reduce riverine flooding of a structure.

In this example, upstream development and climate change have increased the flood risk for a historic structure located along the edge of a large stream, and nuisance flooding on the parcel occurs when rainfall depths exceed a 10-year return period. Physically moving the structure is a very costly option, and stakeholders would like to know if a floodwall can be constructed that will protect the structure for the 100-year event, accounting for future increases in rainfall, and what the approximate cost would be to help them take the next steps to protect it. Figure 10 shows the inundation extent for the 100-year rainfall plus an additional 20% to account for future increases due to climate change.

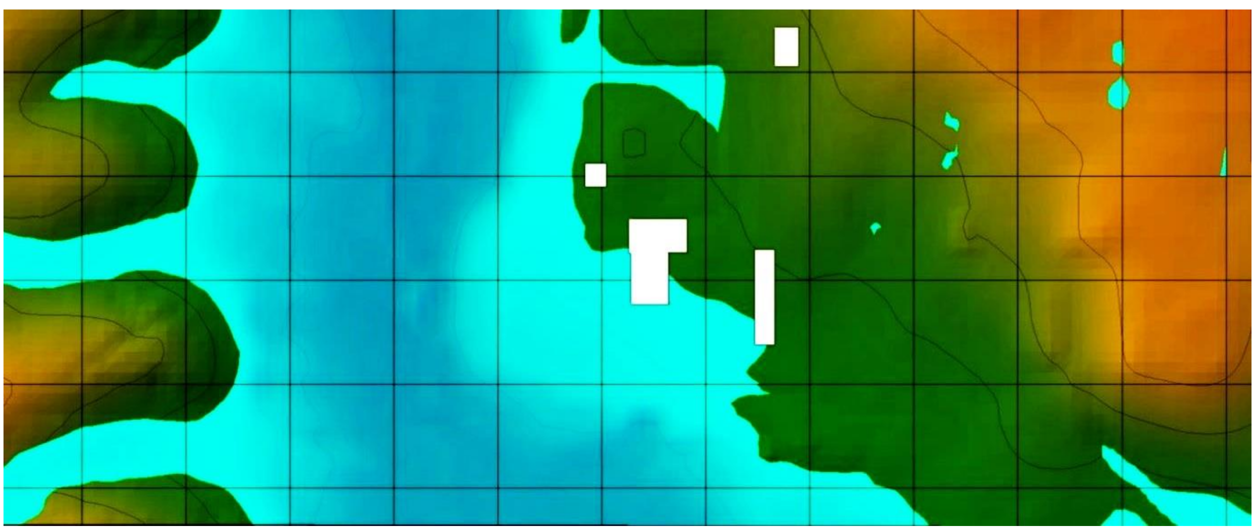

Figure 10: Inundation extent, existing conditions

Figure 11 shows the results using the same rainfall after adding a berm to the terrain using the tools in RAS Mapper and refining the mesh. A breakline was also added along the berm to model the change in the terrain.

Figure 11: Inundation extent with a berm added to the terrain.

The refined model shows that a berm approximately 850 long and approximately 4 feet high will protect from a 100-year storm accounting for climate change while providing approximately 1.5 feet of freeboard. Depending on location, additional controls, such as pumps or drains with flap gates, may be needed in addition to the berm, but such controls were not included in this example. With that information, planning level cost estimates can be generated for various berm options (earthen, steel sheet pile, etc.) and weighed against the cost of physically moving the structure.

D.2 REGIONAL RESILIENCE PLANNING

A critical step in regional resilience planning is understanding what locations and assets may be at risk and what economic losses could occur from a flood event. The models can be used to perform both analyses.

D.2.i Pluvial Flooding Exposure Assessments

The pluvial depth grid data can show exposure to pluvial flooding with varying levels of detail and effort. Users can retrieve a region-wide depth grid mosaic from the AWS Open Data Portal S3 bucket on the DCR Open Data Portal.[10]

The pluvial raster data can be overlayed on top of a focus area to show the extent of flooding, aid initial planning efforts, and recognize the threat of pluvial flooding. For example, in Figure 12 on the next page, the City of Newport News has the 1% annual chance present-day pluvial data overlayed on top of the city to show the extent of flooding.

To evaluate the potential risk of individual assets, a GIS inventory of features such as buildings, roads, or critical assets can be analyzed against the pluvial depth data to determine asset exposure and depths. GIS geoprocessing tools (e.g., “Zonal Statistics as Table” in ArcGIS) can be used to calculate both the area exposed and maximum or average

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[10] Department of Conservation and Recreation. Virginia Coastal Resilience Master Plan Open Data Portal. https://crmp-vdcr.hub.arcgis.com/.

depth of flooding for a polygon based asset inventory. For a point-based asset inventory, similar geoprocessing tools can be leveraged such as "Extract Multi Value to Points" to sample raster depth values at each asset's point location. Assets that have exposure can then be isolated and a hotspot analysis tool could be used to highlight the areas with the greatest concentration of flood risk exposed assets.

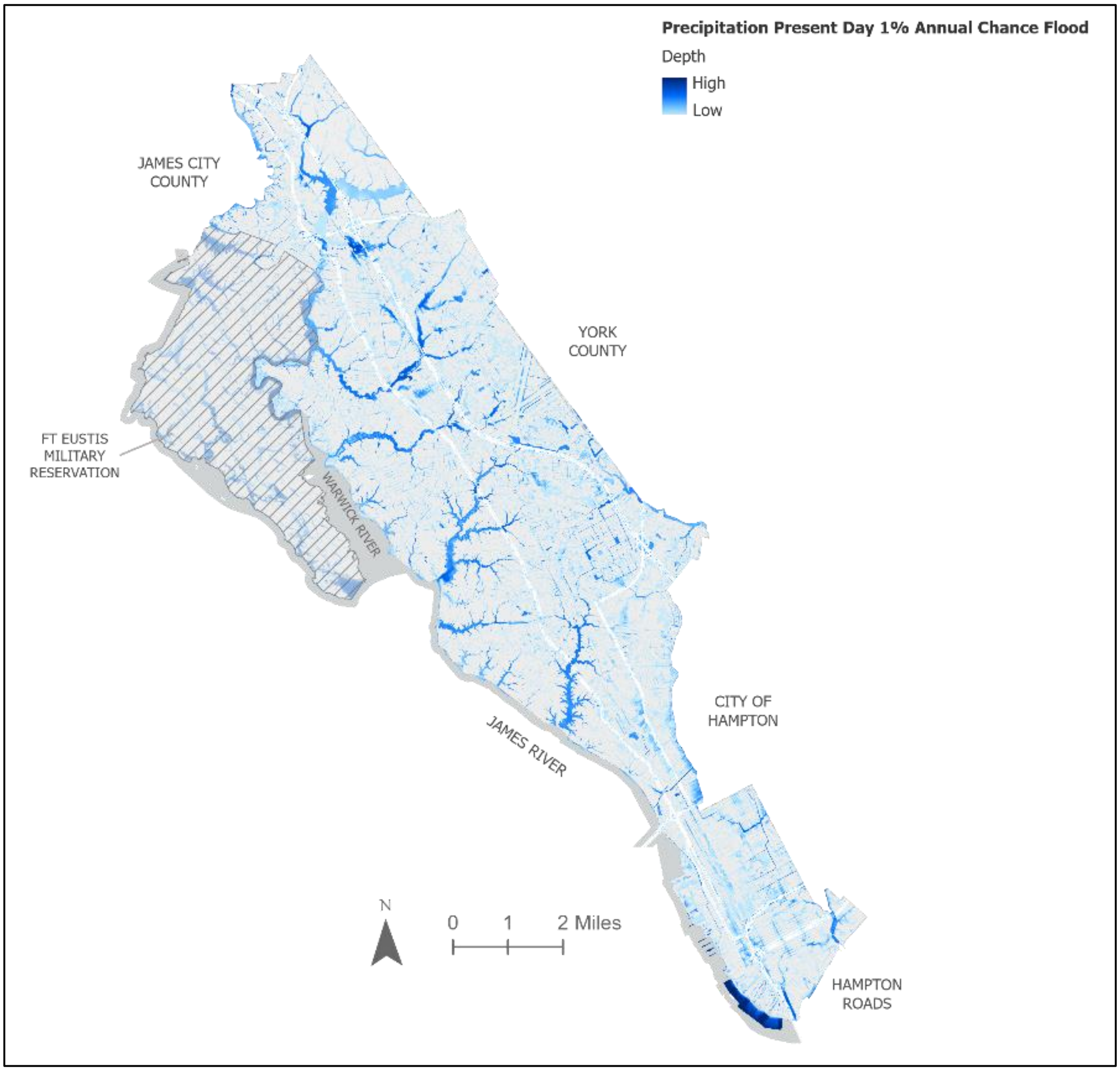

Figure 12: Pluvial flooding in City of Newport News, VA

D.2.ii Pluvial Economic Flood Loss Assessments

The pluvial depth grids can be utilized to estimate economic loss for current and future flooding. FEMA's Hazus-MH (Multi-Hazard) offers a well-documented approach for conducting flood loss analysis and economic loss potential of other natural disasters. Additionally, there is a growing collection of stand-alone open-source tools that do not require ArcMap or ArcGIS Pro.

Hazus includes a built-in library of general building stock that can be used for a baseline analysis that would not require developing and sourcing a complete building asset dataset. While the general building stock data has received updates and improvements with major version releases, this library likely has limitations, such as utilizing statistical assumptions regarding structure first-floor elevations, and may not capture the latest developments for the area of interest for which the user wants to calculate loss data. If newer or higher-accuracy structure data is available, it could be used to update the building dataset, but integrating datasets can significantly increase the analysis's complexity and level of effort. Additionally, Hazus provides numerical loss results aggregated to the census block or tract level and does not provide economic loss estimates attributable to individual structures.

One of the stand-alone tools that has recently become available is Hazus Flood Assessment Structure Tool (FAST).[11] Hazus FAST differentiates itself from Hazus as it allows users to more easily calculate building loss, content loss, and inventory loss metrics that are attributable to individual structures, rather than being limited to results aggregated to census scales. These results can be generated per event frequency using a localized building dataset and as average annualized loss values.

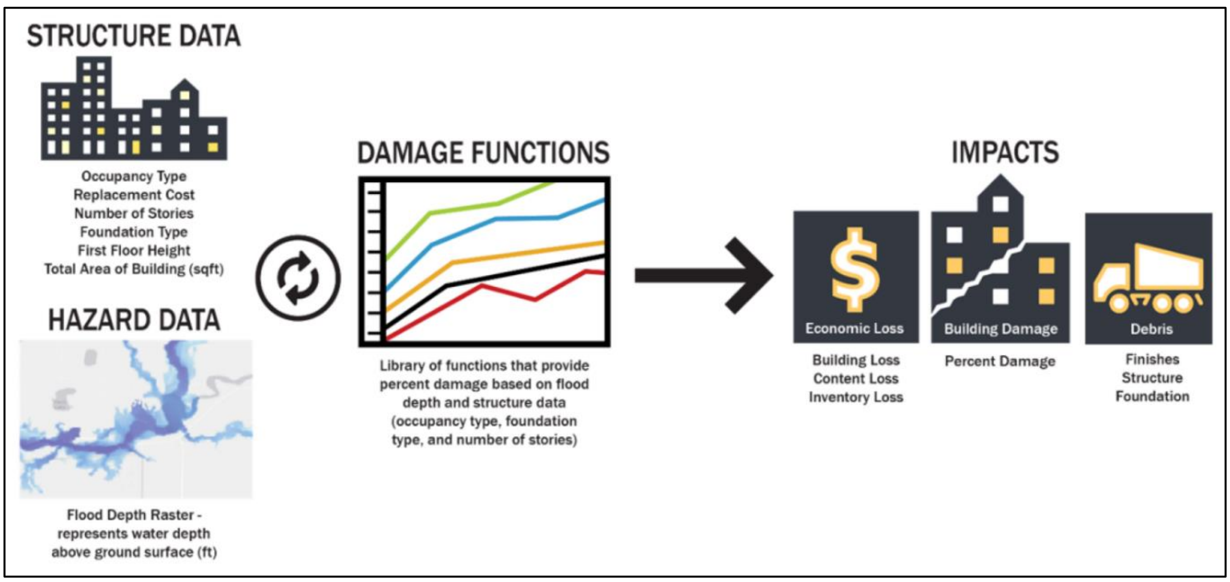

Figure 13: Hazus FAST application[12]

The flood depth is extracted at every building and evaluated against a depth damage function (DDF) to calculate flood losses in dollars. DDFs are a mathematical relationship between the depth of flood water above or below the first floor of a building and the amount of damage that can be attributed to that water. Although DDFs are well-established for coastal and riverine flooding, they are much less mature for pluvial flooding.[13] It is common

[11] Federal Emergency Management Agency. Hazus. FEMA Flood Map Service Center. https://msc.fema.gov/portal/resources/hazus.
[12] FEMA, 2022. Flood Assessment Structure Tool FEMA Factsheet
[13] Porter et al. Estimating Pluvial Depth-Damage Functions for Areas within the United States Using Historical Claims Data, Natural Hazards Review, 2023, 24(1).

practice to use low-velocity riverine DDFs in pluvial loss estimations; however, users are encouraged to review the scientific and engineering literature to inform their application.

Use of HAZUS Fast requires building inventory data to be compiled into the required format from local or other sources and include the key attributes needed for the tool, such as occupancy type, foundation type, number of stories, building replacement cost, building square footage, first-floor height of the building, a unique ID, and the longitude and latitude of the building.

With this approach, Hazus FAST will output the Average Annualized Loss (AAL) for each building, which can be joined in GIS with a unique ID to show geospatially current and future building losses. These building AALs can be visualized in many ways, as shown in the figure below, which shows AALs in a coastal city in Virginia. Here, losses were aggregated into a gridded format to understand flood risk hot spots to inform flood risk reduction strategy development.

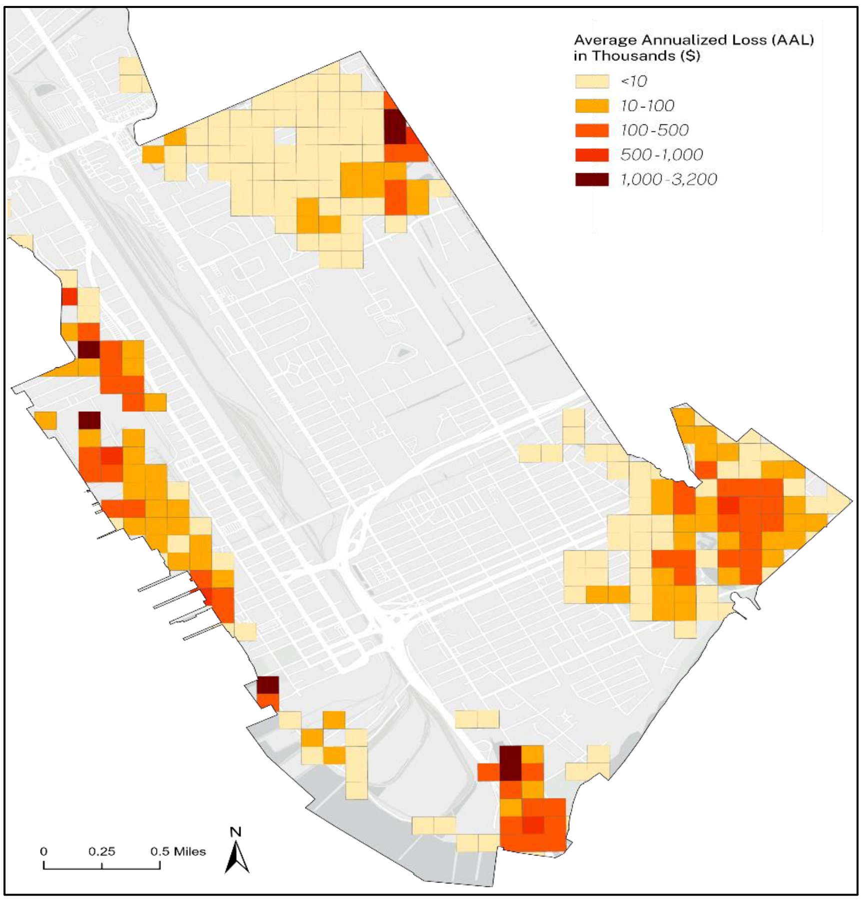

Figure 14: Building average annualized losses in gridded format

D.3 EMERGENCY PLANNING AND PUBLIC SAFETY

D.3.i Evaluation of Hazards by Potential Loss of Life

Flood hazards leading to a potential loss of life can be assessed using one or more flood factors, including depth, extent, rate of rise, duration, and velocity. Thresholds for unsafe conditions are often defined with flood depth times flood velocity. These factors can affect an area directly or indirectly in that one or more factors isolate an area from access or evacuation.

Depth and extent of flooding are readily available as output from the models. To a large degree, the rate of rise and duration may also be readily available in RAS Mapper by dynamically scrolling through the simulation. However, the default model output time steps may be too large to fully assess timing or the default simulation time may not be long enough to capture a sufficient duration. Output time step and model duration can easily be modified in the model for refinement in areas of interest. Velocity or depth x velocity output can also be generated for any model in RAS Mapper.

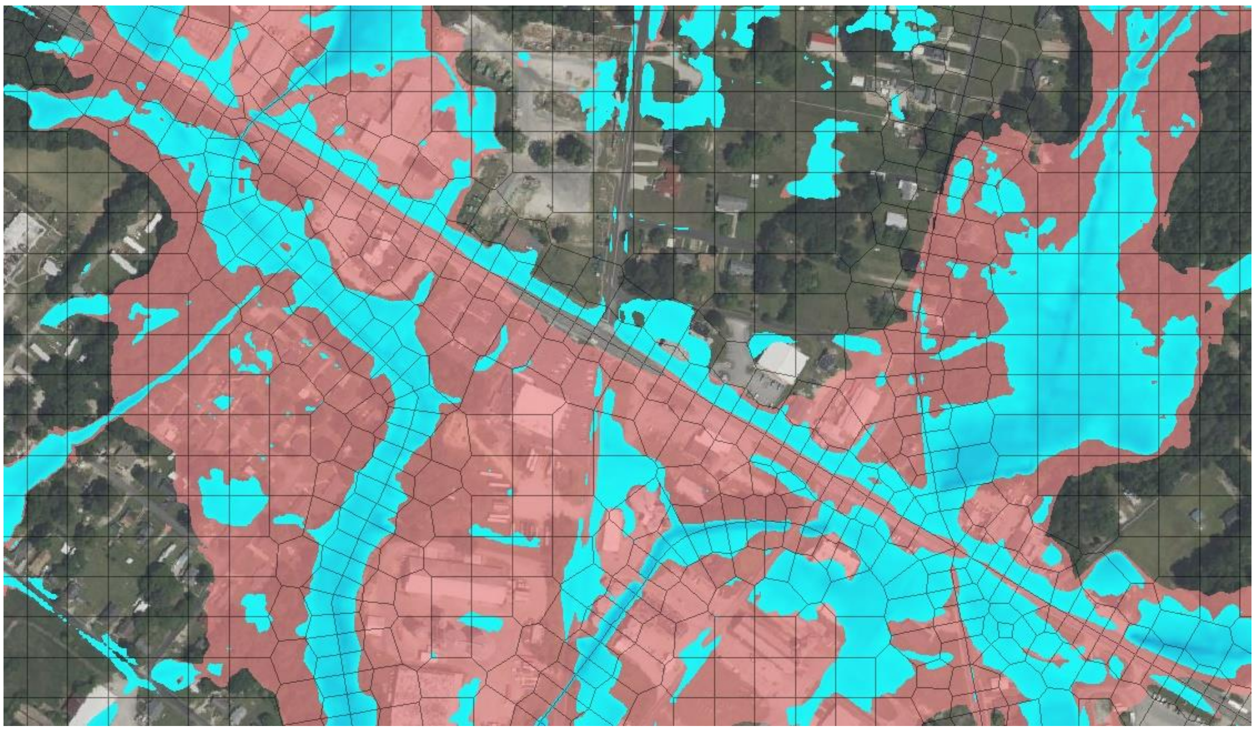

Figure 15: Scenario comparison showing blocked roadways and widespread flooding

Comparison of the multiple scenarios can help identify areas susceptible to cliff edge effects where a seemingly minor increase in rainfall may have widespread effects. The potential consequences of more widespread flooding can be intensified by limited access. As shown in Figure 15, one scenario (depicted in blue) allows access along the main roadway with limited flooding in more low-lying areas. A second scenario (depicted in red) inundates much of the main roadway, and flooding effects are more widespread. Knowing which roads or areas are inaccessible, the scenarios when they become inaccessible, and the duration they may be inaccessible can assist with emergency planning.

D.3.ii Changing Design Storm

In HEC-RAS, users have the flexibility to input spatial precipitation data in three different ways: gridded data, point gage data, or a constant rate. Point-based and gridded frequency precipitation depth-duration data is available from National Oceanic and Atmospheric Administration's (NOAA) Atlas 14 data server. NOAA Atlas 14 provides detailed temporal patterns for specific storm durations and frequencies of occurrence, covering storm durations such as 2-hour, 6-hour, and 24-hour, and frequencies including 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and 500-year events. Users can use the Unsteady Flow Boundary Conditions editor to integrate or update this time series or spatial precipitation data in HEC-RAS. As noted in the Data Products section above, MARISA data was applied to the published Atlas 14 volumes for frequency assignment of future scenarios.

D.3.iii Dam Failure Scenario

As other use cases describe, the models can be augmented by additional datasets such as terrain modifications, land use changes, and bridge or culvert alternatives. Models can also be modified to use observed rainfall input. With these modifications, emergency managers can use the models to better understand hazard scenarios and inform emergency planning.

For example, dam failure scenarios for areas downstream of large reservoirs can be evaluated and used to inform the dam failure Emergency Action Plan (EAP). In Figure 16, a dam breach hydrograph was calculated added as an upstream flow hydrograph boundary condition to evaluate downstream impacts to population or property. While traditional EAPs may have been developed based on 1-D modeling, 2-D models can provide notable advantages particularly as it intrinsically supports multiple flow paths, which is particularly useful in wide/flat floodplains where flooding is prone to spreading out, braided channels, and modeling potential flooding outside the primary channel, such as backwater areas that may not be fully captured in 1-D modeling approaches.

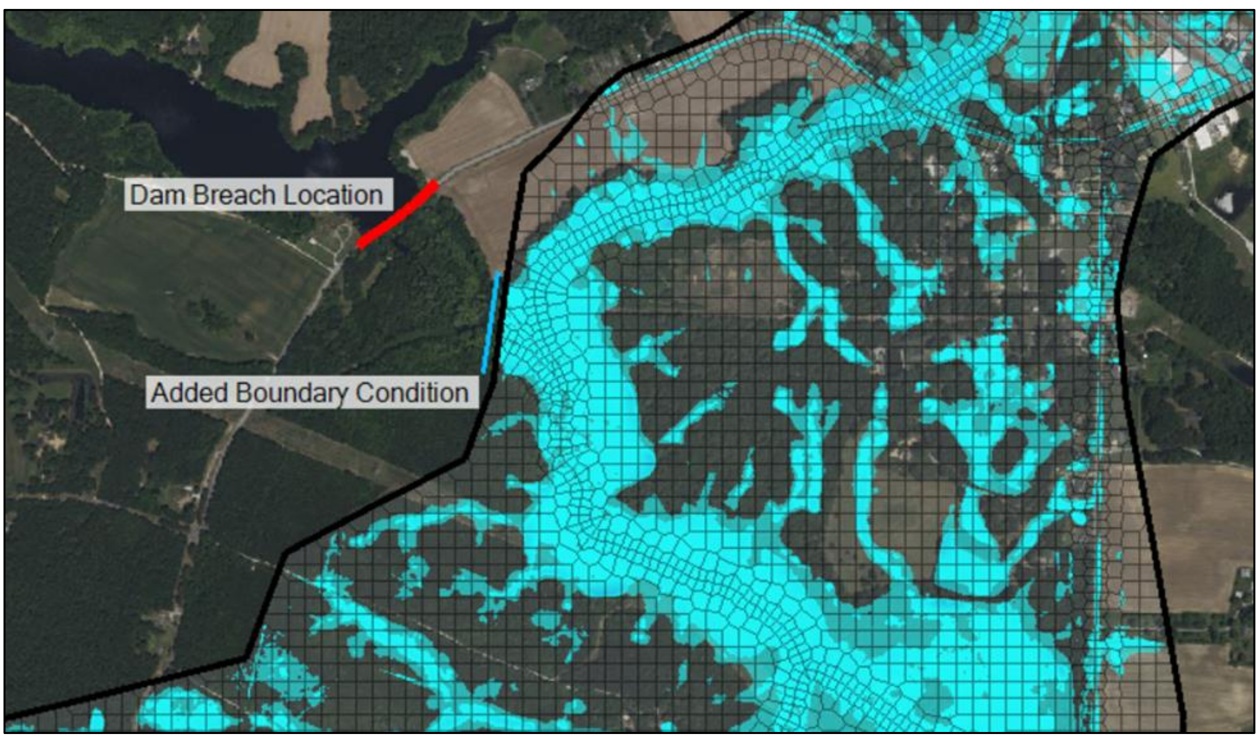

Figure 16: Modified boundary condition to simulate a dam breach

Simplified methods can be used to estimate flow hydrographs for dams and reservoirs without an EAP or the necessary outflow hydrograph information. The failure flow estimates can be added to models to assess if more rigorous methods should be investigated. Inflow hydrographs can also be evaluated with added rainfall to analyze the impacts of coincident events.

D.4 MODEL MODIFICATIONS

The pluvial models provide an excellent starting point for more detailed modeling. The following four examples have wide applicability and may be readily implemented. For detailed technical guidance, refer to the official HEC-RAS documentation.[14]

Table 4: Model modification summary table

Model Modification	Applications	Model Modification Complexity	Related Datasets
Terrain Modifications	Stormwater Management	Low	Terrain, Land Cover
Combining Models	Stormwater Management, Regional Resilience Planning, Emergency Management/Public Safety	Medium	RAS Models, Rainfall, Flow Hydrographs
Breaklines	Stormwater Management	Low	RAS Models, Linear Feature Lines (e.g., Flowlines, Transportation Network)
Compound Flooding	Stormwater Management, Regional Resilience Planning, Emergency Management/Public Safety	Low	Tidal MHW

D.4.i Terrain Modifications

The terrain modification tools in HEC-RAS are rapid and easy to use. They save time by allowing users to modify the terrain without additional software or the extra steps involved in exporting and re-importing the data. In addition, users can copy—or clone—the terrain and modify cloned terrain without changing the original terrain or increasing the file size by having multiple terrain layers in the model. The cloned terrain can be exported or saved as a new terrain layer once users are satisfied with the modifications.

Various modifications can be made to the terrain, but two of the most useful are the ability to add channels and high ground. The modification tools allow users to create those features by simply drawing a line and setting basic geometry such as the channel bottom width and side slope, or in the case of high ground, the top width and side slopes. New channels can be created to redirect runoff, or existing ditches or channels can be widened. The channel tool is often used to cut through roadway embankments to represent culverts

[14] United States Army Corps of Engineers. HEC-RAS Documentation. https://www.hec.usace.army.mil/software/hec-ras/documentation.aspx.

or where bridges are not reflected in the terrain. Embankments, levees, and berms can be added to the terrain similarly to channels.

While the geometry options for these features are somewhat limited, users can make edits to simulate various features by using or combining the tools in multiple ways. For example, the channel tool can create a storage pond by increasing the bottom width and using control points to set the bottom elevation and ground slopes at the beginning and end of the channel modification line.

Figure 17 shows an example of combining the high ground and channel modifications. A high-ground modification line was drawn across a valley in the terrain. This could represent a roadway or other embankment. In this case, it represents a dam with a 30-foot top width and 3H:1V side slopes.

In Figure 18, the channel tool was then used to cut across the dam to represent a spillway. A break line was added, and the mesh was regenerated to enforce the break line and align the cells along the top of the dam.

Users should note that some intersecting modifications can be made simultaneously without issues, such as one high-ground line crossing another at a higher elevation or a high-ground line crossing a channel line. Others, such as illustrated in this example, require the terrain to be saved with the high-ground modification before the channel modification can be used to cut through to create the spillway in the terrain.

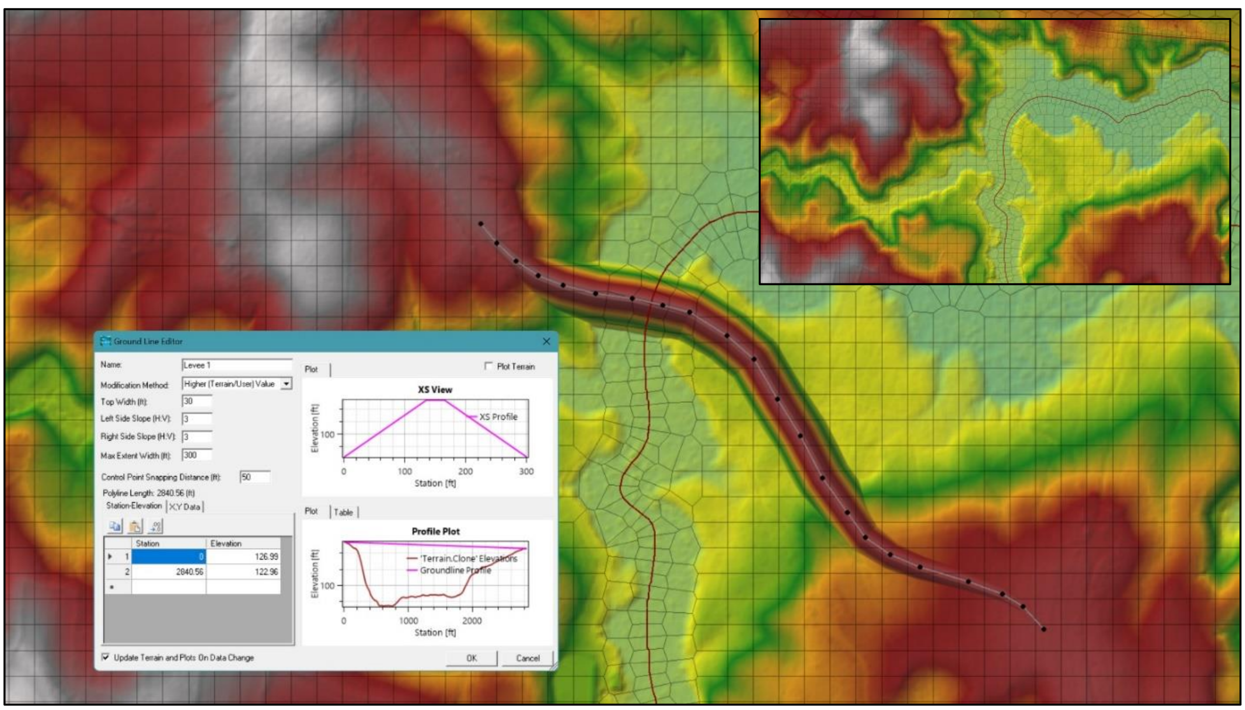

Figure 17: A terrain modification addition of an embankment dam

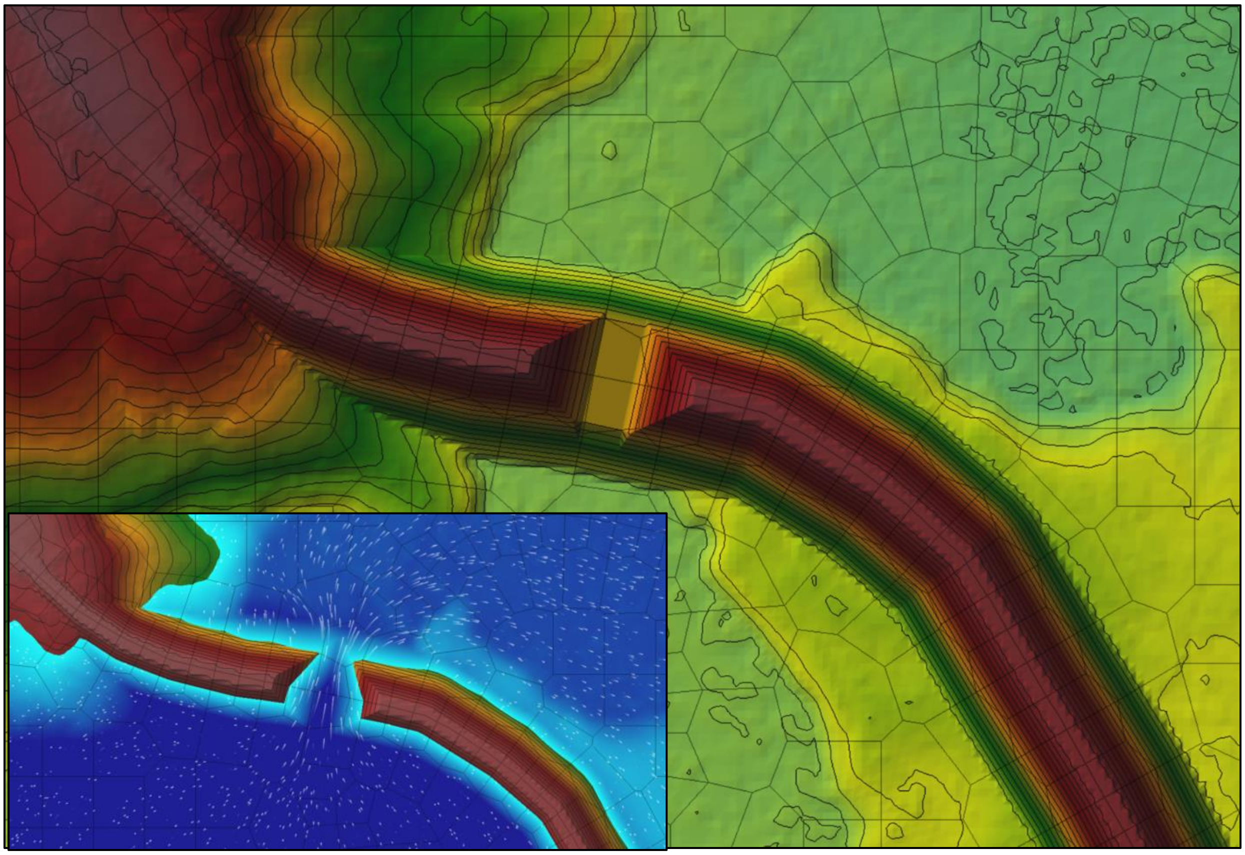

Figure 18: A terrain modification simulated conveyance of an emergency spillway

D.4.ii Combining Models

The HEC-RAS Mapper tool provides a user-friendly interface for viewing, editing, and interacting with model files. One interesting use case for the pluvial models would be incorporating the existing terrains, infiltration/friction layers, and break line datasets from adjacent models to create a larger model suitable for fluvial modeling.

Shown in Figure 19 is an example of data from three pluvial basins (comprising a HUC-12) that have been merged into a new model using the RAS mapper tool. Connecting the models from upstream to downstream, the conveniently buffered datasets provide the foundational layers required to set up an HUC-12 scale model to simulate fluvial or additional pluvial scenarios.

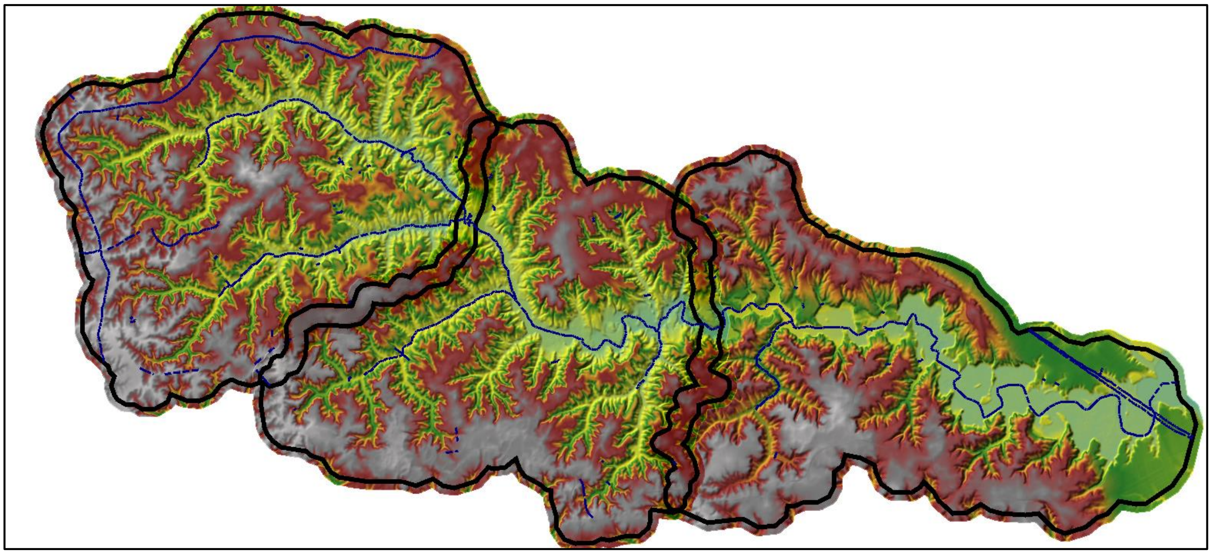

Figure 19: A HUC-12 model merging multiple pluvial models

This use case has many potential applications, including the simulation of frequency-based flows applied in the main stem and or tributaries using historic or synthetic hydrographs. Further pluvial modeling scenarios, such as hindcasting historic events, what-if scenarios using storm transposition, or other more complex or sensitivity analyses using the complete HUC-12 basin, could be performed.

D.4.iii Breaklines

Breaklines are used to align the 2-D cell edges in the model mesh. They are typically used to help define linear features in the terrain, such as berms, levees, or roadway embankments. They are also used along stream and river channels to help direct water through the mesh. Breaklines have already been applied to refine the 2-D model mesh. The breaklines were derived from the stream and river flowlines from USGS's National Hydrographic Dataset (NHD). In addition, road centerlines geometry from the Virginia Geographic Information Network (VGIN) GIS clearinghouse data that crossed over streamlines layer were also used to enforce breaklines. For more details, see Chapter 3.4, Model Refinement of the Pluvial Modeling Technical Report.[15]

Not all roadways and stream channels have associated breaklines in the models, especially in the upstream reaches of watersheds where tributary flowlines are not reflected in the NHD dataset. Users can modify the 2-D cell sizes in the mesh using refinement regions and then add or modify existing breaklines in the models to refine the model in a specific area of interest for further analysis.

Figures 20 and 21 show an example of this. In this example, a user would like to estimate the size of a replacement culvert under an access roadway using a new county rainfall

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[15] Dewberry Engineers, Inc. Virginia Coastal Resilience Master Plan, CO-8A: Pluvial Modeling Final Report. June 14, 2024. https://vadcr-frp.s3.amazonaws.com/Pluvial_CRMP/VACRMP_PluvialModelingReport_Final_20240614.pdf.

design standard that accounts for climate change. Figure 20 shows the unrefined mesh in an upstream area of a watershed where the access road crosses a tributary. The mesh was refined from 100' x 100' cells to 25' x 25' to estimate the required culvert size.

Breaklines were added along the tributary channels and the roadway following the terrain contours. This aligned the cells with stream flows and helped to represent the roadway for preliminary culvert sizing model runs more accurately. For more information, see the 2-D Flow Areas chapter of the HEC-RAS Mapper User's Manual.[16]

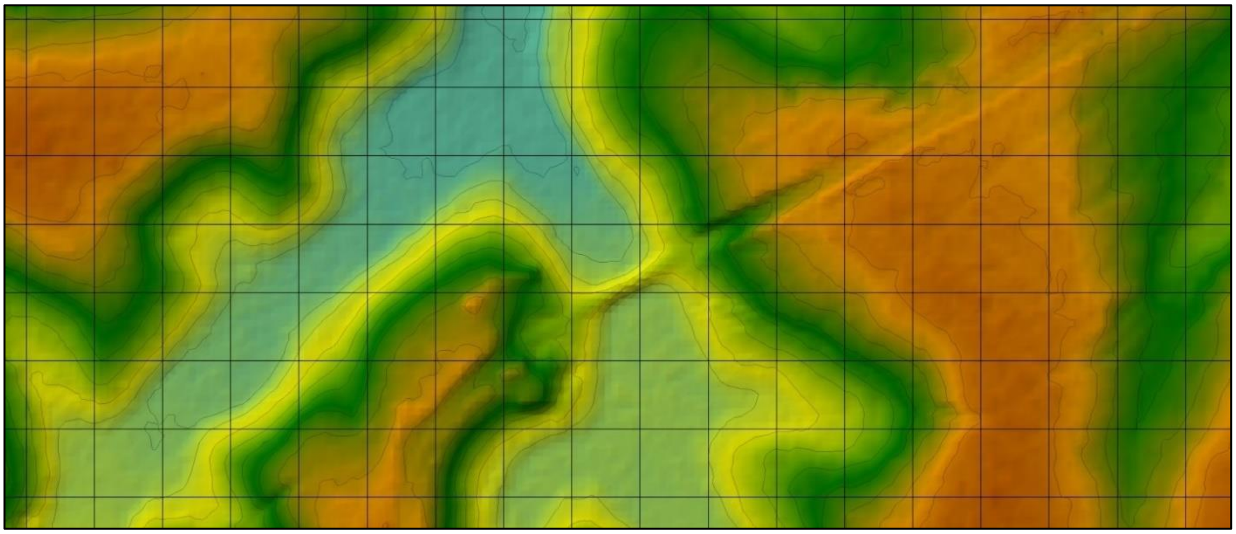

Figure 20: Unrefined mesh in an upstream area

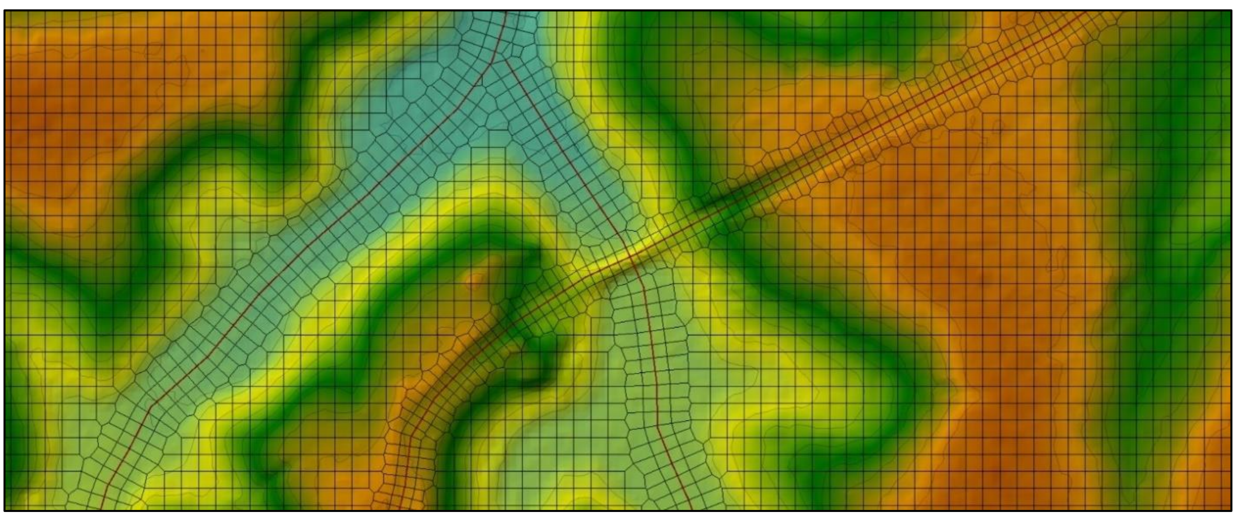

Figure 21: Breaklines added to represent a roadway for preliminary culvert sizing model runs

[16] United States Army Corps of Engineers. (2024). 2-D Flow Areas. HEC-RAS Mapper User's Manual. https://www.hec.usace.army.mil/confluence/rasdocs/rmum/latest/geometry-data/2d-flow-areas.

D.4.iv Compound Flooding

Coastal regions are susceptible to various flooding events, including storm surges, high tides, heavy rainfall, and increased river flow. Compound flooding occurs when two or more of these flooding sources occur simultaneously or within a short timeframe. Compound flooding often leads to more severe consequences than flooding caused by a single factor. Consequently, understanding the interactions between these flooding mechanisms and their combined impact on flood depths and extents is essential for effective mitigation planning, impact assessment on natural and built environments, as well as disaster response and recovery.

There is a growing trend in using 2-D watershed modeling approaches in HEC-RAS nationwide to handle such typical multi-hazard risks. The HEC-RAS 2-D model can simulate the combined impact of varying rainfall intensities and surge events by adjusting the fluvial or coastal flood elevations. This allows for a comprehensive assessment of the potential flood risks and aids in devising effective mitigation strategies.

Compound flooding analyses should consider the joint probabilities of the separate flood events (i.e., rainfall, coastal, or riverine floods). For most of coastal Virginia, joint probabilities are not well established and would need to be analyzed. For example, the City of Virginia Beach established joint probabilities for rainfall and coastal events, which are incorporated into their design standards.[17] Where joint probabilities do not exist, scenario analysis can be performed to help understand potential flood threats from the co-occurrence of these events. The user can select the appropriate combinations of rainfall and then adjust the boundary condition to reflect the scenario-specific riverine or coastal flood elevation.

A recent application of the CRMP pluvial model for adaptation strategy development in Oyster, Virginia, provides an example of compound flood conditions. Marsh enhancement combined with an earthen berm and bulkhead alignment was proposed to reduce mid-term (2040s) flooding up to the 10% AEP coastal storm. The conceptual design recognized the need for a stormwater pump station to mitigate drainage impacts by the berm; however, the magnitude of the potential issues was unknown.

The engineering team identified a preliminary compound scenario comprised of a 50-yr, 24-hour rainfall event for the future condition time frame. A rainfall amount of 8 inches was identified for this condition based on the MARISA data. The corresponding model with a future MHW tidal boundary condition projected to 2040 was retrieved from the Pluvial Model Catalog App. The simulated water surface elevation and flood depth were analyzed for both the existing and proposed conditions.

The modeling results found that water pooled behind the berm to a maximum depth of about 2 feet in some areas. This pooling of water was expected and can be mitigated by a combination of flap gates and a stormwater pump as the design progresses.[18]

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[17] City of Virginia Beach, Joint Occurrence and Probabilities of Tides and Rainfall, 2017; City of Virginia Beach, Design Standards Manual, March 2022.
[18] The Nature Conservancy, Oyster Village Coastal Adaptation and Resilience Plan, October 2024.

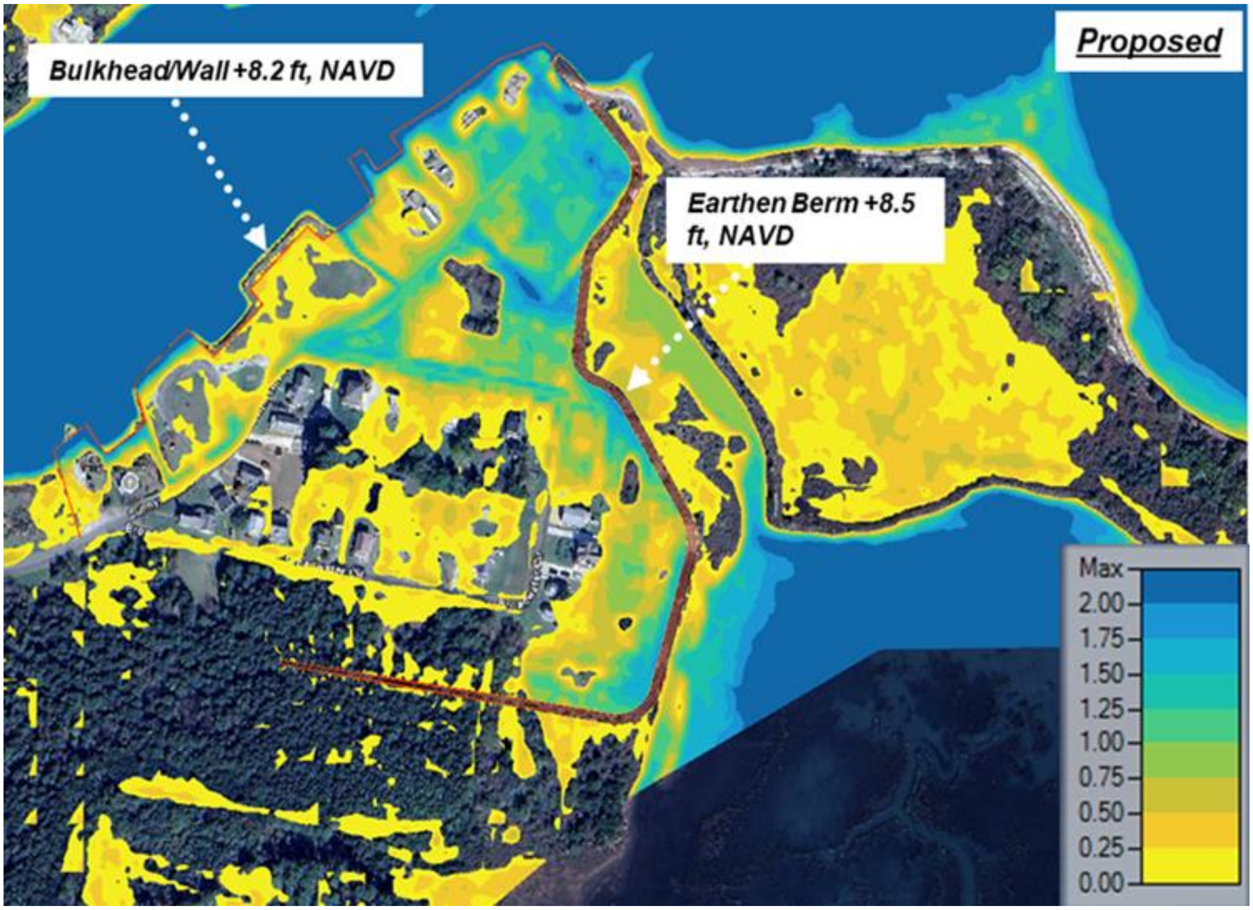

Figure 22: A model evaluation of a conceptual engineering alternative[19]

[19] Courtesy of The Nature Conservancy