NOAA Technical Memorandum NOS CS 53

MODIFICATIONS TO THE ADCIRC HYDRODYNAMIC MODEL TO INCORPORATE PRECIPITATION AND INLAND HYDROLOGY

Silver Spring, Maryland
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National Ocean Service
Coast Survey Development Laboratory

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December 2022

noaa **National Oceanic and Atmospheric Administration**

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ABSTRACT

Flooding due to precipitation and overland runoff can significantly increase coastal water levels during a hurricane or other extreme event. To enable a “total water level” approach where these sources are included along with the more typical tidal, wind, wave, and storm surge forcings, an accumulation (source) term has been added to the Advanced CIRCulation model (ADCIRC). This term allows both distributed (precipitation) and point sources to be easily incorporated in an ADCIRC simulation. Multiple file formats can be supported for distributed rainfall over the wetted ADCIRC domain. Point sources are used to add upland, rainfall-induced streamflow by extracting streamflows from the National Water Model (NWM) and applying them at the end point of any NWM feature that terminates within the wetted ADCIRC domain. Simple test problems are used to validate that both sources conserve mass locally and result in accurate final water levels. Next, a previously vetted model, which includes high refinement of four water bodies within the Tar and Neuse watersheds, and has been used extensively in studies along the North Carolina coast, was used to compare the new methodology to the standard river flux boundary implementation during Hurricane Isabel. Results indicate that the new methodology is consistent with the flux boundary approach. Further tests with the new 120m mesh during Hurricanes Isabel and Irene allow the addition of NWM point sources and indicate that the addition of precipitation and overland runoff do improve the model performance and result in higher flood levels in the coastal regions as well as inland.

Key Words: Total water level, combined flooding, ADCIRC, accumulation (source) terms

1. INTRODUCTION

The ADCIRC hydrodynamic model has been continually developed and improved for over thirty years (Luettich Jr. et al., 1992) to improve its overall modeling capability for a variety of applications, including storm surge, particle tracking, tidal databases and flood mapping. Recent extreme events like Hurricanes Florence, Matthew, Irma and Harvey have underscored the importance of including precipitation and inland flooding in order to accurately capture the total coastal water levels due to the combined effects of storm surge, heavy precipitation and riverine flow (Wahl et al, 2015). This service gap has also been noted by the National Weather Service (Van Cooten et al, 2011).

Traditionally, upland riverine flow and flooding is predicted by hydrologic models while the coastal flooding due to storm surge is predicted by a hydrodynamic model, such as ADCIRC. Other than using inland precipitation to predict the riverine flow with the hydrologic model, the precipitation amounts themselves are not incorporated in the coastal, hydrodynamic model. Rather, the current methodology incorporates only the resulting riverine flow by using existing boundary conditions within the ADCIRC framework (Dresback et al, 2013). Within this paradigm, each model is run independently of one another and input files are created for ADCIRC to synthesize all of the information. The next step in the modeling progression is to incorporate the timing of all sources (rainfall, runoff and surge) to get an accurate picture of the combined flooding due to the storm. Herein, the combined flooding due to tides, storm surge, wind induced waves, precipitation and rainfall runoff (streamflow) is referred to as the total water level (TWL) since it includes all of the major physical processes that contribute to coastal flooding during extreme events.

To facilitate a tighter coupling with this combined or "total water level" (TWL) approach, a new source/sink term has been added to the ADCIRC hydrodynamic model. This term can be used to introduce both distributed sources, such as precipitation, and point sources, such as riverine and lateral inflows. For each type of input the source itself is incorporated at the nodal level within the wetted portion of the ADCIRC computational domain. ADCIRC does not currently have the ability to simulate overland flow due to runoff, so no precipitation or point source is applied over dry regions of the domain. Instead, the streamflows predicted by an inland hydrologic model, as well as precipitation amounts, are only input at wet ADCIRC nodes; point and distributed sources that are over dry regions of the ADCIRC domain are not incorporated in the solution. Herein, the "wet" portion of the ADCIRC domain refers to all nodes that satisfy one of three criteria: 1) the node has a positive bathymetric value indicating that it lies within water; 2) the node lies within a river or stream reach that extends above mean sea level and thus has a negative bathymetric value but has appropriately defined nodal attributes (particularly initial_river_elevation) to indicate that the node does in fact lie within water (insufficient streamflow may cause such nodes to subsequently be flagged as dry during the simulation); or 3) the node has been flagged by the wetting and drying algorithm within ADCIRC to indicate that it is currently "wet".

See Figure 1 for a conceptual diagram of the coupling process; the red and blue boxes indicate the models and output/input, respectively, that are being coupled to ADCIRC with the new source terms. Note that as long as the output can be formatted to fit the input requirements of ADCIRC, any model or observational data can be used for all of the four boxes at the top of the figure.

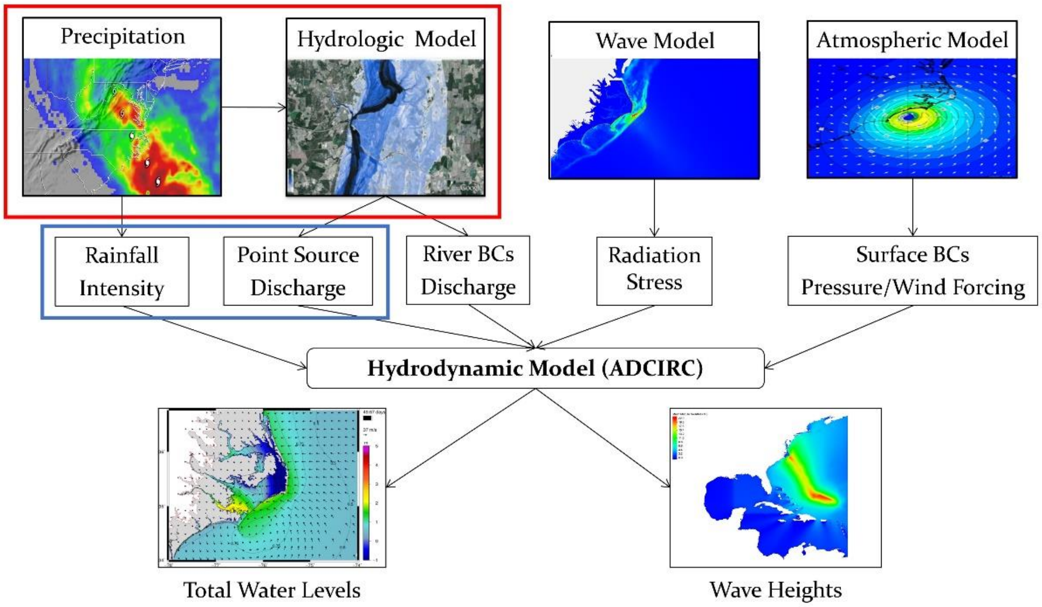


Figure 1. Conceptual framework for coupled system developed to utilize precipitation, hydrologic, atmospheric, wave and hydrodynamic models to obtain total water levels.

As the primary focus of this work is to introduce the new source term, wind induced waves are not included in this study; a complete total water level study of several major storms will be the focus of a future paper. For this study, atmospheric forcing is taken from the Ocean Weather, Inc. (OWI) hindcast products (Cardone et al 2007; Powell et al 1998); precipitation is taken from the Multi-Radar, Multi-Sensor (MRMS) resyntheses products (NOAA NSSL MRMS, 2020) and inland streamflows due to precipitation are taken from the National Water Model (NWM) hindcast dataset (NOAA AWS, 2021). The NWM is based on the WRF-Hydro model developed by the National Center for Atmospheric Research and runs operationally at various time scales for the entire continental United States (https://water.noaa.gov/about/nwm). It has also been run in hindcast mode to examine past events. Data from these hindcast runs are archived in an Amazon cloud bucket for both NWM v1.2 and NWM v2.0, which can be used to simulate past events (NOAA AWS, 2021).

In Section 2, the algorithm to include this new term within the ADCIRC model is described. Section 3 details how the new terms are actually invoked for an ADCIRC simulation and gives a brief background on preprocessing steps that are necessary to incorporate precipitation sources and results from the NWM into ADCIRC, with further detail given in Appendices A and B. Section 4 provides results for idealized tests cases that are used to validate the methodology, as well as actual storm simulations for verification of the practical application. Finally, a summary of this work is provided in section 5.

2. IMPLEMENTATION IN ADCIRC

The new source term is added to the right-hand side of the continuity equation, shown in Eq 1.

$$L \equiv \frac{\partial \zeta}{\partial t} + \nabla \cdot (H\mathbf{v}) = I \tag{1}$$

This equation describes the depth-averaged (2D) conservation of mass for an incompressible fluid, where ζ is the elevation of water surface above the datum, $H = h + \zeta$ with h for the bathymetry and H is the total fluid depth, t is time, $\mathbf{v}$ is the velocity of the fluid for both the x- and y-directions, and I is the rate of the source term. However, ADCIRC uses the generalized wave continuity (GWC) equation (Kinnmark, 1986) in place of the primitive continuity given above when solving for elevations. The GWC equation is shown below in Equation 2.

$$W^G \equiv \frac{\partial L}{\partial t} + \tau_0 L - \nabla \cdot \mathbf{M}^C = 0 \tag{2}$$

where τ_0 is a numerical parameter, which allows for the equation to vary from the pure wave form to the primitive form of the equation, L is the continuity equation (shown in Equation 1) and $\mathbf{M}^C$ is the conservative form of the momentum equation (which is presented in Equation 3).

$$\mathbf{M}^C \equiv \frac{\partial (H\mathbf{v})}{\partial t} + \nabla \cdot (H\mathbf{v}\mathbf{v}) + \tau H\mathbf{v} + \mathrm{H}\mathbf{f} \times \mathbf{v} + H\nabla\left[\frac{p_a}{\rho} + g(\zeta - \alpha\eta)\right] - \mathbf{A} - \frac{1}{\rho}\nabla \cdot (H\mathbf{T}) = 0 \tag{3}$$

where τ is the bottom friction parameter, $\mathbf{f}$ is the Coriolis parameter, p_a is the atmospheric pressure, ρ is density, g is gravity, α is the Earth elasticity factor, η is the Newtonian equilibrium tidal potential, $\mathbf{A}$ is the atmospheric force and $\mathbf{T}$ is macroscopic stress tensor.

Using the modified primitive continuity given in Equation 1, the final form of the GWC equation with the additional source/sink term is given by Equation 4.

$$W^G \equiv \frac{\partial^2 \zeta}{\partial t^2} + \frac{\partial}{\partial t}\big(\nabla \cdot (H\mathbf{v})\big) - \boxed{\frac{\partial I}{\partial t}} + \tau_0 \frac{\partial \zeta}{\partial t} + \tau_0 \nabla \cdot (H\mathbf{v}) - \boxed{\tau_0 I} - \nabla \cdot \mathbf{M}^C \tag{4}$$

Note that there are two additional terms due to the source term in the primitive continuity, $\partial I/\partial t$ and $\tau_0 I$, denoted by boxes in Equation 4. These terms are evaluated in an explicit nature with the temporal term for the source rate evaluated using the present and past times (much like the advective terms) and the τ_0 term evaluated using only the present time (these terms do not use the GWCE weighting factors).

This new source term has been used to add distributed precipitation and lateral inflows (point source) from upland riverine flow to the wet nodes within the ADCIRC hydrodynamic model. For lateral inflows, provided discharges are internally converted to rates (intensities) using the total wet area of all elements that surround the point source, see Figure 2. Note that both source types are only added to active ("wet") ADCIRC nodes – no sources are added to dry nodes as ADCIRC currently does not route overland hydrology (as noted in the introduction).

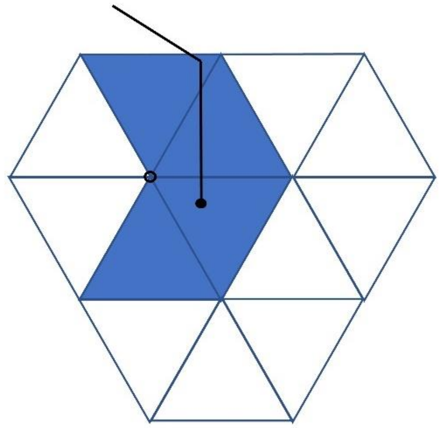


Figure 2. Sample wetted area for ADCIRC internal conversion of stream discharge into point source intensity: adjacent wetted elements shaded in blue, nearest ADCIRC node shown with open circle, NWM stream endpoint shown with black circle and stream by black line.

3. ADCIRC USAGE

In order to implement these new source terms in ADCIRC, additional input data is required. For the initial ("beta") version, this input is provided with traditional text files. In the future, a tight coupling through the ADCIRC Coupling Interface (CAP) system (Moghimi et al, 2019) can be used to communicate output from external models (precipitation and hydrology) to ADCIRC instead of creating input files. For both source terms, a single namelist identifier is included in the fort.15 file to activate the source term. If the user does not wish to include either source term, the namelist line can either be excluded or set to zero; see subsections below for details about each source and any required preprocessing. All preprocessing tools described herein are available on the adcirc.org website (under the ADCIRC Utility Programs page) as a single download: SourceTermPreprocessing.zip.

3.1 Distributed Source (Precipitation):

Currently there are two options for introducing distributed (precipitation) sources into ADCIRC:

0. Distributed (precipitation) sources are not included in ADCIRC (default if no option is specified with the namelist or can use namelist with NCRAIN=0)
2. Raw rainfall data (m/s) files (fort.425) – global file with intensities at all ADCIRC nodes (this option is provided for testing but would not be used in practical applications)
12. Raw rainfall data (mm/hr) files in OWI format (fort.27, fort.425 and optional fort.427 which mirror the format of the fort.22, fort.221 and fort.222 files for OWI winds)

For each of these options, a namelist line must be included at the bottom of the fort.15 file. This line is formatted as:

```
&rainfallcontrol NCRAIN=2, CRAIN_TIMINC=3600 /
```

where the NCRAIN value can be specified as [0, -2, 2, -12, 12] to select one of the options listed above and CRAIN_TIMINC is the increment (in seconds) between successive data sets in the fort.425 and/or fort.427 input file(s). For a hotstart, the use of a negative value for NCRAIN will indicate that the input file(s) begin at the hotstart time, while a positive number indicates that the input file(s) start at the coldstart time.

Possible sources for precipitation intensities include any data-based basin and/or regional radar product, such as quantitative precipitation estimation (QPE), or parametric precipitation models, such as P-CLIPER, which is a predictive model based upon storm track and intensity (Geoghegan et al, 2018). All precipitation must currently be preprocessed into either a global file for option 2 or OWI format file(s) for option 12.

3.2 Preprocessing for Distributed Sources

As stated above, precipitation or rainfall rates can be obtained from any source (model or data) as long as the input files created for ADCIRC are formatted the same as OWI winds, which is currently the only allowed format for practical simulations. Herein, we describe the preprocessing software that has been developed for use with information obtained from Multi-Radar, Multi-

Sensor (MRMS) sources, which is a QPE product. The MRMS information is developed from the NEXRAD radar data and is provided on a regular cartesian grid. This type of precipitation data is similar to the wind fields developed through OceanWeather in that it is the most accurate source for precipitation information for use in hindcast situations. ADCIRC takes the precipitation rates provided from this source in either regional or basin scale, but will only apply it over the wet nodes within the ADCIRC model domain.

These files are provided in a file format called grib2, which is a common data format in meteorology that provides the information in a gridded binary format. A user can utilize software called GDAL(Geospatial Data Abstraction Library) to reduce the information into the regional or basin scale being analyzed in the simulation (data that falls outside of the ADCIRC model domain will not be used and increases the filesize, so users should choose the scale carefully). GDAL will reduce the file to these scales and output as a NetCDF file. Finally, these files are converted into the required ADCIRC format for the rainfall files with the rates given in mm/hr.

Preprocessing of this information occurs in two phases: Phase 1 locates the precipitation information from the different MRMS sources. For the hindcast storms within the years of 2001-2011, the information can be obtained from the following website: http://edc.occ-data.org/nexrad/mosaic/. Each year is contained within its own tar file with the rainfall rates for every day of the year in 5-minute intervals. Once this information is obtained, the days (and time increments) of interest can be extracted from the tar files. Further MRMS data for the years of 2011 to present can be found at the following website: https://mtarchive.geol.iastate.edu/ under the MRMS directories and then under the PrecipRate directories. In Phase 2, the extracted files can be processed with the script in order to develop the ADCIRC input files. A description of Phase 2 and proper usage for all preprocessing tools is provided in Appendix A.

3.3 Point Source:

Currently, there are three options for introducing point sources into ADCIRC:

0. Point sources are not included in ADCIRC (default if no option is specified with the namelist or can use namelist with NCPSOURCE=0)
1. Intensity (m/s) at specific ADCIRC mesh nodes provided in a fort.426 file formatted as follows:

   numPS = number of nodes with non-zero values for that snap (can vary in time)
   for i=1, numPS
           ADCIRC node   intensity (m/s)

   Must have enough datasets for the entire simulation (plus one extra at end of file for temporal interpolation).
2. Discharge (m^3/s) at specific ADCIRC mesh nodes provided in a fort.426 file formatted the same as option 1 but with discharges (m^3/s) instead of intensities specified for each non-zero node.

3. Discharge (m^3/s) for locations specified in degrees longitude and latitude. This option is used to include NWM streamflows in ADCIRC. Two files are required: fort.428 with lon/lat locations and fort.430 with discharges.

   <u>fort.428:</u>
   Point source location file (single set of locations)
   numPS (cannot vary in time and is only included at the top of the fort.428)
   For i=1, numPS
   lon(deg) lat(deg)

   <u>fort.430:</u>
   Point source streamflow file (multiple time snaps)
   Must have at least enough datasets for the entire simulation plus one extra for temporal interpolation. For each time increment, a simple list of discharges, given in the same order as the point source locations in the fort.428 file, is provided. This file is similar to fort.20 file for rivers and contains no header information.

   For k=1, >= number of increments for the entire simulation plus one (due to temporal interpolation)
   For i=1, numPS
   Q (m^3/s)

For each of these options, a namelist line must be included at the bottom of the fort.15 file. This line is formatted as:

```
&psourcecontrol NCPSOURCE=2, CPS_TIMINC=3600, CPS_RAMP=0 /
```

where the NCPSOURCE value is specified as [0 thru 3] to select one of the options listed above, CPS_TIMINC is the increment (in seconds) between successive data sets in the fort.426 or fort.430 input file, and CPS_RAMP is the time (in days) to apply a hyperbolic tangent ramp to all point sources. Note that point sources that end on inactive (dry) ADCIRC elements are automatically deactivated until the element becomes active (wet); also, the ramp for this source is completely independent of all other ramps and should not be necessary in most cases but may be required for spinup from an initial state when there are high streamflows at the beginning of the fort.430 file. For a hotstart, the use of a negative value for NCPSOURCE will indicate that the input file(s) begin at the hotstart time, while a positive number indicates that the input file(s) start at the coldstart time.

Possible sources of streamflow data for point source incorporation include National Water Model and other hydrologic models, USGS gauges, and any other data source that includes a precise lon/lat location and sufficient continuity of streamflow data. For this study, we have used only streamflows from archived NWM hindcasts (NOAA AWS, 2021).

3.4 Preprocessing for Point Sources

For each NWM feature, ADCIRC uses the internal kdtree algorithms with updated search subroutines to locate the nearest node and assign each lon/lat location an ADCIRC node for implementation. Any lon/lat pair that cannot be found within the ADCIRC mesh is deactivated. However, the arrays are sized by how many NWM locations are input, so it is not practical for ADCIRC to be given a list of all NWM features (currently just short of 2.8 million).

Therefore, a number of Fortran and Python tools have been created to facilitate the addition of NWM results within ADCIRC. These tools preprocess the ADCIRC mesh and global NWM shapefiles to determine which features exist within the ADCIRC domain and should be extracted from NWM datasets. Note that if the version for the NWM feature list used for preprocessing does not match the version actually used to create the NWM results (e.g. version 1.2 or 2.0 in the Amazon cloud hindcast database), the user may get errors when extracting the NWM results (e.g., if a newer feature did not exist when older NWM results were created). This can be corrected by either manually removing the missing features from the list of found NWM features or verifying that the version for the global feature list matches the desired NWM results version and then rerunning the preprocessing tools.

Preprocessing occurs in two phases: Phase 1 locates all NWM features within the ADCIRC domain and creates the location specific ADCIRC input file and Phase 2 actually extracts the NWM streamflows and creates ADCIRC streamflow input. A description of each phase and the proper usage for all preprocessing tools are provided in Appendix B.

3.5 Additional considerations for nodal attributes

Finally, additional adjustments must be made to the nodal attribute file (fort.13) for any stream reaches that are above the geoid (zero datum) for the model in question. As discussed above in the Introduction, a node must be classified as wet in one of three ways for the point source to be applied during runtime. The second allowable wet classification requires that nodal attributes must have "water" values for all nodes that are above the zero datum, since otherwise they will automatically be classified as dry due to the negative bathymetry. For this study, the following definition is given to distinguish the "water" portion of the mesh (all future references to water assume this definition): any node that has positive bathymetry or lies within a large enough river or stream reach (above the zero datum) that it will always have non-zero streamflow is considered water. For practical purposes, any river or stream that lies within the National Hydrology Database polygons (National Hydrology Database, 2022) can be considered wet, as ADCIRC will automatically deactivate (within the wetting and drying algorithm) any nodes that dry out due to insufficient streamflow. Additionally, if the streamflow becomes too low, the feature may dry out and be flagged, which could result in no further point source input even when the streamflow increases again; more detail about minimum required streamflows is included in the discussion below for initial_river_elevation.

Experience with such above datum riverine reaches in the North Carolina area has suggested best practices for setting these nodal attributes (Tromble, 2011); however, other values may also result in stable solutions and this remains an area of open research. Three attributes in particular must be carefully set within the nodal attribute file:

- initial_river_elevation (Eta2)

  All river and stream nodes that have bathymetric elevations above zero must be included within the nodal attribute file or they will be flagged as dry, made inactive and no point source can be applied within them. It is recommended that all such nodes have values assigned as follows:

  $Eta2 \geq |DP| + 0.5m$,

  so that the initial wet depth is at least 0.5m (values as low as 0.1m may remain stable but this is very dependent upon the slope of the river/stream and how quickly the water will flow off if no source is input – a minimum of 0.5m is recommended, and in some cases, a higher value of 1.0m may be required). The absolute value function is necessary since bathymetric values above the zero datum are indicated with negative values in the ADCIRC grid file; the initial depth will be set to DP + Eta2. The default value is -99999, indicating that there is no initial river elevation to apply.

  It is important to note that this is only an initial value used to let ADCIRC know that these nodes are in fact “wet”. Once the spinup phase of the ADCIRC run is complete, all upland rivers and streams with sufficient streamflow will compute a water surface elevation that is physically consistent with the input streamflows. However, since this additional amount is only applied during the cold-start, if a streamflow falls below the value sufficient to keep the river channel wet, that upland source will be deactivated and the region of the channel above the zero datum will dry out, unless flooding from other sources causes enough of the channel nodes to be reactivated as wet. Physically, this minimum streamflow will be different for each river/stream, depending upon the slope of the upland river, and it must be carefully selected. However, practicality will determine whether it is feasible to examine each of the NWM features with that much attention to detail. At a minimum, it may be desirable to set some minimum flowrate (for all features) within the extraction phase of the preprocessing steps given in Appendix B. Some trial and error may be necessary when beginning a study in a new region since if the minimum is set too high, the WSEs in the upland region may be artificially elevated during lower flow periods in the NWM hindcast record. Sufficient streamflow must be maintained to keep the river from drying out without causing erroneous water surface elevations; what exactly this minimum streamflow rate should be and whether it will be location specific remains an area of ongoing work. For now, a suggested starting value is 5cms in all features, since 10cms has proven to be too high in smaller features (anecdotally). However, for this study, no minimum value was needed as all four features remained wet during the real-world North Carolina test runs and because the 120m mesh artificially lowers the bathymetry in the upland riverine areas below the zero datum.

- average_horizontal_eddy_viscosity_in_sea_water_wrt_depth (ESLM)

All nodes that lie within the defined water portion of the mesh, regardless of bathymetric value, should have a water value assigned (typically 10.0), while surrounding land nodes are typically assigned a value of 2.0. Automatic mesh generation tools may not catch that these nodes are water since they typically use bathymetry to assign this attribute.

- primitive_weighting_in_continuity_equation (Tau0 or G)

  For stability purposes, it is often necessary to set this attribute higher in rivers and streams that are above the zero datum, particularly when they are insufficiently resolved (only a few elements across) such that the bathymetric profile across the channel is simplified. Typical values used for models that contain such features are as follows:

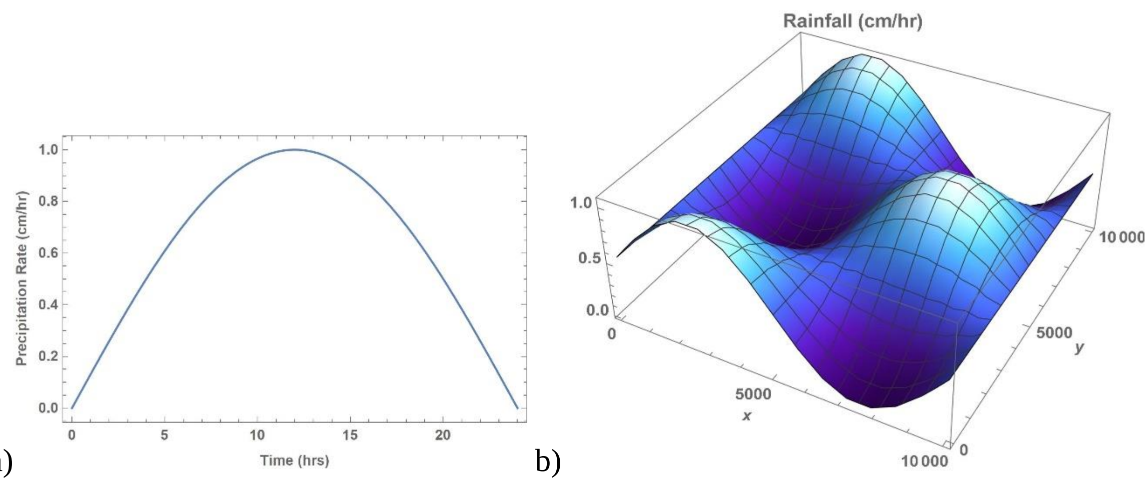
  0.005 in water
  0.03 on land
  0.1 for all river nodes above the zero datum

4. RESULTS

4.1 Idealized Test Cases for Distributed Sources

The new source terms were validated using idealized test cases to ensure that the methodology is appropriate. For distributed sources a constant bathymetry domain with closed boundaries was used and four simple rainfall intensity scenarios (constant in space and time, temporally varying, spatially varying and both temporally and spatially varying) were examined. All additional water entering the system through the distributed source should be contained within the domain and simple integration of the distributions as well as the modeled water surface elevations can verify that the added volume matches the actual modeled volume. A square domain with constant depth of 20m and side lengths of 10km and land boundaries all around is utilized for all of these tests.

For the constant test, a rate of 1 cm/hr was applied over the entire domain for one full day. The temporally varying rainfall varies sinusoidally from 0 cm/hr to 1 cm/hr at 12 hours and then back to 0 cm/hr at the end of the day; the same temporally varying rate was applied over the entire domain. The spatially varying test varies sinusoidally in both the x and y directions, with a maximum rate of 1.08 cm/hr, and is constant in time. Finally, the spatial and temporal variation linearly scales the spatial varied rainfall rate from zero to one at twelve hours and back to zero at 24 hours. Expected water surface elevations (WSE) were calculated by integrating the precipitation input over space and time and dividing by the surface area of the domain; similarly, the final water surface elevation profile was integrated over the domain and divided by the surface area to find the average WSE for each scenario. Figure 3 illustrates the temporally and spatially varying rainfall distributions used for these tests, and Table 1 compares the expected and modeled WSE after one full day of simulation. Results indicate that mass conservation is not impacted by the addition of this new source/sink term.



a) b)

Figure 3: Input for ideal precipitation tests: a) temporally varying and b) spatially varying precipitation; each applied over a 10km square domain for a one-day simulation.

Table 1. Water surface elevation comparison for each of the idealized precipitation test cases after one day

Test Case	Expected WSE due to precipitation input (cm)	Averaged final modeled WSE (cm)
Constant rainfall	24.00	23.99
Temporally-varying	15.29	15.29
Spatially-varying	12.96	12.95
Temporal and Spatial	6.48	6.48

4.2 Real-World Application for Distributed Source: Hurricane Isabel

After verifying that the methodology for adding distributed sources was appropriate, a real-world test was conducted. Hurricane Isabel made landfall as a Category 2 hurricane near Drum Inlet, North Carolina. There was approximately 10-18 cm of precipitation in the eastern portion of North Carolina with a storm surge of 1.8-3 meters (Bevens and Cobb, 2003). In this evaluation, precipitation was obtained from the Mosaic Precipitation Reanalysis (MPE; Zhang and Gourley, 2018) and processed in 30-minute intervals; this data is developed from the network of Next Generation Weather Radars (NEXRAD).

For all results shown herein, note the following definitions: "accumulated precipitation" is the total precipitation that was used as input to ADCIRC and accumulated over the total length of the storm simulation while "applied precipitation" is the total amount of the input precipitation that fell over a node while it was active or "wet". The applied values are what were actually applied within the ADCIRC model during the update of the water surface elevation within the time-stepping routine and the accumulated values are only used to compare the input source with reported observations about rainfall values during an event.

Figure 4a shows the accumulated precipitation (as input to ADCIRC from the MPE data) over the Pamlico Sound region of North Carolina. Note that the time increment used to update the precipitation will affect the total amount of precipitation applied to the wet ADCIRC nodes, as values are linearly interpolated between successive time increment datasets and the wet/dry nodal state is updated at each time step; more detail is provided in Dresback et al (2022). Figure 4b presents the applied precipitation over the wet model nodes (the actual precipitation applied within ADCIRC); note that compared to Figure 4a most, but not all, of the precipitation over the inland area has been reduced to zero since the ADCIRC nodes were not wet throughout the simulation. As new areas become wet due to storm surge or flooding from the riverine areas, precipitation will begin to be applied over the formerly dry nodes. Figure 4c and 4d show the maximum modeled ADCIRC water surface elevations with the addition of rainfall and the difference in water surface elevation (WSE) between a run with precipitation included and a run without. For the WSE difference plot, the magenta colors indicate regions of the mesh that were dry in the base run but become wet with the addition of the precipitation while the cyan colors indicate the reverse.

Since ADCIRC denotes dry nodes with a WSE of -99999, a change from wet to dry or dry to wet results in differences with an absolute value higher than 90000 so the magenta and cyan colors should not be thought of as contours above or below the top scale of ±50cm but simply as nodes that changed from wet/dry to the opposite state (contour limits were carefully chosen to include the maximum range of actual differences without the wet/dry changes). Furthermore, although negative contours in the difference plot (cool colors) technically indicate regions with lower maximum WSEs due to the added precipitation, that does not seem physically realistic. A close examination of these regions indicates that the without precipitation runs are developing localized “mounds” of water on the floodplain (specifically, where there are localized topographic high spots on the floodplain). These mounds in the WSE are due to errors introduced in the wetting and drying algorithm and do not exist when precipitation is included. Previous studies have indicated the presence of such non-physical “mounds” of water due to the wetting and drying algorithm when atmospheric forcing is applied (Dick et al, 2013; Tromble, 2011; Dick, 2011).

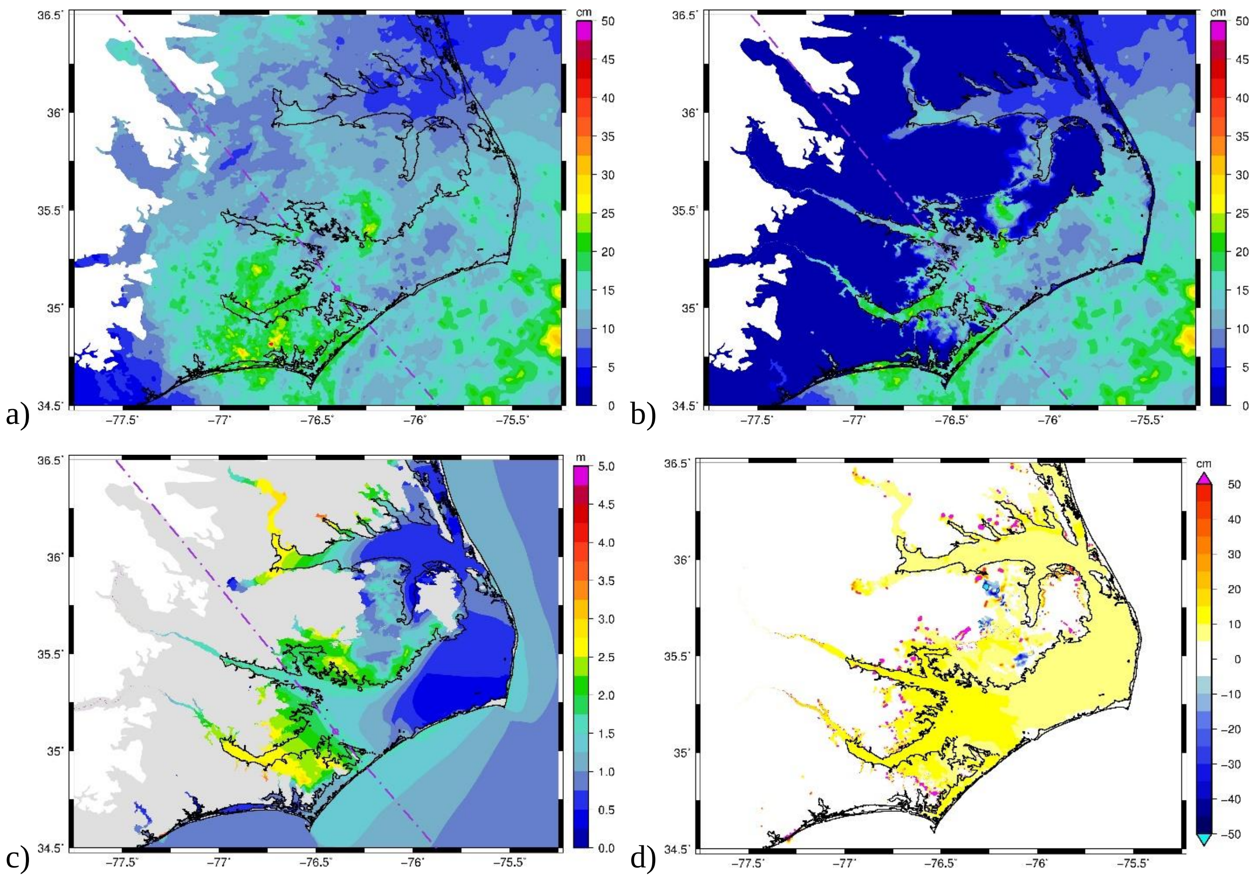


Figure 4: a) Accumulated precipitation (cm), given by MPE processed data, for Hurricane Isabel using a 30-minute time interval, b) applied precipitation (cm) over wet nodes added within ADCIRC, c) modeled ADCIRC maximum water surface elevations (m) with precipitation and d) difference in maximum water surface elevations (cm) due to the inclusion of precipitation. Storm track indicated by lavender dashed line and solid black lines are from the shoreline used in the Generic Mapping Tools software (Wessel, 2013) but do not delineate the full water-only model domain.

4.3 Idealized Test Cases for Point Sources

The use of the accumulation term to represent a point source, such as discharge from a river model, was tested to verify its validity in a controlled test. For this purpose, an idealized channel of constant depth and surrounded by a constant floodplain is utilized with the same 10km square footprint used in the precipitation test. The channel is five meters deep with surrounding land of one meter above MSL. All of the boundaries are set to land so that no water can escape the system. Essentially, this is a narrow bathtub. An equivalent streamflow of 5 m^3/s is applied for one full day using three mechanisms: river flux boundary condition, point source, and distributed source. The forcing is applied at the center of the channel at the topmost node and it is expected that each forcing method will result in a similar final depth in the channel. Since this is an idealized case with steady input, we can calculate the expected WSE in the channel as

$$WSE = \frac{flowrate * time}{surface\ area\ of\ channel}$$

Using a flowrate of 5 m^3/s for one day, and noting that the channel has a surface area of 5,000,000 m^2, the final WSE in the channel should be 0.085m. This ideal value would only be reached throughout the channel if the simulation was run with no additional forcing for some increment of time, such that steady-state is reached. However, it should be close to this value near the input node after 24 hours.

A second idealized test with the same domain but a linearly increasing flowrate (from 0 to 23 m^3/s) was also examined. In this case, the linear temporal distribution is integrated over one full day to determine the total volume of water added to the domain; that value is then used to determine the expected water surface elevation in the channel at the end of the simulation.

Figure 5 shows the idealized domain with node numbers indicating locations where station output is recorded, as well as the constant (with ramp) and linearly varying point source input and the final channel WSE profiles using point source forcing for each input type. The water surface elevation profiles are plotted along the channel starting from the top of the domain (node 861) where the point source is input and going down to the bottom (node 821). Table 2 summarizes the final WSE for both input types and various forcing methods (results for different methodologies are only shown for the constant point source input). Note that the vertical scale for the final profiles is exaggerated to show detail, but the average is comparable to the steady-state value, as indicated in the figure and table.

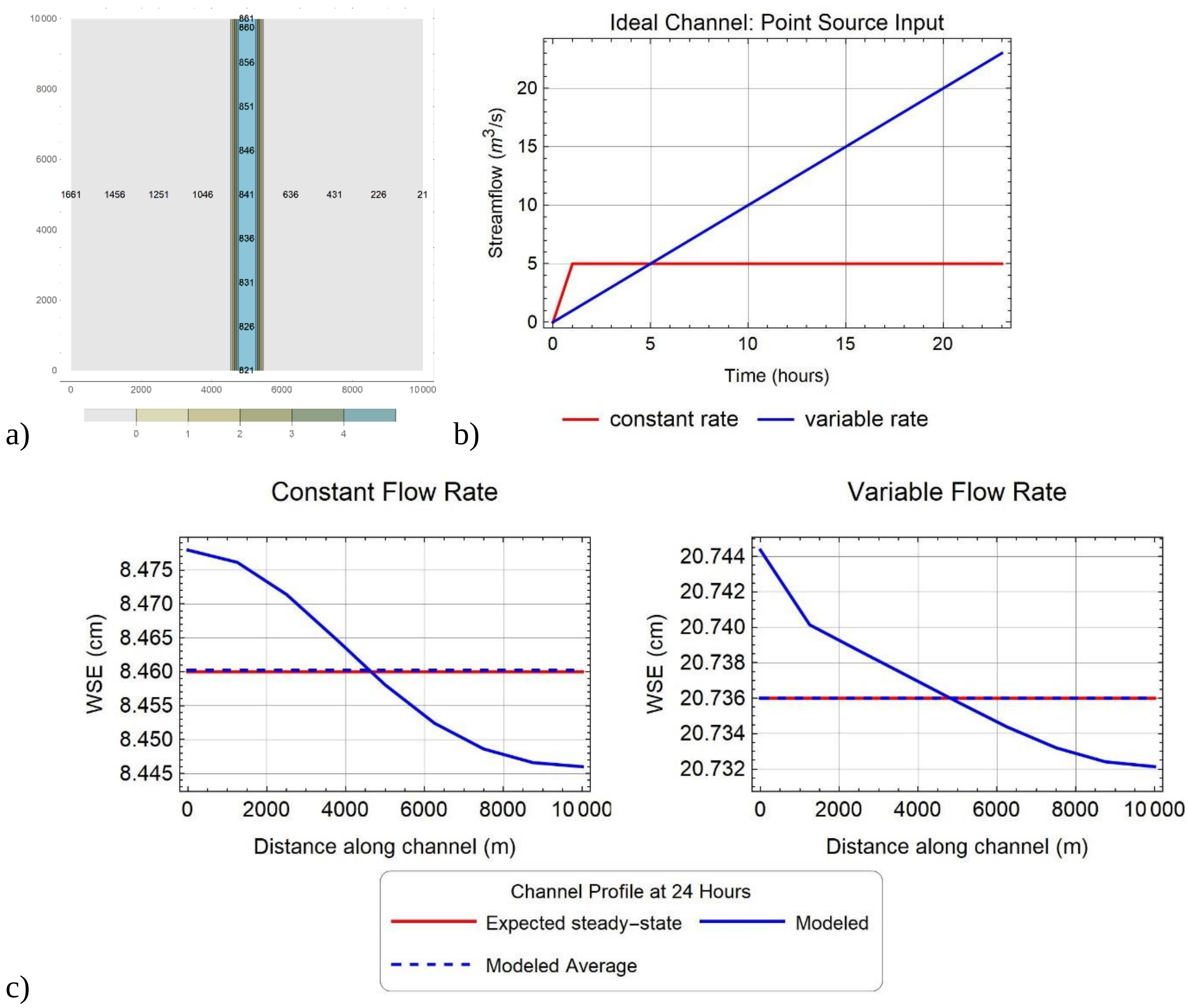


Figure 5: a) idealized channel domain, b) constant and linearly varying point source inputs, c) final channel water surface elevation profile after 24 hours for constant point source and temporally varying point source as compared to the expected steady-state.

Table 2. Comparison of final WSE and expected steady state WSE for idealized channel.

Input Method	WSE at input node (cm)	Average channel WSE (cm)	Expected steady-state WSE (cm)
Constant source test cases			
River flux	8.46	8.45	8.46
Point source	8.48	8.46	8.46
Precipitation	8.48	8.46	8.46
Temporally varying source test case			
Point source	20.74	20.74	20.74

Note that all three input source methods (river flux, point source and distributed source) produce consistent results for the constant rate idealized test and closely match the expected steady-state channel elevation. Similarly, for the temporally varying test case, the point source methodology accurately captures the expected behavior.

4.4 Real-World Verification for Point Sources: Hurricane Isabel

Next, a real-world application is used to compare the different forcing methodologies to ensure that this consistent behavior extends to practical problems. An ADCIRC mesh with riverine features resolved in the Tar and Neuse River basins of the North Carolina region is used to simulate Hurricane Isabel with riverine, tidal and wind forcing (no precipitation); this mesh has been used in previous riverine studies using the CREST hydrology model, and its response has been validated (Dresback et al, 2013). Two different methodologies using hindcast data from the NWM are compared: traditional river flux boundary forcing and the newly added point source forcing. Figure 6 shows a detailed view of the river basin portion of the mesh with the four main riverine features (Tar River, Neuse River, Fishing Creek and Contentnea Creek) shown. Herein, data from the NWM is applied at the nearest wet node at the termination point of the NWM features for point source implementation (indicated by red circles in Figure 6) and directly at the ADCIRC boundary for the river flux method. Note that the terminating point is well inside the domain for Tar River and Fishing Creek, which will be discussed when results are presented.

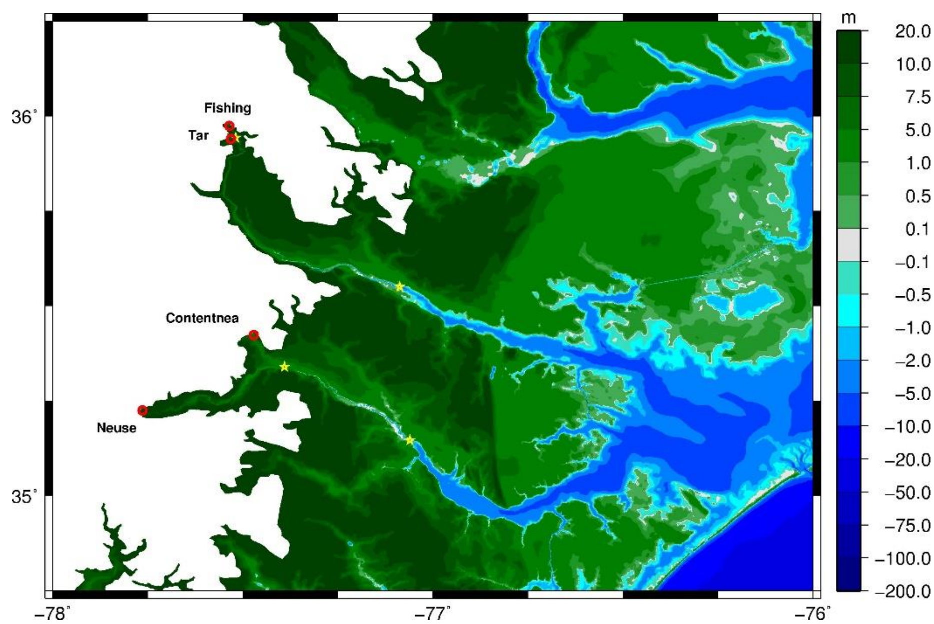


Figure 6. Topographic and bathymetric detail of Neuse and Tar River basins with four main features highlighted. Red circles indicate the location for point source input and yellow stars indicate the endpoints of the transects down the center of each main feature.

Tides and riverine flows are spun up within the simulation domain for a period of 20 days before the storm approaches the coastline and then winds are added during the storm. Modeled results are saved along a transect down the center of each channel. The endpoints for these transects are indicated by yellow stars in Figure 6, note that these points are located at the confluence with the larger river in the case of Fishing and Contentnea Creeks and within the tidal estuary for the Tar and Neuse Rivers. The modeled water surface elevations for each of these transects near the end of Hurricane Isabel are shown below in Figure 7.

Note that an exact match with the river flux boundary method is not expected above the location where the NWM point source is input (vertical light-grey line), since no riverine flow is being added upstream from that location for the point source methodology. However, both river flux and point source inputs are consistent downstream of these points for this real-world application, further validating the methodology used to add riverine and lateral inflows as point sources.

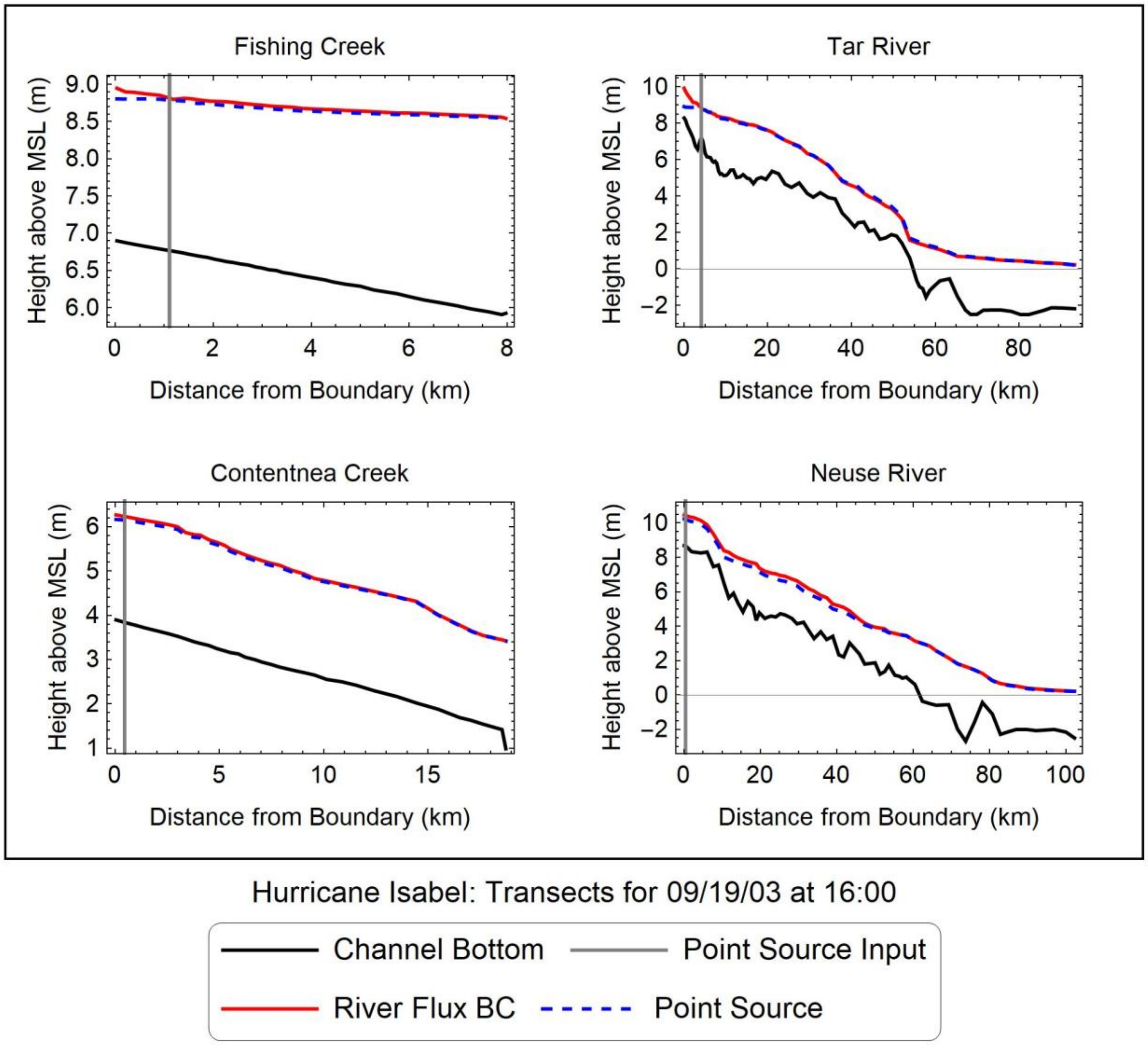
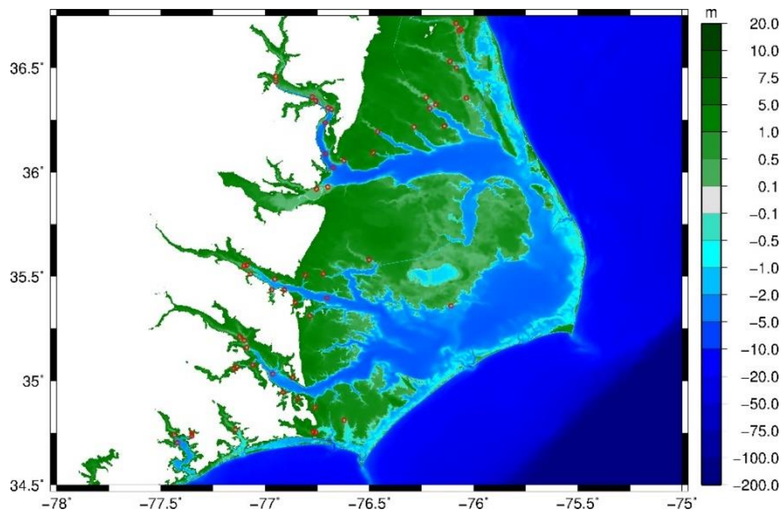


Figure 7. Water surface elevations along each feature for Hurricane Isabel on Sept 19, 2003 at 4pm. Vertical light-grey lines indicate the channel location where the point source is input within ADCIRC from the NWM, while river flux inputs are all located at 0km from the river boundary.

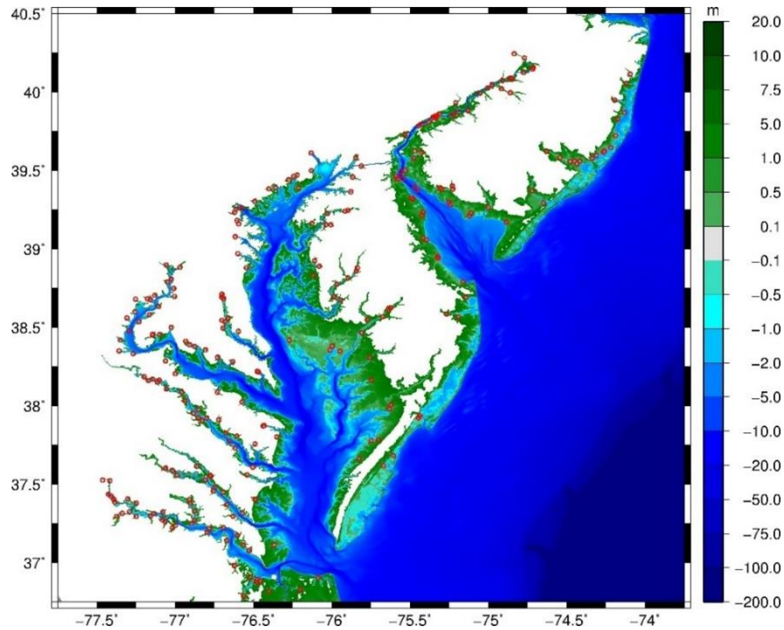
4.5 Real-World Application for Distributed and Point Sources: Hurricanes Isabel and Irene

Finally, the newly created 120m v2p2 mesh (M. Contreras Vargas, personal communication, March 2021) is tested for distributed and point sources during Hurricanes Irene and Isabel. These simulations are included as proof of concept for the NWM inclusion process but are not actual validation results, as wind-induced waves and a tidal spinup were not included in the ADCIRC simulations. No fine tuning was done to any of the methodology or ADCIRC mesh and nodal attribute files. Rather the preprocessing tools provided in the Appendices were applied directly to the ADCIRC meshes for the 120m model and then a simulation with point and distributed sources was run using the resulting input files.

For these storms, results will be shown for the Pamlico Sound region along the North Carolina coast, as well as within the Delaware and Chesapeake Bay area. Figure 8 shows the bathymetric and topographic detail for these two regions, along with the location of NWM feature endpoints that are included through the new point source capability. Note that the nearest NWM feature endpoint that lies in water is selected for each feature, so although the figure may show multiple NWM sources along the center of a main channel, each of these is actually a contribution from various tributaries. Additionally, a procedure/data source for automatically defining the bathymetry of upland rivers from surveyed cross sections created for HEC-RAS models or other riverine bathymetry sources has not been developed, so that the upland bathymetry is not necessarily reflective of actual conditions.



a)



b)

Figure 8. Topographic and bathymetric detail of a) North Carolina and b) Delaware Chesapeake regions for the operational mesh. NWM feature endpoints indicated by red disks.

Additionally, the location of two COOPS stations (blue) and a transect along the center of the Delaware River (magenta) are shown in Figure 9. Time series will be shown for these stations to further illustrate the additional water due to the point and precipitation sources. The zero point indicates where distance will be marked as "zero" along the transect and corresponds to where the Delaware and Chesapeake Bays are connected near Delaware City; the transect proceeds upstream from this point past Trenton, NJ (about 129km along the river thalweg) to the ADCIRC model boundary.

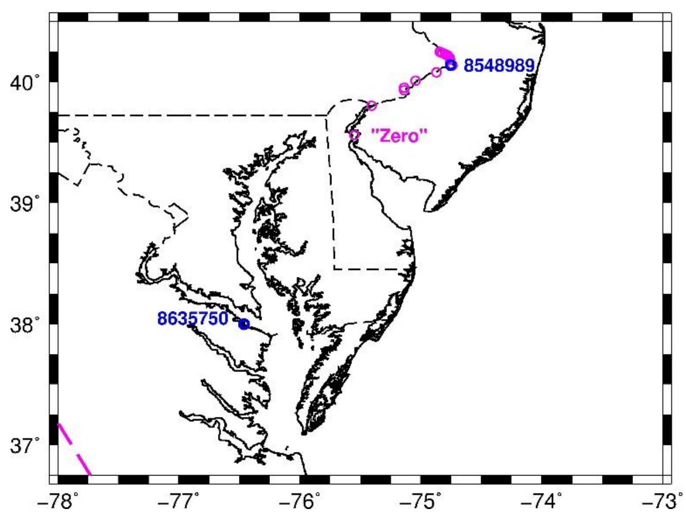


Figure 9. Locations of COOPS stations and transect for time series comparisons.

Hurricane Isabel. Cumulative precipitation measured over the eastern seaboard during Hurricane Isabel is shown in Figure 10. Note that the majority of the rainfall follows the storm track over the Pamlico Sound with 3-5 inches and very little precipitation falls over the Delaware and Chesapeake Bays.

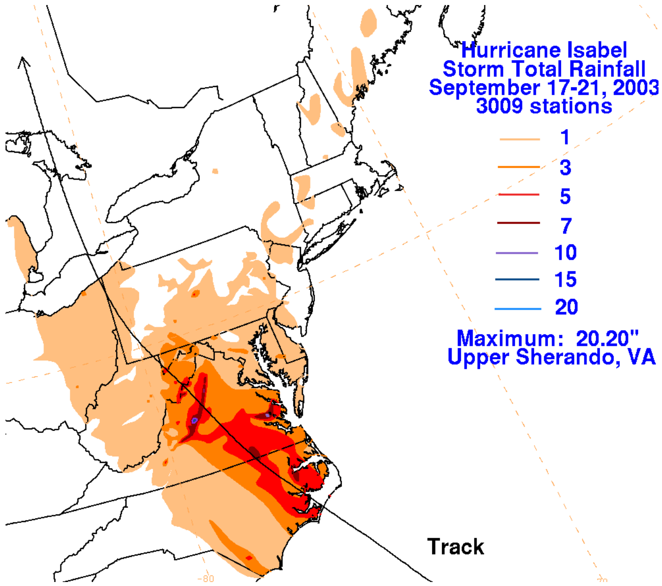
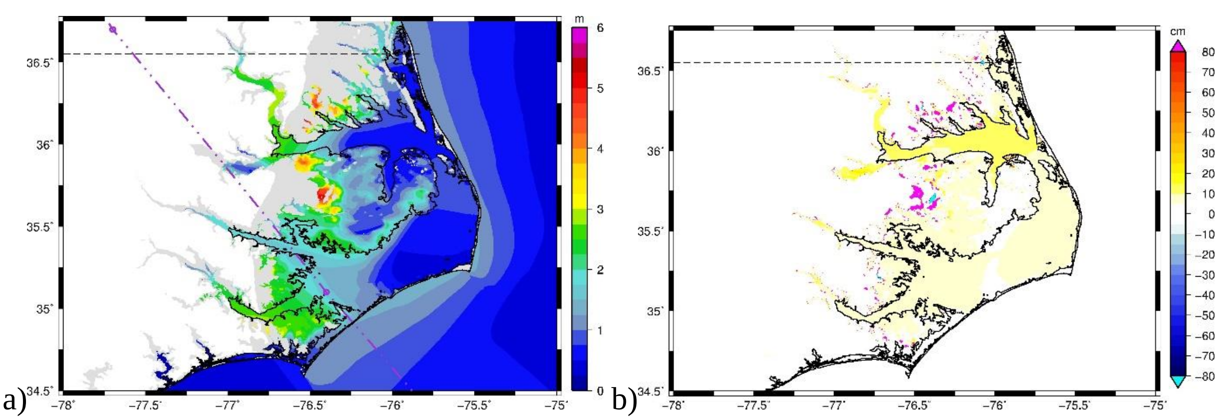


Figure 10. Cumulative rainfall for Hurricane Isabel (Beven and Cobb, 2004, NOAA TC, 2021)

Results for Hurricane Isabel over the North Carolina coast and Chesapeake-Delaware Bays are shown in Figures 11 and 12 respectively. For each figure, the combined water level with both rainfall and point sources, the water level differences due only to precipitation, the water level differences due only to NWM point sources and the water level differences due to both sources are shown. As in Figure 4 above, magenta colors on the difference plots indicate regions that are wet with the additional sources but were dry with the tide and wind only simulation while cyan regions indicate the opposite. Also note that differences of less than 5cm are not visible on the difference plots.



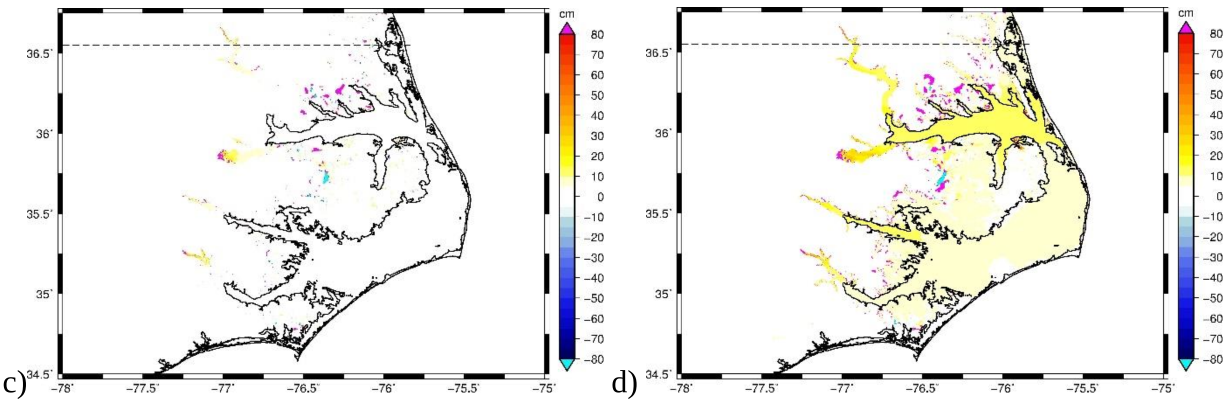
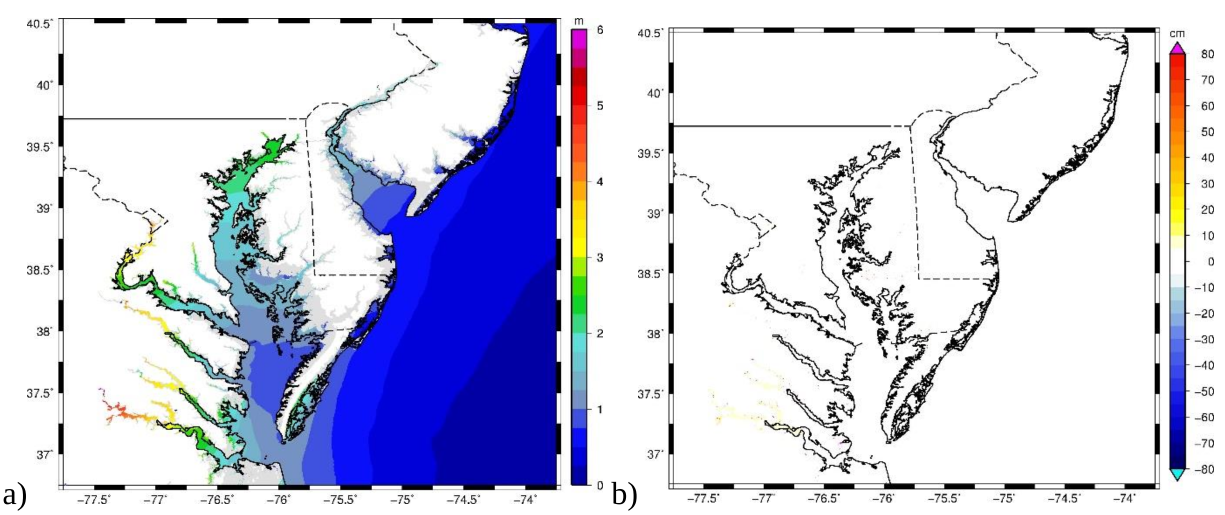


Figure 11. Results for Hurricane Isabel over the North Carolina coast: a) combined water level with tides, winds, rainfall and NWM, b) water level differences due only to precipitation, c) water level differences due only to NWM streamflows and d) water level differences due to both sources. Storm track indicated by the dashed lavender line in panel a) and solid black lines denote the coastline.

Note that an additional 5-15cm of water surface elevation is gained in the Pamlico sound region due to the precipitation (as indicated in Figure 11b), with higher values in the upland regions due to the localization of the heavier precipitation. Also note that the additional water due only to point sources (Fig 11c) is much more localized during the storm itself. The upland regions, and hence NWM streamflows being fed into ADCIRC as sources, are delayed as the rainfall is routed within the overland area and then fed into the streams and rivers. This hydrological process takes more time, and the riverine flooding will often happen after the storm has completely passed the region. Finally, notice that the differences for the combined flooding with all sources (tides, wind, precipitation and streamflow) shown in Figure 11d is not just a linear superposition of the precipitation and point source contributions shown in Figures 11b and 11c. Rather the combined WSE is often greater as further wetted nodes allow each individual source to be activated earlier than they would on their own.



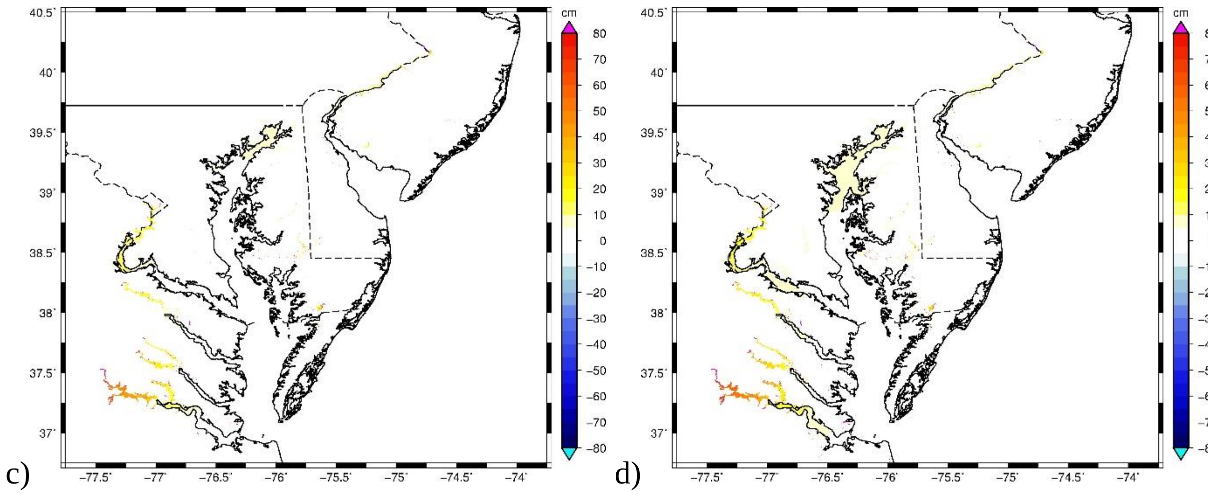


Figure 12. Results for Hurricane Isabel over the Chesapeake and Delaware Bays: a) combined water level with tides, winds, rainfall and NWM, b) water level differences due only to precipitation, c) water level differences due only to NWM streamflows and d) water level differences due to both sources. Solid black lines denote the coastline.

In the Delaware and Chesapeake Bay region, where there was little precipitation, no discernible difference is noted when precipitation is added as a source (Figure 12b). However, the addition of NWM streamflows over the western edge of the Chesapeake Bay upland region is more significant owing to the higher precipitation and thus runoff (Figure 12c). Finally, when both sources are included (Figure 12d) the upland regions along the Chesapeake have slightly higher elevations due to the combined sources. This is further illustrated if we compare the time series at the two stations presented above, which are shown in Figure 13.

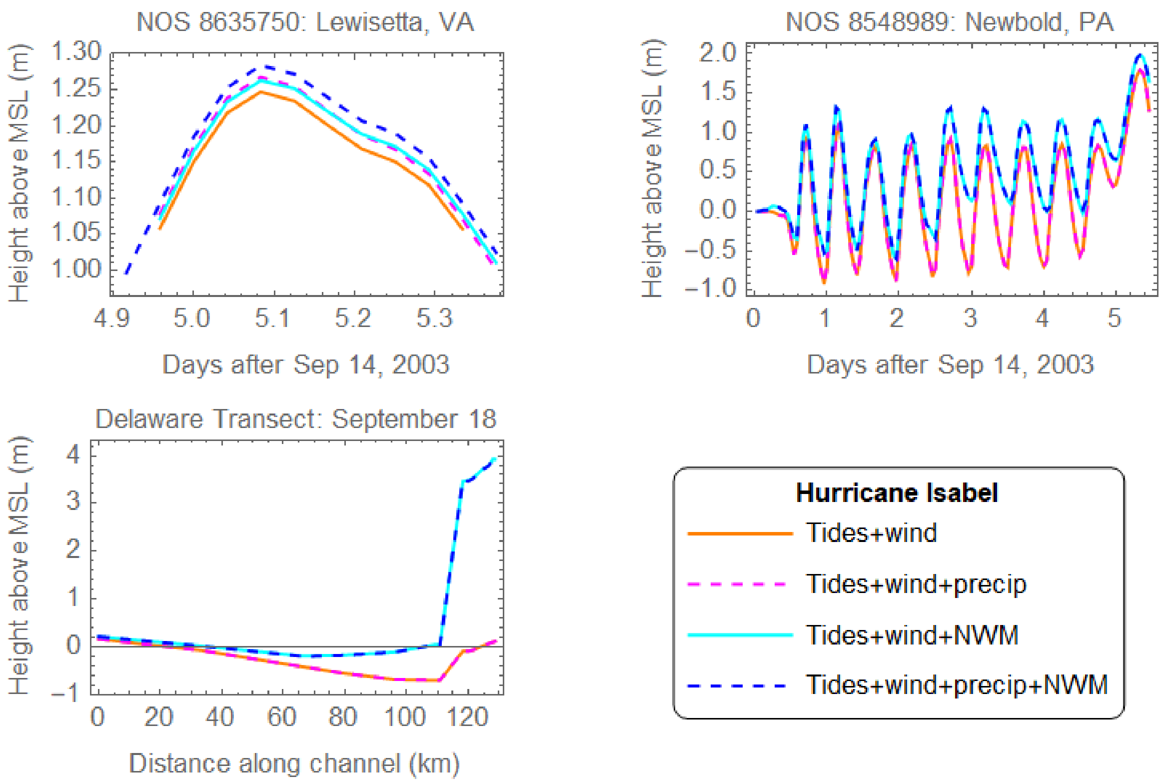


Figure 13. Sample station timeseries in the Delaware and Chesapeake region for Hurricane Isabel: a) timeseries at Lewisetta, VA, b) timeseries at Newbold, PA, c) Delaware River transect on September 18, 2003 (precipitation does not significantly affect results at this location).

Looking first at Newbold, PA where there was little rainfall during Hurricane Isabel, we note that there is no discernible elevation change due to precipitation (the solid and dashed lines overlay one another). Meanwhile, at Lewisetta, VA the station is only wetted near the end of the storm and there is a minimal change due to precipitation (less than 5cm for the base tides+wind results versus the total tides+wind+precip+NWM simulation; so it is not visible on the difference plots). Conversely, the temporal differences due to the addition of the NWM streamflows is higher at Newbold (up to 0.5m) where the Delaware River flows are significant, even though only about 20cm is noted in the difference of the maxele files. Meanwhile, there is only an addition of 0.02m at Lewisetta due to the NWM streamflows. Along the length of the Delaware River, the addition of the NWM streamflows is most impactful in the upland region with differences between 3 and 4m near the boundary of the mesh. While not shown in these plots, the bathymetry in the Delaware River is locked at 0.2m (or -0.2 on the transect panel) for all nodes above about 120km along the channel in the 120m model domain. Since there are no boundaries specified in the 120m mesh, the streamflows from the NWM are able to flow back into this flat region and get trapped at the boundary, perhaps building artificially high elevations. Either correct elevations for these mesh nodes or the use of a radiation boundary condition at the boundary of any channel would be necessary to prevent this behavior.

Actual changes in peak water surface elevation compared to the measured NOS peak are provided in Table 3; note that these values are only provided for comparison as this is not a true validation since a tidal spinup was not completed and wind-driven waves were not included. To save space, simulations are abbreviated as follows: tides+wind (TW), tides+wind+precip (TWPr), tides+wind+NWM (TWP), combined (TWPPr). Note that the addition of precipitation and hydrology produces a more accurate peak water surface elevation and that once again, the combined peak is not necessarily a linear superposition of the individual contributions for these new sources.

Table 3. Comparison of select peak WSE (m) with new source terms for Hurricane Isabel.

	Peak Water Surface Elevations (m)				
Station	NOS observed	TW	TWPr	TWP	TWPPr
Lewisetta	1.43	1.247	1.268	1.263	1.284
Newbold	2.02	1.788	1.791	1.979	1.980

Hurricane Irene. Cumulative precipitation measured over the eastern seaboard during Hurricane Irene is shown in Figure 14. Note that the storm track follows parallel to the coast and heavier rainfall (7-10 inches) falls over both of the study regions with peak precipitation of 15 inches over parts of the Pamlico Sound.

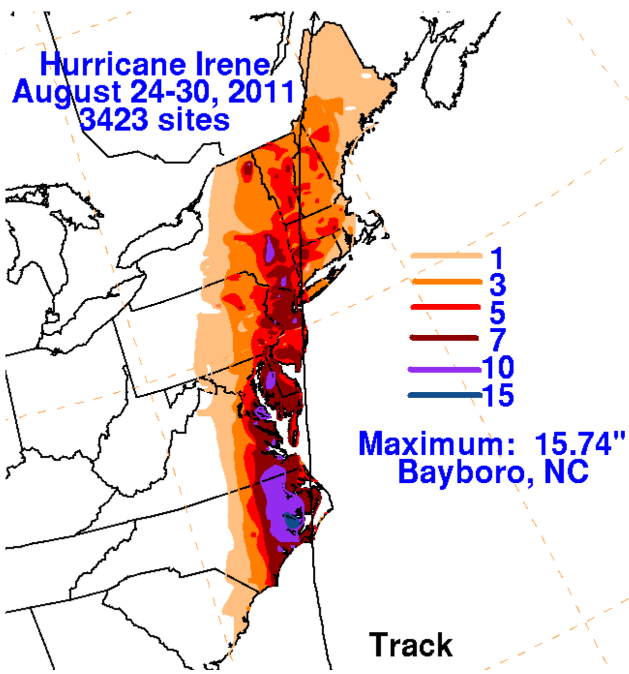


Figure 14. Cumulative rainfall for Hurricane Irene (Avila and Cangialosi, 2011, NOAA TC, 2021)

Results for Hurricane Irene over the North Carolina coast and Chesapeake-Delaware Bays are shown in Figures 15 and 16 respectively. For each figure, the combined water level with both rainfall and point sources, the water level differences due only to precipitation, the water level differences due only to NWM point sources and the water level differences due to both sources are shown. Once again, the magenta contours indicate regions that are wet with the additional sources.

Again, only about 5-15cm of additional water surface elevation is gained in the Pamlico sound region due to the precipitation (as indicated in Figure 15b). Since precipitation is distributed over a large area, it is more readily “absorbed” within ADCIRC and spread over the region; therefore, the higher WSE additions due solely to precipitation are often found over the narrower upland channels, which are slower to transfer the additional water to the surrounding nodes. Additionally, notice that there is very little additional WSE due to point sources during the storm itself and that it is very localized. Again, this is due to the time it takes for the precipitation to be routed into the hydrological model (NWM) before it is contributed to ADCIRC as point source streamflows. Similar patterns are noted for the results in the Delaware and Chesapeake Bays.

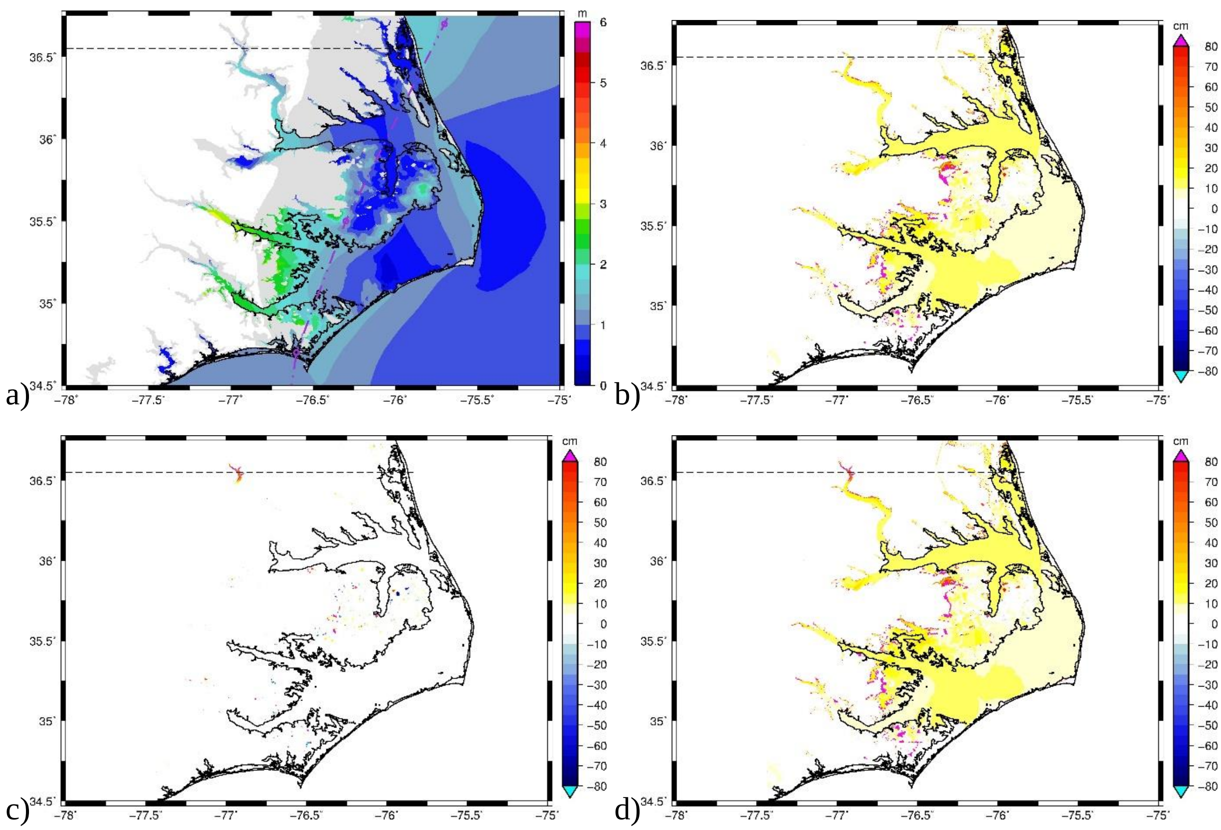


Figure 15. Results for Hurricane Irene over the North Carolina coast: a) total water level with tides, winds, rainfall and NWM, b) water level differences due only to precipitation, c) water level differences due only to NWM streamflows and d) water level differences due to both sources. Storm track indicated by the dashed lavender line in panel a) and solid black lines denote the coastline.

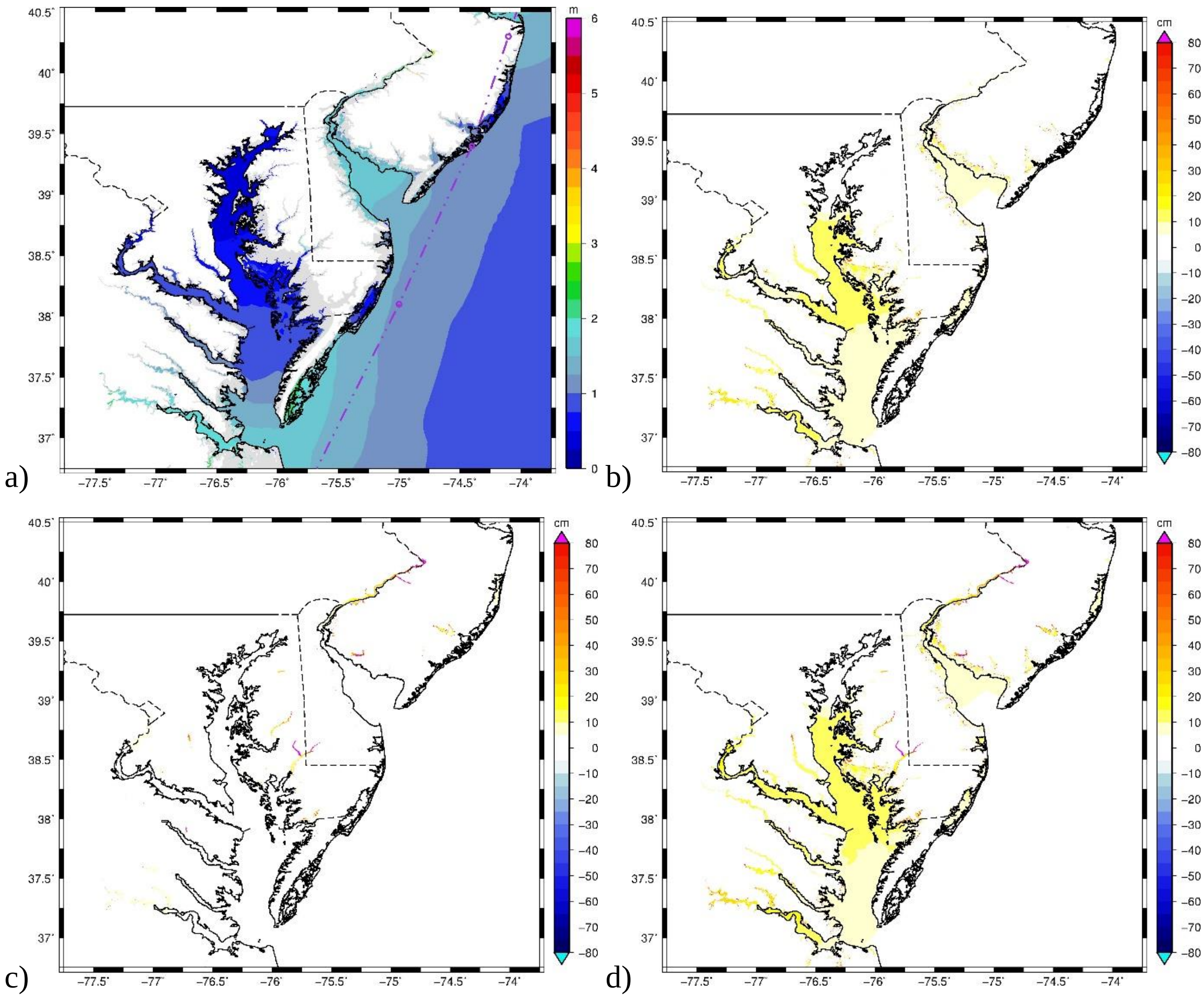


Figure 16. Results for Hurricane Irene over the Chesapeake and Delaware Bays: a) total water level with tides, winds, rainfall and NWM, b) water level differences due only to precipitation, c) water level differences due only to NWM streamflows and d) water level differences due to both sources. Storm track indicated by the dashed lavender line in panel a) and solid black lines denote the coastline.

Timeseries plots and a single snapshot of the Delaware River transect for Hurricane Irene are shown in Figure 17. In contrast to the results for Hurricane Isabel, the precipitation makes a more discernible difference at both locations. For Lewisetta, VA the station remains dry throughout the simulation when only wind+tides are input; however, it begins to get wet at about 2 days when wind+tides+precip are used as input and the addition of precipitation makes a difference of 5-8 cm from about day eight and on and is more significant than the NWM input. Meanwhile at Newbold, precipitation does not make any difference in the water levels, but the addition of NWM streamflows makes a significant contribution after day eight, with a 2m peak difference. Along the transect there is evidence that precipitation makes a small difference, while NWM streamflows contribute about 20cm of extra water elevation in the lower reaches and 1 to 3m in the upper reaches (although as discussed above for Isabel, most of this is likely due to the artificial channel topography).

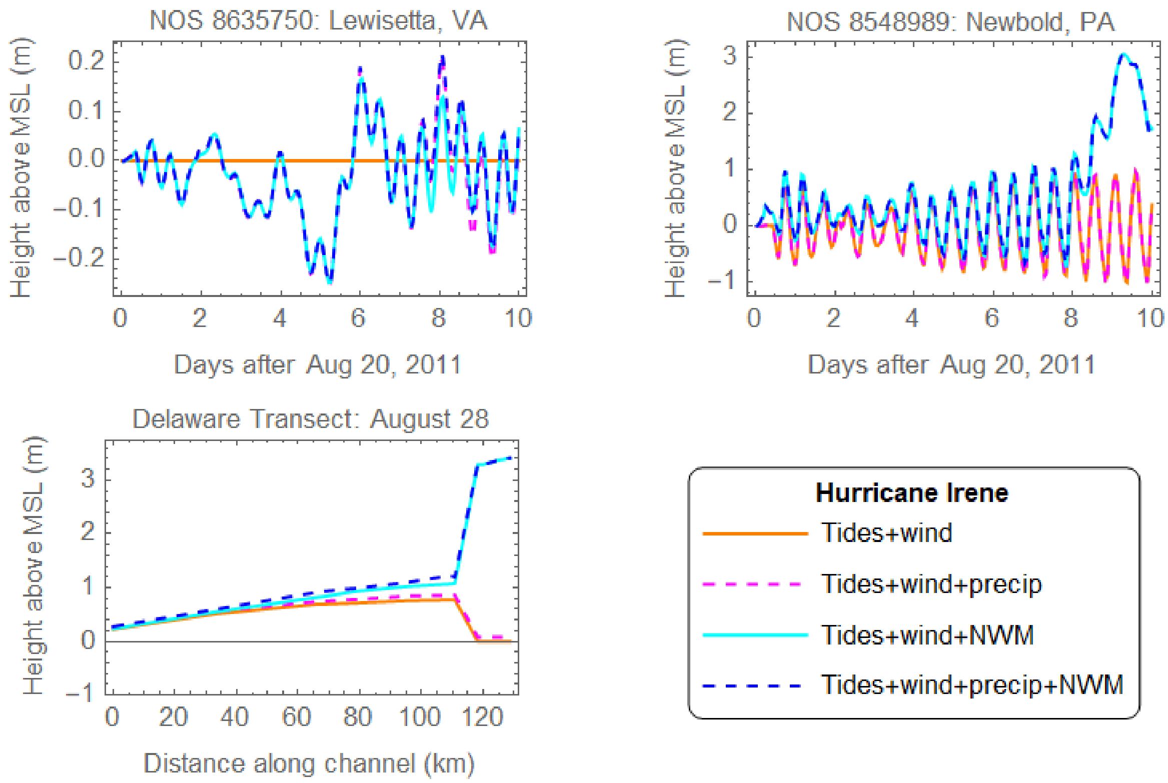


Figure 17. Sample station timeseries in the Delaware and Chesapeake region for Hurricane Irene: a) timeseries at Lewisetta, VA, b) timeseries at Newbold, PA, c) Delaware River transect on August 28, 2011.

Actual changes in peak water surface elevation compared to the measured NOS peak are provided in Table 4; again, this is not a true validation but only a comparison. Note that the addition of precipitation and hydrology produces a more accurate peak water surface elevation and that once again, the combined peak is not necessarily a linear superposition of the individual contributions for these new sources.

Table 4. Comparison of select peak WSE (m) with new source terms for Hurricane Irene.

	Peak Water Surface Elevations (m)				
Station	NOS observed	TW	TWPr	TWP	TWPPr
Lewisetta	1.13	0	0.209	0.168	0.219
Newbold	2.37	0.977	1.004	3.077	3.051

5. SUMMARY

A new algorithm for adding distributed and lateral/point sources to ADCIRC has been presented. The methodology was validated for idealized and real-world test cases and then applied to the new operational grid. This new capability allows a soft coupling of the NWM and precipitation products to ADCIRC in order to obtain a total water level flooding prediction during extreme events.

Results indicate that the methodology is stable and consistent with other forcing options. At this time, a soft coupling using input files and requiring pre-processing of NWM output and precipitation data is required to complete a total water level simulation. However, future work will include a more dynamic coupling through the CAP system, as well as options for adaptive coupling wherein the NWM/ADCIRC interface can move upstream as the domain is wetted.

It is important to note that the addition of upland hydrology through the NWM coupling is only as good as the bathymetry provided in these upland regions. Without proper bathymetry, the channels act as a conduit where water is allowed to backup into the region with unrealistic bathymetry, creating a lake above the input point of the sources. High streamflows will tend to flow back into these flat regions until they reach a barrier in the form of higher topography causing unrealistic pooling of water and potential instabilities. Note that higher elevations are occurring "upstream" of the NWM input locations due to low lying topography in these regions. It is important that the slope of these channels follow the natural slope of the surrounding terrain: even if they must be artificially deepened to a constant "depth", that depth must also reflect the slope of the underlying topography and not simply be a constant bathymetric value.

Figure 18 shows the difference in maximum elevations due solely to the addition of NWM sources for Hurricane Isabel using the 120m mesh; the location of the NWM input points are shown in green. Note that most isolated magenta areas, which indicate regions that were not previously wet in the winds+tides simulation, are wet due to disconnected channels and/or isolated low-lying areas in the model while magenta regions connected to obvious channels (warm colored difference contours) are the result of the above-mentioned pooling.

Thus, this is an area that requires further research as data sources are not readily available or in a usable form for upland channels, i.e., any hydrologic features added from the National Hydrography Dataset (NHD) (DeWald, 2015) that are above the tidal coastline will include the geographic extents but not the actual bathymetric depth. At the present, the most reliable source of data for these features are surveyed cross sections used to create hydraulic models (e.g., HEC-RAS). However, to our knowledge, there is no national repository that stores this data; rather it is often treated as the intellectual property of the organization that conducted the survey and/or created the hydraulic model. Some elevation data may be available through the NHDPlus High Resolution dataset (Buto, 2020), but to our knowledge any available elevation information from this source has not been utilized.

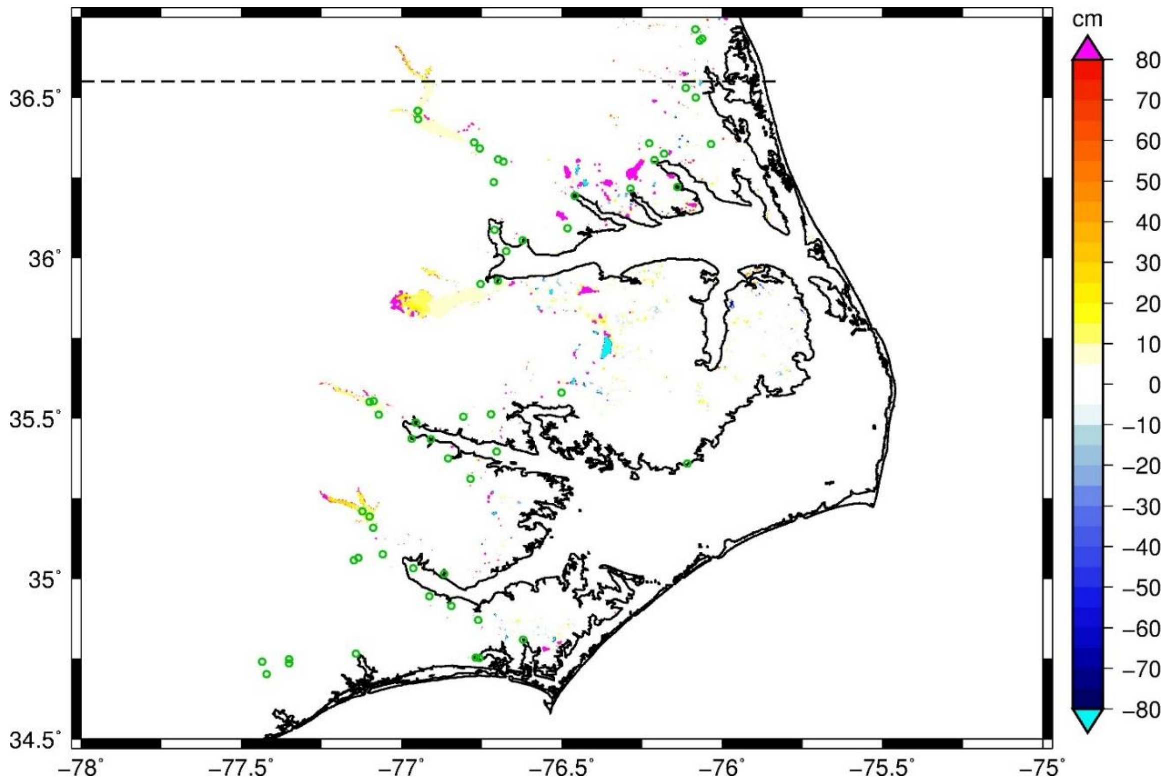


Figure 18. Location of NWM input points overlaid on WSE differences due only to NWM sources for Hurricane Isabel in the North Carolina region of the 120m model. Solid black lines denote the coastline.

ACKOWLEDGEMENTS

Figures 4, 6, 8, 9, 11, 12, 15, 16 and 18 were produced using the FigureGen plotting tool (Dietrich et al, 2013). FigureGen is a wrapper for the Generic Mapping Tools (GMT; Wessel et al, 2013).

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APPENDIX A: PREPROCESSING SCRIPTS FOR PRECIPITATION

Preprocessing occurs in two phases: Phase 1 has been described in the text of the document on where to obtain the information for MRMS and Phase 2 is to actually extract the MRMS precipitation rates and create ADCIRC precipitation input (fort.425 and fort.427). A description of Phase 2 and the tools that it uses, as well as the input that they require, is provided below.

Phase 2: Prepare ADCIRC precipitation rates input

The second setup phase takes the MRMS archived products and creates the precipitation input for an ADCIRC run for a user specified time frame. The user must be careful to choose an appropriate time frame for the given storm/scenario. This phase will be run multiple iterations – once to develop the spinup phase of the simulation, once for the storm phase of the simulation and once for the spindown phase of the simulation. This is done to limit the size of the input files for ADCIRC. To ensure that ADCIRC does not run into an issue with the number of snaps in the file, it is suggested to add at least one additional snap to the file. For example, for Hurricane Irene, if the spinup for the simulation runs from Aug. 10, 2011 at 00:00:00 GMT to Aug 19, 2011 at 23:00:00 GMT taking rainfall rates at every hour then one would need to provide information up to Aug. 20, 2011 at 00:00:00 GMT.

For the beta version, this is a script process: Part 1 of the Bash script converts the precipitation files from MRMS that encompass the entire continental US to the area of interest for the storm using the GDAL commands and then produces the NetCDF files for the second part of the script. Part 2 of the script takes the NetCDF files developed from the first part and develops the ADCIRC files in the OWI format.

<u>rainfall_development_files.sh: (Bash)</u>

This script queries the user for the time range that they wish to setup for a MRMS rainfall enabled ADCIRC simulation. It takes the downloaded files from the website and the script uses GDAL commands and calls a Fortran program to develop the ADCIRC precipitation file. All files must either be located in the calling directory or referred to by full path.

Required modules: GDAL and NetCDF. The NetCDF module must be the same one utilized in compiling the Fortran program. Each of these are called in the script, which may have to be updated according to your computer. See lines 80 and 240 for module loads and edit as necessary for your system.

Uses: prec_netcdf.f90 (must be in the calling directory)

User input: (10 lines if using redirected input)

- filepath: Working directory – full name is needed (i.e., /scratch/yourname/rainfall)
- startdate: Start date for rainfall – needs to follow this format: YYYY MM DD HH MM SS (GMT time)

- endtime: End date for rainfall – needs to follow this format: YYYY MM DD HH MM SS (GMT time)
- source: Type of rainfall (i.e., MRMS)
- hurricane: Name of the storm (i.e., Isabel, Sandy)
- inttime: Time interval between the rainfall files in seconds (i.e., 1800) to be processed in ADCIRC
- timeset: Time interval between the MRMS data files in seconds (i.e., 300)
- methoddata: Methodology for filling missing precipitation information (1 or 2)
- dimenbox: Corners of the box for either the regional or basin scale – needs to follow this format: xmin ymin xmax ymax
- gridres: Grid resolution in each direction – needs to follow this format: xres yres

Script output:

This script, in combination with the called Fortran program (see below), creates an ADCIRC precipitation input file (fort.425) for the date/time range specified by the user. Note that the file developed will appear in the directory with the NetCDF files and will have the name prec.425. Also note that if both regional and basin scale files are needed, then this setup will need to be run twice. The MRMS or other format's precipitation files will be looked for in the directory defined from the working directory the user gives plus the type of rainfall and name of the storm – thus the directory structure for a MRMS run for Hurricane Isabel would have the files in directories – filepath/MRMS_Isabel/. under that each of the days would have its own directory with the 5 (or the time frame available) minute snaps of the rainfall files for that day (e.g., filepath/MRMS_Isabel/ MRMS_PrecipRate_20030914). Note that if information is missing from the data files (i.e., time snaps missing) then the user can choose from two different methodologies to fill the missing data. Here are the two different methodologies:

1. The first methodology will utilize the previously available data in the time interval. For example, if the record is missing the precipitation at time 2100 and your time interval for the precipitation input to ADCIRC is 1800 seconds (30 minutes) then it will try to utilize the precipitation information from 2030 to fill the missing 2100 precipitation. If there are multiple missing files, the program will continue to examine other files at the given time interval until it has reached a 3-hour window from the time on the missing file. For example, it would only continue to look until it reaches 1800.
2. The second methodology will utilize the previously available data in the data interval. For example, if the record is missing the precipitation at time 2100 and your data interval for the precipitation files is 300 seconds (5 minutes), then it will try to utilize the precipitation information from 2055 to fill the missing 2100 precipitation. If there are multiple missing files, the program will continue to examine other files at the given data interval until it has reached a 3-hour window from the time on the missing file. For example, it would only continue to look until it reaches 1800.

prec_netcdf.f90 (Fortran)

This program changes the developed netcdf file from the first part of the script and develops the ADCIRC file for the precipitation. This fortran program will be called several times in the second phase of this script. It will output each time-snap for the given range of dates and times in the fort.425 or fort.427 files.

Required modules: Requires that NetCDF program be loaded during this part of the script. Note the NetCDF program must be the same one you compiled the program with. See line 240 for module loads and edit if necessary for your system.

User input: (4 lines if using redirected output)

- filename of the NetCDF file developed in the first part of the script
- countread – number of times the program is called – script keeps track of this number (number indicates whether to start or append to the file)
- currenttime – the time associated with the current NetCDF file
- endtime – the time associated with the final time to be written to the file. This is included in every write for the fot.425 file.

Script output:

This script will develop the file for the ADCIRC precipitation input file (fort.425) for a user specified date and time range. This range is controlled by the calling Bash script.

APPENDIX B: PREPROCESSING SCRIPTS FOR NWM

Preprocessing occurs in two phases: Phase 1 to locate all NWM features within the ADCIRC domain and create the location specific ADCIRC input file (fort.428/429) and Phase 2 to actually extract the NWM streamflows and create ADCIRC streamflow input (fort.430). A description of each Phase and the tools that it uses, as well as the input that they require, is provided below.

Phase 1: Find all NWM features and prepare location input files

The first setup phase should only need to be completed once for each new grid or anytime the coastline/river delineation changes. The first step finds all NWM features that end in the ADCIRC domain (classified by water or floodplain) and the second step filters these by a user selected minimum stream order and creates optional GIS files for visual QAQC. The second step can be rerun multiple times independently if the user wishes to compare different minimum stream orders; each time a new ADCIRC location input file will be created.

NWM_findin_ADCIRC.f90: (FORTRAN)

This program uses the kdtree algorithms to search the ADCIRC model domains and determine if the NWM features end in water, on the floodplain, or lie within water (all features that are entirely within the ADCIRC water domain are excluded as point sources, as they represent features that have already been included upstream). Users must include two ADCIRC model domains: one for water-only (with no land included but all above zero datum water features must be included) and one with the floodplain included, as well as a list of NWM features. Additionally, the user must specify an acceptable distance (meters) for a feature to be considered “near water” for further processing (see Important Usage Notes at bottom of this section for more details).

Required modules: The compiler used to create the executable must be loaded into the current session.

User input:

- water-only ADCIRC model (fort.14) – waterGrid
- central lon/lat for water grid – slam0, sfea0
- full ADCIRC model including floodplain (fort.14) - fpGrid
- NWM feature list for version of NWM being used (e.g. nwm_fcst_points_comid_lat_lon-v1-2_ALL.csv) - nwmFile
- Filename description for all output (e.g. NWM-DelBay-v5) - descrip
- Buffer distance (meters) for “nearness” to water – buffer (*For the Beta version, users should set this value to 0.0 – testing is ongoing to optimize the buffer algorithm to reduce the level of human QAQC required. If the user wishes to play with this value and compare results, 25.0 is the recommended default value.)*

Either user prompts or redirected input from a file can be used: NWM_findin_ADCIRC.x < search.in

Program output:

- **descrip-water_Features.csv**: list of found features that end in water, formatted as follows:

  OBJECTID, featureID, Shape_Len, xlat, ylon, xlat_up, ylon_up

  where the midpoint information for the NWM feature has been removed from the original list provided as input, but otherwise the format is the same.

- **descrip-floodplain_Features.csv**: list of found features that end on floodplain, same format as output water_Features list
- **descrip-nearwater_QAQC.csv**: list of found features that may end in water – requires visual QAQC and further processing and contains all of the original information provided in the NWM feature input list

<u>NWM-preprocess.py: (Python)</u>

This program queries the NWM shapefiles to determine the flow network of features found in the above program, as well as further process the list of QAQC features using feature lengths and classification of "how the feature was near water" from the above search.

Required modules: GDAL (uses ogr from osgeo) for processing the GIS files and Python v3.6 or higher must be loaded in your current session.

User input:

- Choose if want GIS shapefiles created for visual QAQC in addition to ADCIRC input files (1-shapefiles, 2- input only)
- NWM shapefile that goes with NWM feature list above, e.g., nwm_channels_v12.shp (required even if choose 2 above since need to query database for feature information, e.g., stream order and network)
- Descriptor for input/output filenames, must be same as descrip for NWM_findin_ADCIRC.f90 as it will create input filenames
- Minimum NWM stream order to include in the results, acceptable range is [1,6]. Choose 1 if you want to see all NWM features.
- Are you going to run ADCIRC with the NWM floodplain network activated (NCPSOURCE = 4) or only include the features that end in water (NCPSOURCE = 3)? Please verify that option 4 has been activated in ADCIRC before selecting 4." Enter 3 or 4:

Program output:

- **descrip-water_fort.428/429** (formatted as required for fort.428/429)
  # features that end in water
  lonEnd latEnd fort.428
  featureID lonEnd latEnd *(lonTo latTo)* fort.429
- **descrip-floodplain_fort.429** (formatted as required for fort.429)

features that end on floodplain
featureID lonEnd latEnd lonTo latTo
ONLY TO BE USED WITH NCPSOURCE=4 OPTION

ONCE THIS OPTION IS ACTIVATED, THE SCRIPT WILL BE UPDATED TO COMBINE BOTH THE WATER AND FLOODPLAIN FORT.429 FILES INTO A SINGLE FORT.429 FILE (WITH WATER FEATURES LISTED FIRST).

- **descrip-qacq_Details.csv**: information from the shapefiles about the features that remain to be visually QAQCed

  # features that need visual inspection
  featureID lonEnd latEnd lonTo latTo streamOrder Length

  This format allows the user to easily copy any features that they deem should be included and incorporate them in the fort.428/429 files already created, as well as provide useful information for future automation of this process. At the moment, this is all done manually, although the intention is to create a "finalizing" script that will take as input a list of features (from this file only) that the user wishes to include in the simulation and automatically add them (in featureID order) to the previously created fort.428/429 file(s).

- Optional: shapefiles for found water, floodplain and QAQC features

Additionally, a user friendly "master" script has been created to call each of the tools in order and create various input and QAQC products with a single command; both of the above tools must be in the calling directory. Similar input (as for the tools themselves) is required with the addition of a few user prompts to select the options that are desired. Either user interaction or redirected input from a file may be used when calling this script.

Find-NWM-inADCIRC.sh: (Bash)

This script queries the user for input and calls the above programs automatically. In addition to the programs themselves, several modules must be available on your computing system.

Required modules: same as above programs. Changes must be made within this script starting at line 110 (or search for module load).

User input: (12 lines if using redirected input)

- Descriptor for input/output filenames
- Full filename for ADCIRC water only grid
- Central longitude of the water only grid
- Central latitude of the water only grid
- Buffer distance for "near water" in meters – enter 0.0 if do not want to use
- Full filename for ADCIRC floodplain grid
- Full filename for list of NWM feature locations - nwm_fcst_points_comid_lat_lon-v1-2_ALL.csv for version 1.2

- QAQC selection: 1-create GIS files for visual qaqc and ADCIRC feature location input file, 2-only create ADCIRC location input
- GIS shapefile with NWM network details (all accompanying GIS files must be in call directory) – *this will change for NWM v2.0 depending upon structure of database*
- Minimum stream order to filter found NWM features [valid choice 1-6]
- How will ADCIRC be run? NCPSOURCE=3 (only features that end in water) or 4 (also include floodplain features)
- Filename containing list of any NWM features that should be excluded as point sources, e.g., if they are included in ADCIRC as river boundaries instead

Script output:

Same as above programs, except creates either fort.428 file of water-only features or fort.429 file with all water and floodplain features depending upon user selected choice for NCPSOURCE.

Important Usage Notes

While preprocessing has been automated as much as possible, it is still necessary to complete a visual QAQC check when one moves to a new study area. This is particularly true to identify features that are misaligned in the NWM implementation versus the ADCIRC model domain due to the coarser resolution of the CONUS scale NWM. This is primarily set by the buffer parameter used within the NWM_findin_ADCIRC.f90 tool. This value is specified in meters and should be closely tied to the minimum resolutions of the NWM and ADCIRC model domains. For example, if the NWM has a minimum resolution of 100m while ADCIRC has a minimum resolution of 30m, the user would want to specify a buffer value within that range [30,100]. The buffer works by comparing the distance from the NWM feature start/end point to the baricenter of the closest ADCIRC element (DIS) with the circumscribing radius of the same element (Rmax), see Figure B1. For this reason, users are cautioned against choosing too large of a buffer, otherwise too many features may be flagged for the user to visually inspect. Features that fall within this buffer difference from the ADCIRC water-only mesh go through additional tests to determine if they should be visually inspected or can be classified as water or floodplain features automatically. For the Beta version, very few additional tests are used, but several algorithms are being tested for the final scripts.

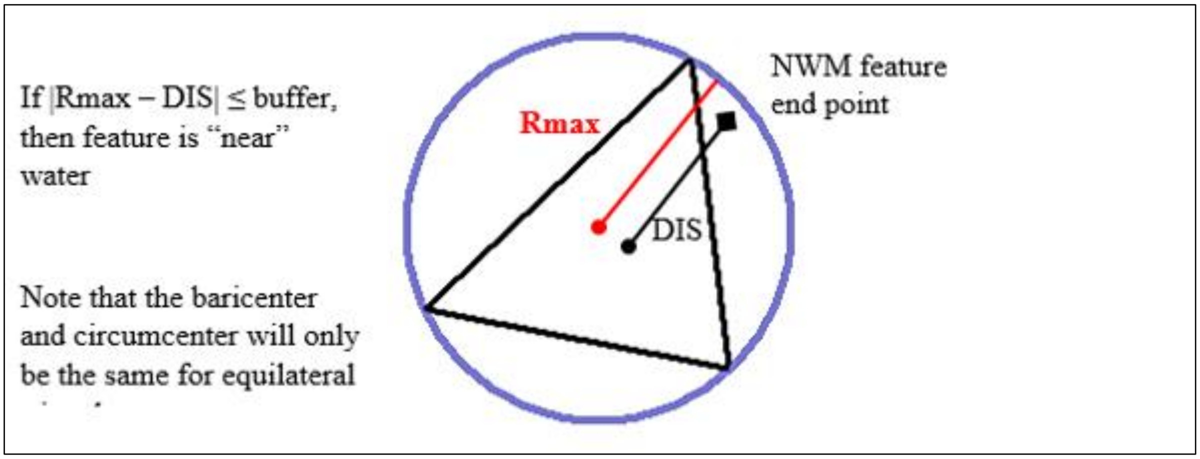

Figure B1. Example measurements used with buffer when finding NWM features that are near water.

Phase 2: Download NWM output from cloud and prepare ADCIRC streamflow input

The second setup phase actually queries NWM archived products and creates the streamflow input for an ADCIRC run for a user specified time frame. The user must be careful to choose an appropriate time frame for the given storm/scenario. This phase will be run multiple iterations – once for each storm/event that the user wishes to simulate.

For the beta version, this is a two-script process: 1) a Bash script controls setting up the date/time range, downloading the NWM output from archives, creates filenames and calls a second Python script; then 2) this Python script extracts the necessary streamflows in order to create the second required ADCIRC input file.

Setup-NWM-forADCIRC.sh: (Bash)

This script queries the user for the time range that they wish to setup for a NWM enabled ADCIRC simulation. It downloads the required files from the archived cloud server and calls a Python script to actually exact the streamflow for a user specified set of NWM locations, which are created during Phase 1. All files must either be located in the calling directory or referred to by full path.

Required modules: Python v3.6 or higher and netcdf4-python must be loaded in the current session

Uses: NWM-extract.py (must be in calling directory)

User input: (11 lines if using redirected input)

- AWS archive bucket choice: 1 – NWM v1.2 or 2- NWM v2.0 (currently not working)

- Short descriptive name for the created streamflow file (fort.430), e.g. Isabel_120m-grid, cannot contain spaces. The time range is automatically appended to this description so DO NOT include it.
- Filename containing the list of NWM featureIDs to extract streamflows for. These should be given in the same order as the NWM location file and is automatically created during phase 1 for each location file (fort.428/429).
- startY – 4-digit year at start of simulation
- startM – 2-digit month at start of simulation
- startD – 2-digit day at start of simulation
- startH – 2-digit hour at start of simulation
- endY – 4-digit year at end of simulation
- endM – 2-digit month at end of simulation
- endD – 2-digit day at end of simulation
- endH – 2-digit hour at end of simulation

Script output:

This script, in combination with the called Python script (see below), creates an ADCIRC point source/streamflow input file (fort.430) for the date/time range and list of NWM featureIDs specified by the user.

NWM-extract.py (Python)

This script accesses the NWM netcdf output file and extracts streamflows for a user specified list of NWM features. This list is created during Phase 1 of the preprocessing and will ensure that streamflow values are output in the same order as the lon/lat locations are read into ADCIRC. Users are cautioned against specifying a custom list at this step of the process unless they have verified the order in the accompanying fort.428/429 location file.

Typically, this script will be called several times from another script to populate streamflows for an entire range of dates and times. Each NWM output file only contains one time-snap of data.

Required modules: Requires that Python v3.6 or higher and netcdf4-python be loaded in the current session. Also uses numpy if not automatically loaded. See lines 64ff for module loads and edit if necessary for your system.

User input: (3 lines if using redirected input)

- filename for list of found featureIDs (first line should have the # of found features)
- filename for actual production or historical NWM channel output; naming convention is currently: YYYYMMDDHH00.CHRTOUT_DOMAIN1.comp
- filename for writing streamflow output (fort.430); if the file already exists, then streamflows will be appended at the end, otherwise the file will be created. This allows the script to be called multiple times to populate the ADCIRC input file from numerous NWM output files.

Script output:

This script will continue to append to an existing ADCIRC streamflow input file (fort.430) for a user specified date and time range until the full fort.430 file has been created. This range is controlled by the calling Bash script.

Tar Archive of NWM-ADCIRC Coupling Tools

A zipped tarfile containing all of the necessary tools to prepare NWM-ADCIRC runs is available. Please read the header information for each script/program to verify usage and necessary input, as well as any NOTES files provided in each subdirectory. This tarfile contains:

NWM-ADCIRC/

NOTES.txt details about file structure for this archive

find/ Phase 1: Find all NWM features and prepare location input files

Notes.txt	Description of all subdirectory files
NWM_findin_ADCIRC.F90	Step 1a: Identify NWM features in ADCIRC domain
NWM_preprocess.py	Step 1b: Create ADCIRC input and QAQC files
Find-NWM-inADCIRC.sh	Master script to complete both steps 1a and 1b
submit_find.sh	Batch submit script for Step 1a
submit_preprocess.sh	Batch submit script for Step 1b
submit_Find-NWM-inADCIRC.sh	Batch submit script for combined
TestFiles/	Sample input/output files for Phase 1
nwm_fcst_points_comid_lat_lon-v1-2_ALL.csv	list of all v1.2 NWM features start/end locations

setup/ Phase 2: Download NWM output from cloud and prepare ADCIRC streamflow input

Notes.txt	Description of all subdirectory files
NWM-extract.py	Python tool to extract from NWM output and append to ADCIRC input file
Setup-NWM-forADCIRC.sh	Shell script to query user for storm/event dates and then download the NWM files from Amazon Cloud Archive. Calls NWM-extract.py to actually extract from these files.
submit_Setup-NWM-forADCIRC.sh	Batch submit script for Phase 2
TestFiles/	Sample input/output files for Phase 2