DEMONSTRATION PLAN

Resource Conservation and Resiliency

Comparative Assessment of Total Water Levels for Coastal Military Facility Readiness and Resilience Using Numerical Models – Naval Station Norfolk (RC21-5028)

Jack A. Puleo (University of Delaware)
Chris Lashley (University of Delaware)
Fengyan Shi (University of Delaware)
Casey Dietrich (North Carolina State University)
Jenero Knowles (North Carolina State University)

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LIST OF ACRONYMS

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
ADCIRC	Advanced Circulation model (Class II)
BAA	Broad Agency Announcement
BEWARE	Bayesian network model for predicting runup
CACR	Center for Applied Coastal Research
CCAP	Coastal Change Analysis Program
CERA	Coastal Emergency Risks Assessment
CoNED	Coastal National Elevation Database
CONUS	Continental United States
CPU	Central Processing Unit
CRM	Coastal Relief Model
CSHORE	Cross-shore hydrodynamic and sediment transport model (Class II)
CUDEM	Continuously Updated Digital Elevation Model
Delft3D	Deltares 3D hydrodynamic model (Class II)
DEM	Digital Elevation Model
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
ETS	extratropical storms

FEMA	Federal Emergency Management Agency
FM	Flexible Mesh
FUNWAVE	Fully Nonlinear Wave model (Class III)
FY	Fiscal Year
GAHM	Generalized Asymmetric Holland Model
GEBCO	Generic Bathymetric Chart of the Oceans
GITHUB	Hosting service for software development
HPC	High performance computer
IG	Infragravity
IPCC	Intergovernmental Panel on Climate Change
L	Wavelength
lidar	Light detection and ranging
MPI	Message Passing Interface
MSL	Mean Sea Level
NaN	Not-A-Number
NCEI	National Centers for Environmental Information
NearCom	Nearshore Community Model (Class II)
NHC	National Hurricane Center
NLSWE	Nonlinear Shallow Water Equations
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NSN	Naval Station Norfolk
NTHMP	National Tsunami Hazard Mitigation Program
NWS	National Weather Service
RC	Resource Conservation and Resiliency (ESTCP program area)
RMW	Radius of Maximum Winds

SHORECIRC	Nearshore circulation model
SLOSH	Sea, Lake and Overland Surges from Hurricanes model
SLR	Sea Level Rise
SRTM	Shuttle Radar Topography Mission
SS	Sea and Swell
SWAN	Simulating Waves Nearshore model
XBeach	Deltares hydrodynamic model (Class II or Class III)
TVD	Total Variance Diminishing
TWL	Total Water Level
US	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VLF	Very low Frequency
WGS	World Geodetic Survey

LIST OF VARIABLES

B	Bathymetry factor (Russo model)
B_M	Mean normalized bias
C	A factor to account for hurricane speed and angle with respect to the shoreline (Russo model)
C_D	Wind drag coefficient
H	Wave height
i	Station location
K	Constant in the Hunt runup equation
n	Manning's roughness coefficient
N	Number of stations

NRMSE	Normalized Root Mean Square Error
P	Central pressure correction factor (Russo model)
r	Radius
R^2	Coefficient of determination
R	Runup
RB	Relative Bias
R_{max}	Maximum radius
RMSE	Root Mean Square Error
$R_{2\%}$	2% runup exceedance
S	Storm surge elevation
SI	Sensitivity index
U	Wind speed (Delft3D FM)
V	Velocity (wind)
V_{max}	Maximum wind velocity
β	Beach slope
ξ	Iribarren number
σ	Standard deviation of water level
χ	Value of estimated parameter after model perturbation
ψ	Model parameter being assessed

1.0 INTRODUCTION

1.1 BACKGROUND

Projected sea level rise (SLR) and associated storm intensity will cause an increase in total water levels (TWL) at coastal United States (US) military facilities over the coming decades (e.g. GAO, 2019; Hall et al., 2016; UOCS, 2016). Total water levels consist of the mean sea level, high tide, storm surge, and wave-induced runup (Figure 1). Numerous scenarios exist for SLR (IPCC; Hall et al., 2016; Parris et al., 2012; Sweet, et al., 2022) with ranges from 0.2 to 2.0 m over the next 100 years.

SERDP/ESTCP and other entities have funded research efforts for TWL to understand potential risk to military installations, coastlines, and infrastructure (e.g. Burks-Copes and many others, 2014; Donoghue et al., 2013; Hall et al., 2016). Many past efforts focused on single modeling group frameworks (e.g. Burks-Copes et al., 2014) to address these topics. A common framework is the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model used by the National Hurricane Center (e.g. Mayo and Lin, 2019). Typical approaches ignore relevant wave-induced components such as setup, swash (together called runup; Figure 1), and infragravity (IG) motions (Hall et al., 2016). However, operational models do not normally account for runup because of the computational expense. The United States Geological Survey (USGS) and National Weather Service (NWS) are remedying that defect by coupling the Extratropical Surge and Tide Operations Forecast Systems with empirical runup formulations (https://coastal.er.usgs.gov/hurricanes/).

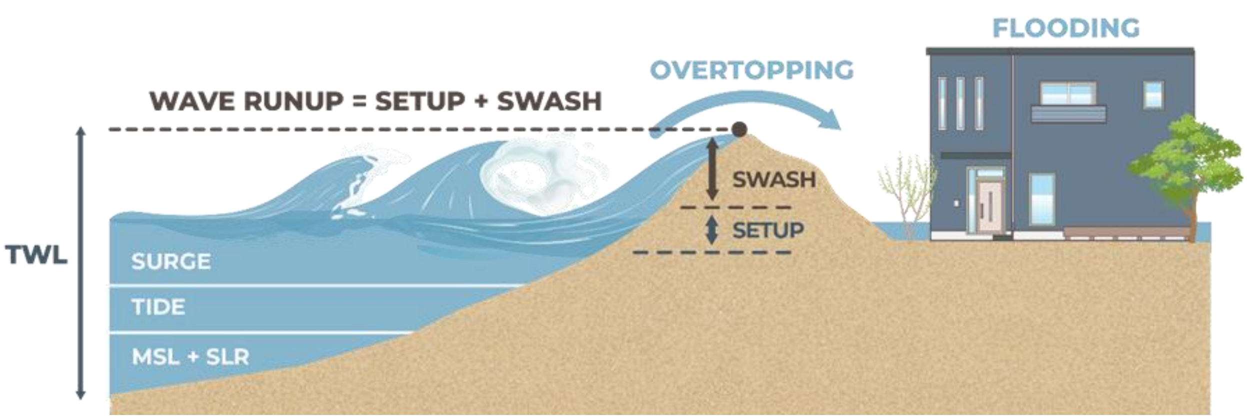

Figure 1. Schematic showing description of the different components of total water level.

Without waves, the underestimation of the TWL can be in excess of 20% (Mayo and Lin, 2019) on shallow sloping coasts and may exceed an order of magnitude on steeper coasts. For example, the largest SLOSH simulation errors (up to 80%) were identified for Hurricane Ernesto at Norfolk, VA (Mayo and Lin, 2019). Similarly, under non-extreme event forcing wave overtopping on shallow sloping beaches was an order of magnitude underpredicted when IG waves were neglected

(Lashley et al., 2020). Waves, IG, and other low frequency motions are also important for runup and overtopping on fringing reef-lined shorelines with steep offshore bathymetry (e.g. Cheriton et al., 2016; Quataert et al., 2020). Most modeling approaches do not account for active morphodynamics. Indeed, Hall et al. (2016) developed a comprehensive regional sea level scenario for over 1800 military installations. They indicate the approach taken in their study does not account for wave motions, non-linear response of storm surge processes, nor active morphodynamics. Yet, altered bathymetry may change the hydrodynamics and erosion during extreme event onset may exacerbate flooding risk (e.g. Van der Lugt et al., 2019).

1.2 OBJECTIVE OF THE DEMONSTRATION

Our objective is to enhance military installation readiness and resilience by performing a comparative assessment of a suite of projection methods for TWL and flooding. Ultimately, demonstrations will be conducted at three military installations spanning a range of geomorphologic and hydrodynamic forcing conditions. **This demonstration is associated solely with Naval Station Norfolk and adjacent areas (hereafter referred to as NSN)**. Projections will be made using a range of SLR scenarios (Sweet et al., 2022) and other modifications with the main emphasis on TWL induced by extreme event forcing, such as cyclones and extratropical storms (ETS).

The overarching objectives of this demonstration are to assess a range of modeling approaches that include wave, IG, and other nearshore processes, directly simulated or parameterized, to determine applicability, validity, computational cost, and skill in determining TWLs for NSN. We will undertake the demonstration along two thrusts: 1) Test a range of numerical models for predictions of TWL for Hurricane Irene as compared to the available in situ and anecdotal data, and then modify Hurricane Irene parameters to determine the impact on TWL; 2) Conduct model degradation studies for three additional hurricanes that focus on model performance by altering the boundary conditions. We aim to quantify model predictive capability relative to availability, accuracy, and resolution of forcing and bathymetry information (Figure 2).

1.3 REGULATORY DRIVERS

This demonstration project is in direct response to the FY 2021 Statement of Need for the ESTCP Resource Conservation and Resiliency (RC) program area (BAA, Topic area: B6: Coastal Total Water Level Model Comparative Assessment) that calls for efforts to assess presently available empirical, analytical, and numerical models for current and future coastal TWLs. In addition, the Department of Defense (DoD) climate change roadmap (DoD, 2014) identified SLR and storm surge among the top four climate change phenomena that may impact DoD activities.

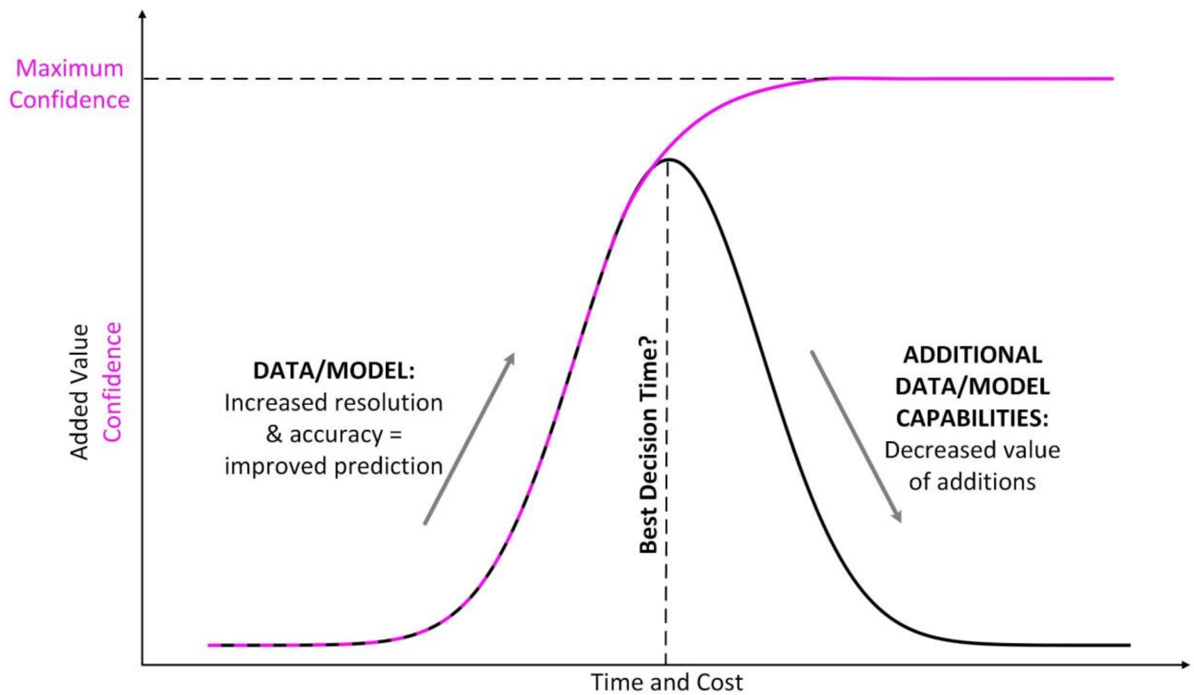

Figure 2. Schematic showing added value and model confidence as a function of time and cost

2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

TWLs will be predicted using a suite of simulation models from simple, low-cost empirical to complex, high cost (computation and effort) physics-based. Table 1 provides the proposed list and technical aspects of the models. The modeling approaches can be grouped into three classes. Class I includes empirical approaches that focus on simplified equations for storm surge (Russo, 1998) and runup (Stockdon, et al., 2006). Class II includes (coupled) process-based numerical models such as ADCIRC (Dietrich et al., 2011b; Luettich and Westerink, 2004), NearCoM (Shi et al., 2013) and Delft3D (Lesser et al., 2004). The models are essentially based on the Nonlinear Shallow Water Equations (NSWE) and resolve tides, surges, and statistical wave conditions. The models are dynamically coupled to spectral wave models such as SWAN (e.g. Sebastian et al., 2014). These models (except ADCIRC) have morphodynamics modules to compute sediment transport and bed level changes. Class III includes dynamical wave models that resolve the waves. The model used here is called FUNWAVE-TVD (Shi et al., 2012). The model is computationally demanding and can include morphological change. Class III models predict the effects of incident sea and swell (SS), IG, and very low frequency (VLF) waves on TWL (Gawehn et al., 2016); processes largely ignored in past efforts.

Table 1. Pros and cons of the models used in the demonstration.

Model	Pros	Cons
Empirical (Class I)	• Simple • Inexpensive • Widely adopted	• Poor resolution • Heavily parameterized physics • Limited validation
Delft3D (Class II)	• Well-validated for storm waves and surge • Unstructured meshes allow resolution to vary over several orders of magnitude • Computational efficiency allows simulations over 100's of kilometers and timescales of several days	• Model resolution limited to tens of meters at critical infrastructure • Does not resolve wave runup
SWAN+ADCIRC (Class II)	• Well-validated for storm waves and surge • Unstructured meshes allow resolution to vary over several orders of magnitude • Parallel efficiency to tens of thousands of computational cores	• Model resolution limited to tens of meters at critical infrastructure • Does not resolve wave runup
NearCom (Class II)	• 2DH with 3D dispersive effect • Consider breaking rollers and undertow	• Analytical solution-based vertical current profile • coupling between wave and current may be costly in the MPI scheme
FUNWAVE (Class III)	• Wave-resolving • Wave-current interaction • IG wave generation	• Computationally expensive; limited to domains spanning < 10 km and timescales < 1 hour • Shallow water limitation • Requires boundary conditions from Class II models

2.1A - Empirical Models

Empirical models for components of TWL are largely data-driven or based on machine learning (e.g. Pearson et al., 2017; Suanez et al., 2016; Tadesse et al., 2020). The empiricism is generally manifested through two components: storm surge and runup. Storm surge is the excess water level due to the wind stress acting over the ocean surface. However, surge magnitudes will also vary based on atmospheric pressure, forward storm speed, angle of shoreline approach, radius of maximum winds, coastal topography/bathymetry, and funneling into narrow water bodies (e.g. Irish and Resio, 2010; Needham and Keim, 2014; Resio et al., 2009). Simplistic approaches relate the surge, S, as (see Russo, 1998)

$$S = PBC, \tag{1}$$

where P is a central pressure factor, B is a bathymetry correction factor, and C is a factor to account for hurricane speed and angle with respect to the shoreline. All three factors have additional empirical formulations embedded within. Other relations generate surge with respect to some factor multiplied by the square of the wind speed divided by depth (e.g. WMO, 2011) or develop surge hydrographs as a function of time related to the peak surge elevation at landfall, storm duration, radius of maximum wind and forward speed (e.g. Xu and Huang, 2014). Only the Russo (1998) empirical approach is used for surge in this demonstration.

Runup, R, is the summation of wave set up and swash motions. Most empirical relations for runup incorporate the Iribarren Number, ξ, (Iribarren and Nogales, 1949) sometimes referred to as the surf similarity parameter that relates the beach slope to the offshore wave steepness. Hunt (1959) suggested the normalized runup (by wave height) is a function of ξ as

$$\frac{R}{H} = K\xi = K\frac{\beta}{\sqrt{\frac{H}{L}}} \tag{2}$$

where H is wave height, K is a constant, β is the beach slope, and L is the wave length. The majority of subsequent empirical relations for runup or the 2% runup exceedance, $R_{2\%}$, use the Hunt formula as the root form (e.g. Holman, 1986; Park and Cox, 2016; Stockdon, et al., 2006). It is noted that until recently (Park and Cox, 2016) the Hunt type formulations did not explicitly include beach profile geometry other than beach slope. The Stockdon et al. (2006) equation for runup exceedance is

$$R_{2\%} = 1.1\left[0.35\beta(HL)^{0.5} + \frac{\left(HL\{0.563\beta^2+0.004\}\right)^{0.5}}{2}\right], \tag{3}$$

where the wave height and wave length are the deep water values. Equation (3) can be simplified greatly for extremely dissipative conditions (NOT the case at NSN) to

$$R_{2\%} = 0.73\beta(HL)^{0.5}. \tag{4}$$

2.1B – Delft3D

Delft3D (Figure 3) is an open-source flexible integrated modeling suite, which simulates one-dimensional (1D), two-dimensional (2D; in either the horizontal or a vertical plane) and three-dimensional (3D) flow, sediment transport and morphology, waves, water quality and ecology and is capable of handling the interactions between these processes. The suite is designed for use by domain experts and non-experts alike, which may range from consultants and engineers or contractors to regulators and government officials, all of whom are active in one or more of the stages of the design, implementation, and management cycle. The Delft3D Flexible Mesh Suite (Delft3D FM) is the successor of the structured Delft3D 4 Suite, and it is developed and maintained by Stichting Deltares Netherlands as open-source software (www.deltares.nl).

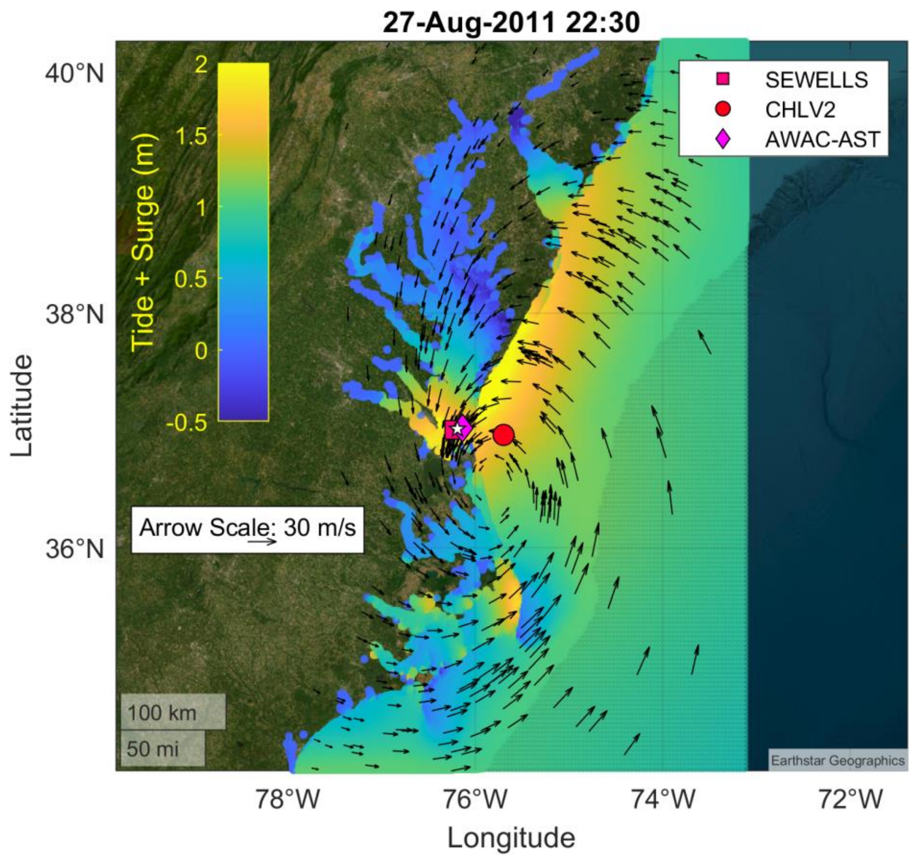

Figure 3. Example Delft3D FM output showing surge and tide at Norfolk (star marker) under hurricane forcing.

Delft3D allows simulation of the interaction of water, sediment, ecology and water quality in time and space. The modeling suite is mostly used for the modeling of natural environments like coastal, river, and estuarine areas, but it is equally suitable for more artificial environments like harbors and locks. Delft3D consists of a number of well-tested and validated modules, which are integrated with one another including D-Flow, D-Hydrology, D-Waves, and D-Morphology (Figure 4). In this demonstration, the D-Flow FM and D-Wave modules are coupled to simulate the interaction between the hurricane-induced wind, waves, currents, and surge.

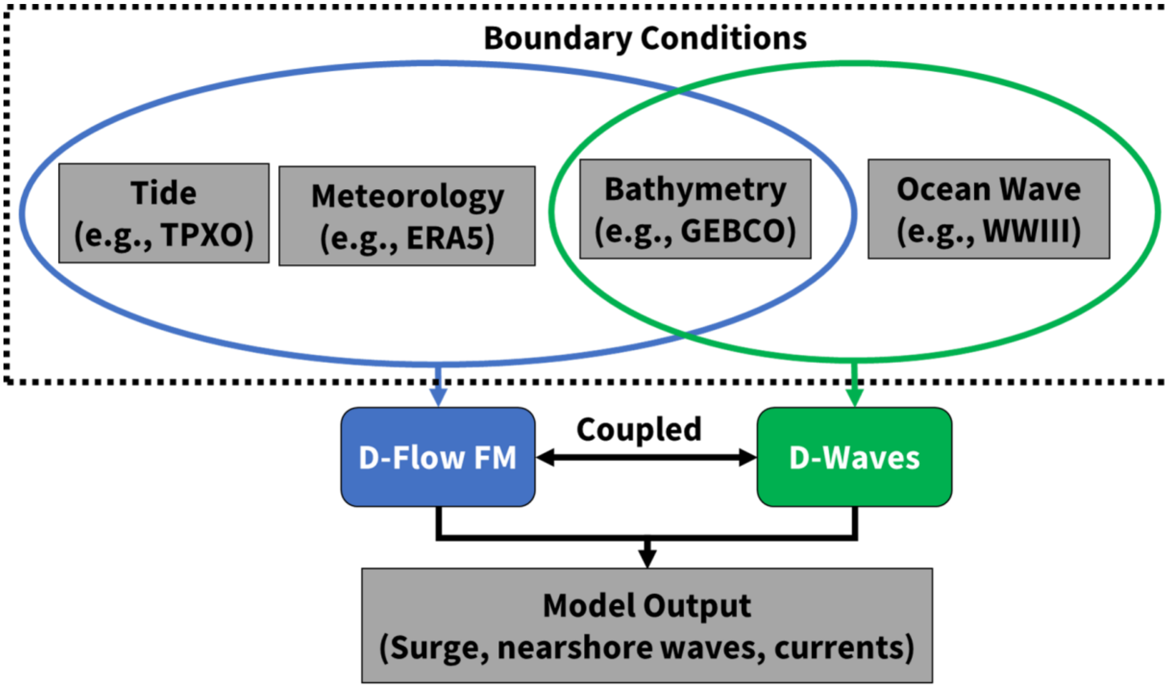

Figure 4. Schematic showing modeling process of Delft3D FM.

<u>2.1C – ADCIRC</u>

The ADvanced CIRCulation (ADCIRC; Figures 5,6) model uses the continuous-Galerkin finite element method to solve modified forms of the shallow water equations on unstructured meshes (Luettich and Westerink, 2004; Westerink et al., 2008). Water levels are calculated using the generalized wave continuity equation, which is a combined and differentiated form of the continuity and momentum equations (Kinnmark, 1986). Depth-averaged current velocities are calculated from the vertically integrated momentum equations. ADCIRC has achieved prominence in storm surge forecasting (Blanton et al., 2012; Fleming et al., 2007), hindcasting (Bunya et al., 2010; Thomas et al., 2019), evaluation and design of protection systems (Ebersole et al., 2007), and development of flood risk maps (FEMA, 2021). ADCIRC has been coupled with the Simulating WAves Nearshore (SWAN) model (Booij et al., 1999; Zijlema, 2010) to yield SWAN+ADCIRC (Dietrich et al., 2011b, 2012). SWAN+ADCIRC has been used operationally to forecast waves and coastal flooding during recent hurricane seasons, with guidance posted online (CERA; 2020; https://cera.coastalrisk.live) and shared directly with managers (Rucker et al., 2021).

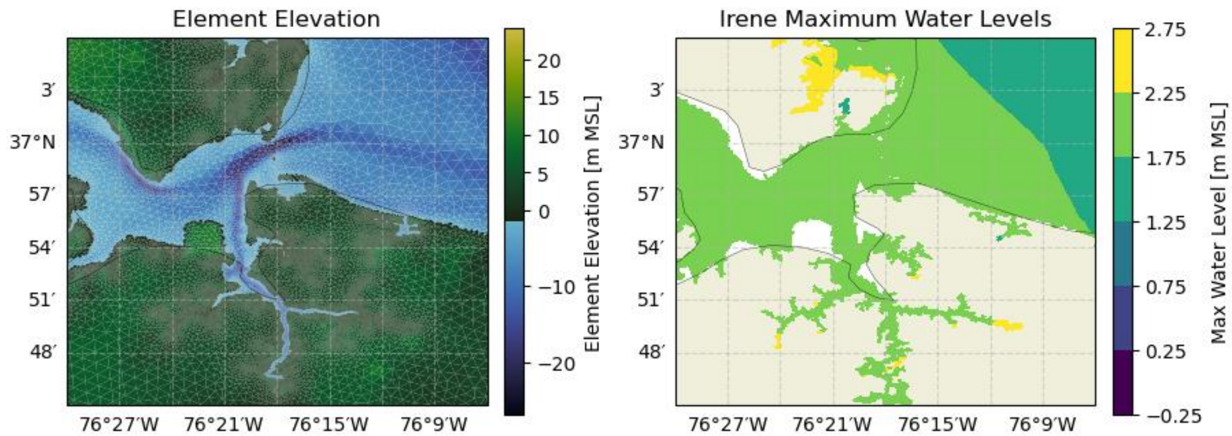

Figure 5. Schematic showing the preliminary mesh (left) and model results of flooding (right) near NSN in southwest Virginia from ADCIRC.

ADCIRC uses unstructured meshes with resolution ranging from kilometers in open water, to hundreds of meters near the coastline and through floodplains, and to tens of meters in the small-scale natural and man-made channels that convey surge into inland regions. Early project activities have included the development of meshes focusing on southwest Virginia (Figure 5), with mesh resolution down to 60 m near NSN. Pre-processing of the meshes included selecting digital elevation model (DEM) tiles with higher resolutions near Norfolk while reducing the resolution into the Atlantic Ocean. Using the DEMs, a shapefile was developed to represent the coastline and floodplains of the mesh to focus only on southwest Virginia. With the minimum resolution staged across the domains, most of the elements are centered at the NSN. A minimum resolution of 1 km was used across the Mid-Atlantic region and 10 km over the remainder of the Atlantic Ocean. OceanMesh2D (Roberts et al., 2019) was used to generate these finite element meshes.

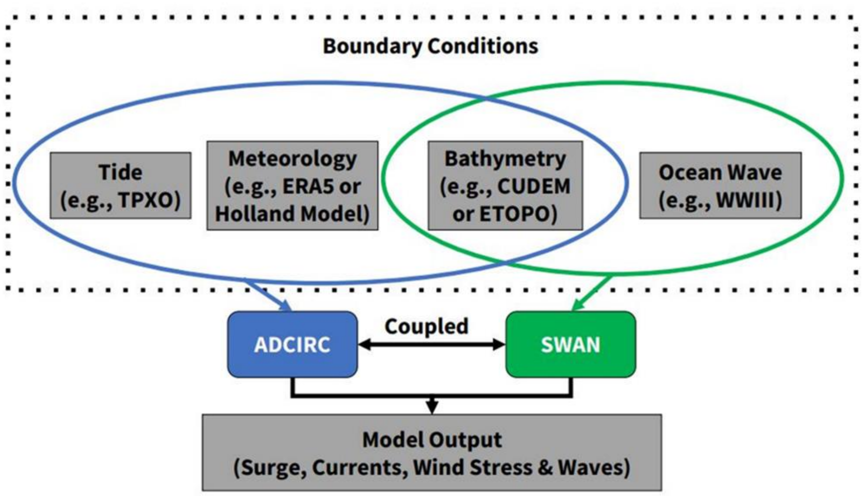

Figure 6. Schematic showing modeling process of ADCIRC

2.1D – NEARCOM

The Nearshore Community Model (NearCoM) is an extensible, user-configurable model system for nearshore wave, circulation and sediment processes developed during the National Oceanographic Partnership Program (NOPP). The model consists of a "backbone"; the master program, handling data input and output as well as internal storage, together with a suite of modules, each of which handles a focused subset of the physical processes being studied (Figure 7-8). A total of 10 modules exist; developed by a large group of researchers from various institutions. Example modules are: 1) A wave module simulates wave transformation over arbitrary coastal bathymetry and predicts radiation stresses and wave-induced mass fluxes; 2) A circulation module simulates the slowly varying current field driven by waves, wind and buoyancy forcing, and provides information on the bottom boundary layer structure; and 3) A seabed module simulates sediment transport, determines the bedform geometry, parameterizes the bedform effect on bottom friction, and computes morphological evolution resulting from spatial variations in local sediment transport rates.

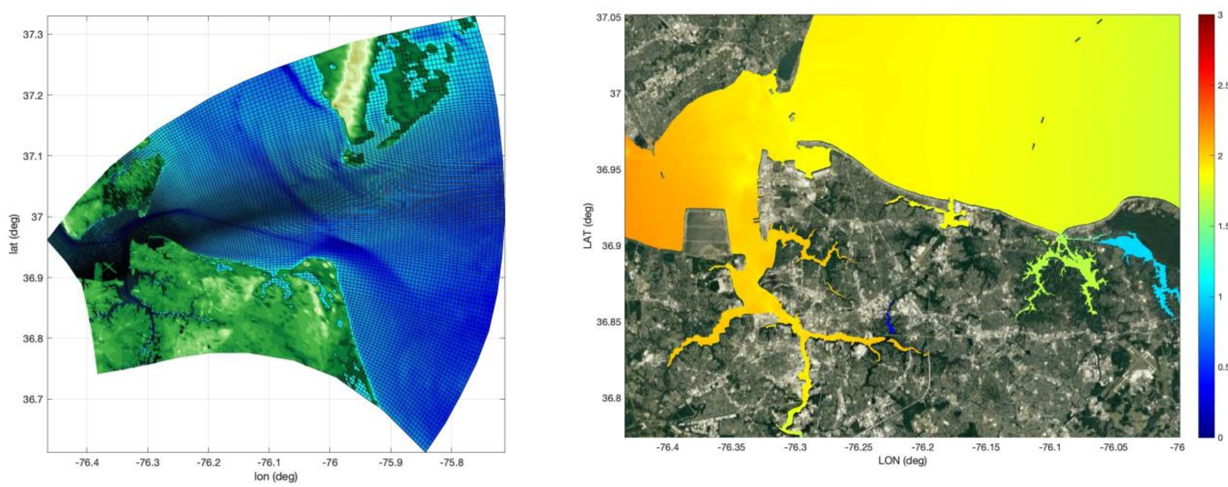

Figure 7. The computational grid (left) and an example of modeled surface elevation induced by an extreme storm event at Norfolk (right).

Recently, a new model coupling system called NearCoM-TVD (Total Variation Diminishing) was developed based on the MPI-based parallel computing framework. NearCoM-TVD couples a nearshore circulation model, SHORECIRC, using a hybrid finite-difference finite-volume TVD-type scheme on a generalized curvilinear grid, the wave model SWAN, and several selectable sediment transport modules (e.g. Kobayashi et al., 2008; Soulsby, 1997; Van Rijn et al., 2011) as shown in Figure 8. NearCoM-TVD is the standard version open to public and maintained in the GITHUB repository. Figure 7 shows the generalized curvilinear grid with the fine grid resolution at NSN and an example of modeled surface elevation by an extreme storm event at Norfolk. NearCoM-TVD is an open source code maintained in GITHUB with report (Chen et al., 2014; Shi et al., 2013) and online (WIKI page: https:// fengyanshi.github.io /NEARCOM-TVD /WIKI/ _build/ html/index.html) documentation.

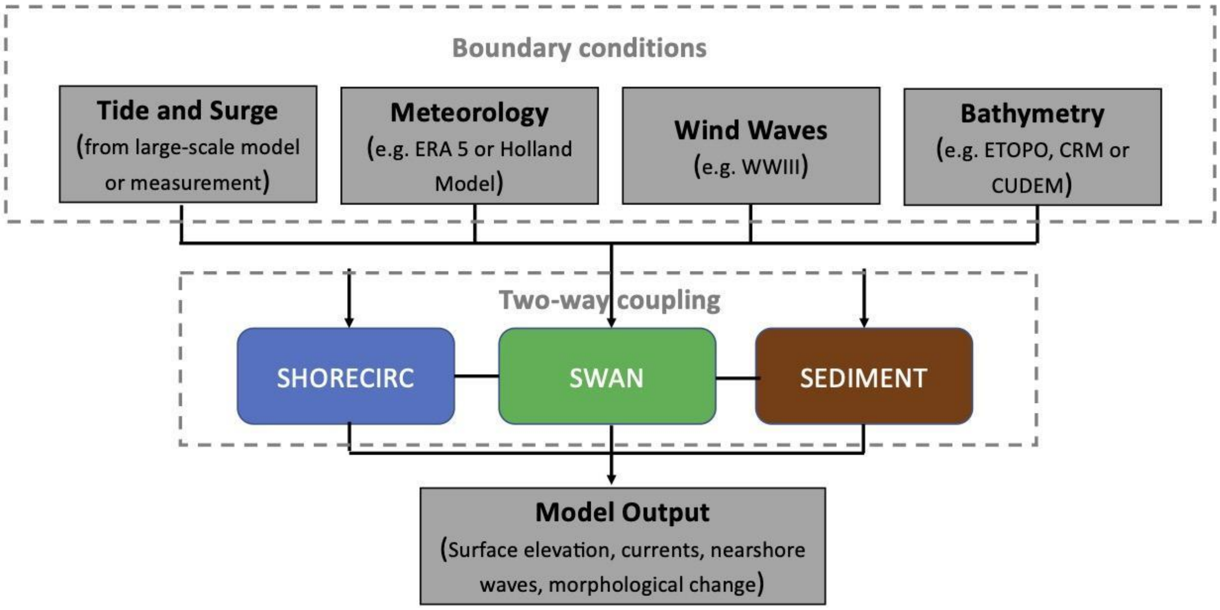

Figure 8. Schematic showing modeling process of NearCoM-TVD.

<u>2.1E – FUNWAVE-TVD</u>

FUNWAVE–TVD (Figure 9) is the TVD version of the fully nonlinear Boussinesq wave model (FUNWAVE) developed at the University of Delaware (Shi et al., 2012). It is a public domain model maintained by a group of institutions, including the Center for Applied Coastal Research (CACR) at the University of Delaware, Coastal Hydraulics Laboratory, USACE, and the University of Rhode Island. The FUNWAVE model was initially developed by (Kirby et al., 1998) based on (Wei et al., 1995). The development of the TVD version was motivated by a growing demand for phase-resolving modeling of nearshore waves and coastal inundation during storm or tsunami events, and predicting sediment transport and short-term morphological processes in a wave-resolving manner.

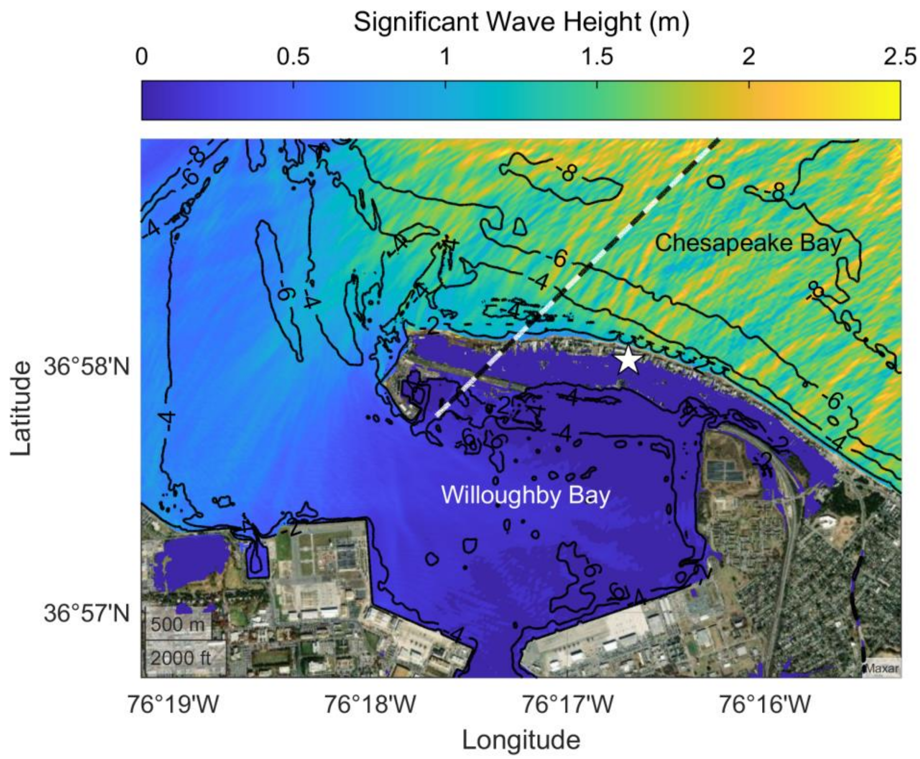

Figure 9. Example FUNWAVE output showing nearshore significant wave heights at Norfolk, VA under hurricane forcing.

As a nearshore shallow-to-intermediate water Boussinesq-type numerical wave model, FUNWAVE can resolve many coastal processes. Related to the scopes of this demonstration project, it can predict wave propagation/transformation, refraction, diffraction, reflection, nonlinear shoaling, wave-induced nearshore circulation, nonlinear wave-wave interaction, wave-current interaction, wave breaking, runup and overtopping, IG waves, nearshore sediment transport, and short-term morphological changes. The TVD-type solver particularly has an advantage in resolving wetting and drying processes accurately in modeling storm-induced coastal inundation. FUNWAVE-TVD has been benchmarked for wind wave application in a series of the USACE-funded projects, and tsunami application during the National Tsunami Hazard Mitigation Program (NTHMP) which provided the benchmarking standard for judging model acceptance for use in development of coastal inundation maps and evacuation plans. Source code, documentation, and descriptions and input files for carrying out benchmark tests and various example calculations are available at the FUNWAVE-TVD site (https://fengyanshi.github.io/build/html/index.html). In this demonstration plan, FUNWAVE is used to simulate the contribution of wave runup to coastal flooding under hurricane forcing with workflow shown Figure (10).

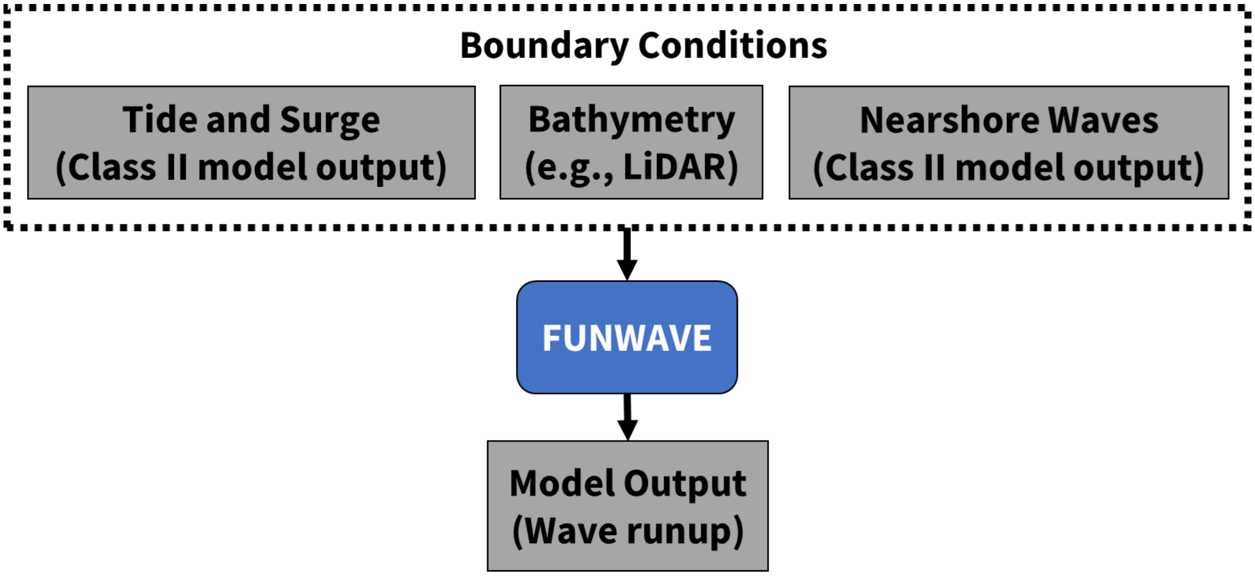

Figure 10. Schematic showing modeling process of FUNWAVE.

2.2 ADVANTAGES / LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

The demonstration seeks to determine suitability of a variety of prediction tools and identify ability to reach certain performance metrics. Of course, there are trade-offs depending on the numerical model used, the accuracy and output sought, the computational need, and manpower cost (Table 1); the latter related to expertise and experience with a particular modeling approach. The empirical models (Class I) are the most simple and cost-effective, but also provide the least fidelity. The different Class II models used are similar in their output and cost. The three models have been validated under a range of scenarios by the scientific and engineering community. However, the models lack the ability to resolve waves. The lone Class III model tested in this demonstration resolves waves, has a high spatial and temporal resolution, and a high computational cost. It cannot resolve tide and surge and requires Class II models to provide nearshore boundary conditions for model forcing.

There are numerous other numerical models used for hydrodynamic predictions; and only a subset can be realistically tested in this demonstration. For example, the Class II models (Delft3D, ADCIRC) share similar strengths and weaknesses to other models in this class. For example, one similar model is SLOSH which is used extensively by the U.S. National Weather Service (NWS) to estimate storm surge heights resulting from hurricanes (Jelesnianski et al., 1992). SLOSH solves simplified forms of the shallow water equations on a polar, elliptic, or hyperbolic grid, telescopic outward with a finer resolution near the center (coastline). SLOSH storm surge predictions depend strongly on accurate meteorological input such as hurricane size, intensity, forward speed, trajectory, and atmospheric pressure (Forbes et al., 2014). SLOSH-based models are computationally efficient and are used for ensembles of predictions in real-time and for climatological surge studies (Glahn et al., 2009; Zachry et al., 2015). SLOSH's strength is its efficiency; a SLOSH simulation can be carried out in a few minutes on a single computational core once bathymetry and forcing conditions are available. Thus, SLOSH can be applied for ensemble simulations to account for uncertainties in storm predictions. However, SLOSH's weaknesses include a relatively coarse model resolution that limits the accuracy in any single simulation, and it has only recently been extended to include tides and wave coupling.

Similarly, for Class III models, FUNWAVE is comparable to tools like XBeach Nonhydrostatic (XB-NH; Smit et al., 2010) and SWASH (Zijlema et al., 2011). XB-NH computes the depth-averaged flow due to waves and currents using the nonlinear shallow water equations with a nonhydrostatic pressure correction. It is often used to simulate nearshore wave propagation and runup along reef-lined coasts (Quataert et al., 2020). SWASH in one-layer mode uses the same formulations as XB-NH. However, SWASH can resolve variations in flow over the water depth by adding multiple vertical layers. As a result, SWASH is often used to simulate wave-structure interaction, including wave runup and overtopping, where variations in flow with depth can play a significant role (Suzuki et al., 2017).

3.0 PERFORMANCE OBJECTIVES

This demonstration project will test a variety of performance objectives related to numerical model setup and simulation, accuracy of prediction, timing of prediction, and spatial extent of TWL-induced flooding at NSN (Table 2).

Objective 1: We will document the time required to develop the model bathymetry from DEMs and the forcing boundary conditions. This effort should take no more than 2 weeks for Class I models, 4 weeks for Class II, and 6 weeks for Class III models. Note: These time considerations are identified for an expert on a particular model. Subsequent simulations will require less time as the DEM will not need to be modified.

Objective 2: We will document the run time and computational architecture used to conduct the various simulations. There is no universal approach for comparison because simulations are architecture-dependent. Thus, we aim to complete a particular simulation, at the highest resolution, in no more than 3 hours for Class I models, 24 hours for Class II models, and 30 hours for Class III models. Note that completing a particular simulation may include an iterative process of running simulations, examining errors, refining model forcings, and running the subsequent simulation extending beyond the time frames identified here.

Objective 3: We will quantify the model skill in predicting the timing of peak surge using available tide station data. The predicted time of peak surge should be ± 3 hours of the actual time of peak surge.

Objective 4: We will quantify the model skill in predicting the magnitude of peak surge using available tide station data. Model root mean square errors (RMSE) should be less than 20% for non-wave-driven simulations and less than 30% for wave-driven simulations.

Objective 5: We will quantify the model skill in predicting the duration of a particular flooding level using available tide station data. The predicted duration of a particular flooding level should be ± 3 hours of the actual duration.

Objective 6: We will identify flooded spatial area as a function of time and flooded depth and compare the results to available anecdotal data.

Objective 7: We will compare the Class III full physics model (FUNWAVE) with the Class II models for the open coast portion of the study to determine the importance of the wave component to TWL. There is no performance metric. However, these simulations provide critical information on whether a Class III model is needed to resolve TWL in a geomorphological setting similar to NSN.

Objective 8: We will conduct "degradation simulations" to the base model simulation to quantify prediction error when there is a deficit of information (resolution and/or accuracy). There is no performance metric. However, these simulations provide critical information on prediction confidence when input and forcing data are imperfect (always the case in a predictive scenario). The range of degradation simulations are provided in Section 5.1.

Objective 9: Model simulation results will be provided as layers in a webpage simulation for program manager review. The qualitative metric is related to ease of use and ability for technical-level personnel to understand and use the data.

Table 2. Performance objective for the NSN demonstration.

Performance Objective	**Metric**	**Data Requirements**	**Success Criteria**
Quantitative Performance Objectives			
1) Model setup	Quantify time required to generate DEM and boundary conditions	Database supplied bathymetry, wind or storm parameters, waves, offshore water level	< 2 weeks (Class I) < 4 weeks (Class II) < 6 weeks (Class III)
2) Model run time	Quantify time required to conduct simulation as a	Time and computational resource used	< 3 hours (Class I) < 24 hours (Class II) < 30 hours (Class III)

	function of architecture		
3) Test models' capability in predicting the timing of peak surge	Comparison with available water level data and reference full physics model runs when possible	Water level data from multiple tide stations	± 3 hours of actual timing
4) Test models' capability in predicting the magnitude of peak surge	Comparison with available water level data and reference full physics model runs when possible	Water level data from multiple tide stations	< 20% RMSE; non-wave-driven < 30% RMSE; wave-driven
5) Test models' capability predicting the duration of particular TWL	Comparison with available water level data and reference full physics model runs when possible	Water level data from multiple tide stations	± 3 hours of actual duration
Qualitative Performance Objectives			
6) Test models' capability predicting the spatial extent of flooding for a particular depth and timing	Comparison with available anecdotal data of flooding and reference full physics model runs when possible	Anecdotal data from community reports (note anecdotal data will be incomplete)	Express value in comparing the different model output of flooding extent
7) Compare full physics model with Class II models	Importance of the wave component to TWL	Model data from different simulations	Quantification of the importance of the wave component
8) Model degradation simulations	Importance of resolution and accuracy of model inputs and forcing	Model data from different simulations	Quantification of the model output relative to the base simulation with "perfect" inputs
9) Web interface: Ease of use	Ability of technical-level personnel to use/understand output	Personnel feedback on interface	Technician-level personnel can select results suitable for the installation

4.0 SITE DESCRIPTION

4.1 SITE SELECTION

Naval Station Norfolk was chosen as one of three sites for the overall ESTCP project to provide an end member of geomorphological setting and hydrodynamic forcing (Table 3). The geomorphological setting with a wide continental shelf (Section 4.2 and 4.3) would suggest that waves may have less importance than surge. However, this concept has not been quantified at NSN. Similarly, NSN experiences hurricane forcing, and possible ETS forcing at different times of the year making it a suitable location to test model capability under these varied forcing scenarios.

Table 3. Setting of Naval Station Norfolk

	Naval Station Norfolk
General Location	Atlantic Coast, VA
Geomorphic Setting	Mild continental shelf, land subsidence, bulkheads, narrow channels
Primary forcing	Mesotidal, moderate wave climate, hurricanes and nor'easters

4.2 SITE LOCATION AND HISTORY

Norfolk is located on the south shore of the Chesapeake Bay approximately 30 km west of the Atlantic Ocean in southeastern Virginia (USA) (Figure 11). The city has a population of approximately 250,000 people and is home to the active military facility (Naval Station Norfolk). With most of its elevation within 5 m of mean sea level (MSL), the city is highly vulnerable to the impacts of SLR, nuisance flooding at high tides, and surge during tropical and extratropical storms.

In August 2011, during Hurricane Irene, the city experienced significant flooding and damage on the order of USD 12 million. Just offshore of Norfolk, the hurricane brought combined tide and surge levels of up to 1.89 m above MSL, maximum wind speeds of 27 m/s and significant wave heights of up to 2.62 m.

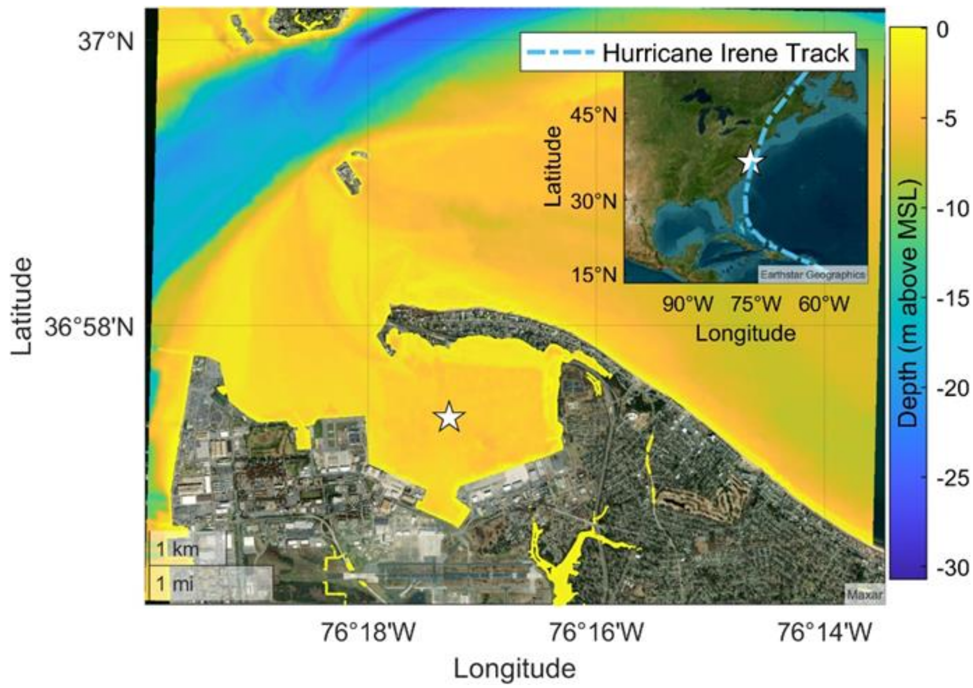

Figure 11. Satellite imagery of Norfolk (VA, USA) overlayed by color-coded bathymetry showing the shallow water conditions just offshore with water depths < 10 m. Inset shows the study site location (star marker, for reference between the main figure and inset) relative to the wider USA. The track of Hurricane Irene (2011) is shown as the dash-dot curve in the inset

4.3 SITE CHARACTERISTICS

The area has a mean tidal range of 0.74 m and typically experiences an east-south-easterly wind-wave climate with significant wave heights of 0.4 m and peak periods of 5 s (averaged over data from 2006 to 2021). The coastline is characterized by average beach and surf zone (wave breaking region) slopes of 1:30 and 1:40, respectively; where the beach is defined as the region $\pm 2\sigma$ around the mean shoreline elevation (setup), σ is the standard deviation of the continuous water level record, and the surf zone is defined as the area between the setup location and the location of wave breaking.

4.4 SITE-RELATED PERMITS AND REGULATIONS

No permits are required as this demonstration is a numerical modeling demonstration plan.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The demonstration plan will be conducted along three thrusts:

1) Hurricane Irene simulations: We will conduct numerous simulations using the Class I empirical models, and Class II and Class III numerical models for Hurricane Irene. These simulations will be referred to as base simulations for comparison to subsequent simulations and serve as the output for model calibration / validation. We will then perturb Hurricane Irene forcing to determine the effect of altering forcing parameters. For example, we will modify SLR, central pressure, hurricane track, and windspeed changes.

2) Conduct model degradation simulations: We select three additional storms from NOAA's Historical Hurricane Tracks database (Table 4; Figure 12; https://coast.noaa.gov/hurricanes/#map=4/32/-80). Hurricane Isabel (2003) was chosen because the hurricane track approached NSN from the south-east crossing land south of the facility. Hurricane Sandy (2012) was chosen because it approached from a shore-normal (easterly) position and crossed land north of the facility. Hurricane Michael (2018) was chosen because the hurricane track approached NSN from the southwest and crossed from land to sea. Degradation studies are needed to infer the output accuracy/fidelity when imperfect initial and boundary conditions are provided. Altered inputs of bathymetric resolution, bathymetric accuracy, National Hurricane Center (NHC) track error, radius of maximum winds (RMW), and overall wind field magnitude (Table 5) will be used. We will conduct an additional simulation for each hurricane of the "worst case scenario" of degraded data.

Degradations (Table 5) consist of:

A) Coarsening the model bathymetry resolution by factors of 5, 20, and 50. That is, a base simulation that may have a grid size of 100 m, would be degraded to 500 m, 2000 m and 5000 m, respectively.

B) Bathymetric accuracy for the elevation data included in the DEMs are 0.3 m (CoNED Topobathy DEM; https://coast.noaa.gov/dataviewer/#/lidar/search/where:ID=8656/details/8656); 0.5 m (CUDEM; https://coast.noaa.gov/dataviewer/#/lidar/search/where:ID=8483/details/8483); 1 m (NCEI Coastal Relief Model; https://www.ncei.noaa.gov/products/coastal-relief-model); and unknown (GEBCO; https://www.gebco.net/data_and_products/gridded_bathymetry_data/). Each dataset also has varied horizontal resolution: 1 m, 3 m, 90 m, 450 m respectively. We choose vertical elevation degradations commensurate with the stated vertical accuracy of the data sets: +/- 0.3 m, +/- 0.5 m, and +/- 1 m.

C) NHC track errors are provided based on the forecast guidance at 36, 72, and 96 hours. The corresponding track errors are 50-55 nm (93-102 km), 90-100 nm (167-185 km), and 130-140 nm (241-259 km). Simulations will use a track shifted above or below the actual track using the mean of each error range.

D) Radius of maximum winds (RMW) are one descriptor of storm "size". RMW will be varied by a decrease of 10% and increases of 10% and 25%.

E) Wind field magnitude represents the strength of the vector resultant wind velocity at each grid points. Magnitudes will be varied by a decrease of 7.5% and increases of 7.5% and 22.5%.

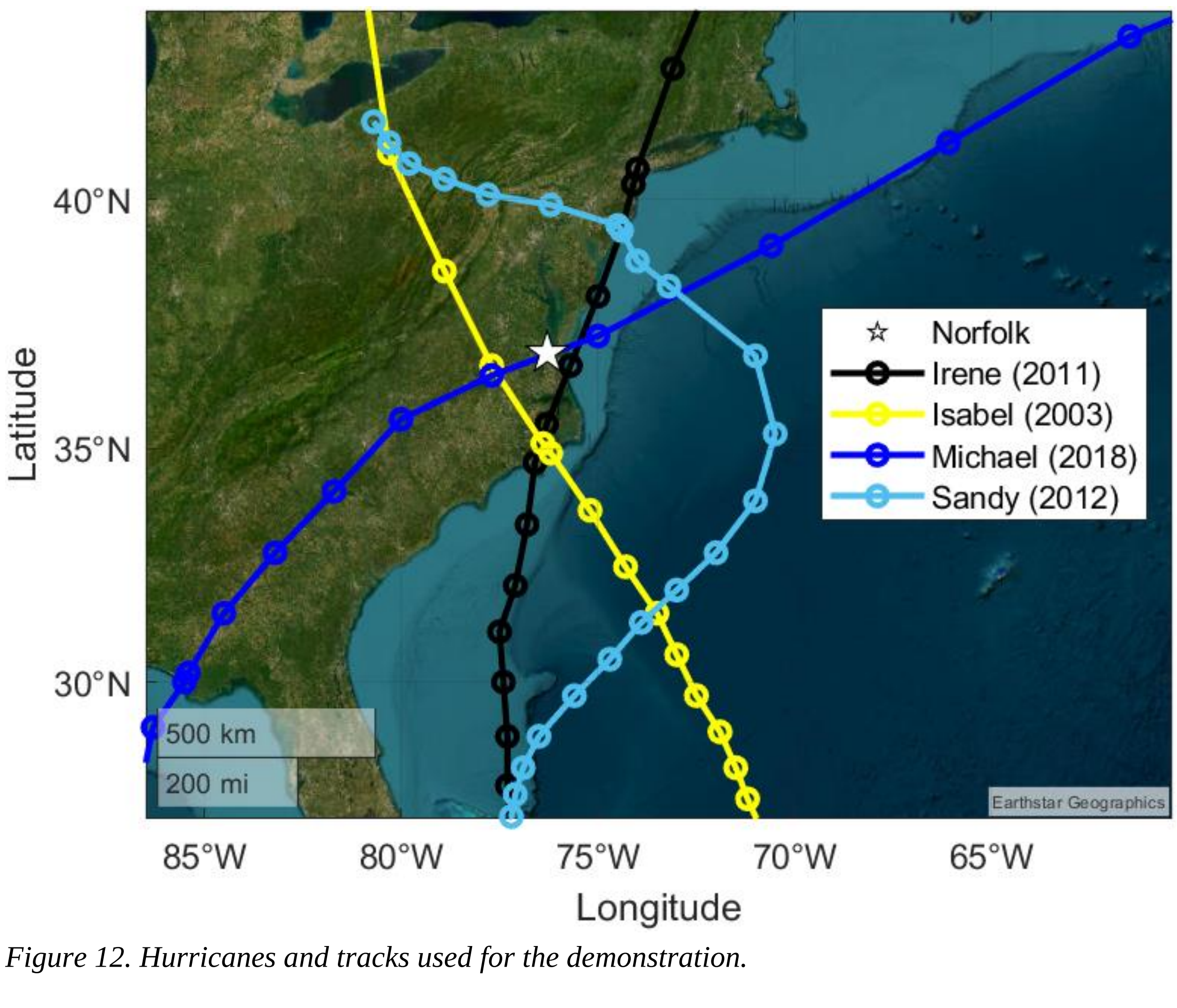

Figure 12. Hurricanes and tracks used for the demonstration.

Table 4. Demonstration hurricanes and associated parameters.*

Hurricane	Maximum Category	Maximum Wind Speed (m/s)	Minimum Pressure (mb)
Isabel (2003)	5	75	915
Irene (2011)	3	54	942
Sandy (2012)	3	51	940
Michael (2018)	5	72	919

*https://coast.noaa.gov/hurricanes/#map=4/32/-80.

Table 5. Degradations applied to the different model simulations.

Parameter	Alteration 1	Alteration 2	Alteration 3
Model bathymetry resolution	Degrade by a factor of 5	Degrade by a factor of 20	Degrade by a factor of 50
Bathymetry accuracy	Add gaussian noise of +/- 0.3 m	Add gaussian noise of +/- 0.5 m	Add gaussian noise of +/- 1 m
NHC track errors	50-55 nm (36 hour forecast)	90-100 nm (72 hr forecast)	130-140 nm (96 hour forecast)
Radius maximum winds (RMW)	Decrease by 10%	Increase by 10%	Increase by 25%
Wind field magnitude	Decrease by 7.5%	Increase by 7.5%	Increase by 22.5%

3) Investigate parameterized vs modeled wind/pressure fields: The major forcing mechanism in the Class II models is the wind/pressure field. The entire wind/pressure field can be obtained in a hindcast mode using model validated wind fields via European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis v5 (ERA5) *after* the event has occurred. ERA5 also provides predicted wind fields at hourly intervals. A second forcing option relies on a parameterized wind field that contains only the hurricane wind field forcing; referred to as the Holland model (Holland,

1980). There are tradeoffs to using the Holland model vs the ERA5 model (Table 6) and this demonstration provides an opportunity to quantify the varied model output depending on the most widely used forcing approaches.

Table 6. Strengths and weaknesses of the ERA5 and Holland model approaches.

	ERA5	**Holland Model**
Strength	• Better representation of complexities of the wind field • Reanalysis products include data assimilation • Accounts for background wind/pressures (those not generated by the storm) • Routine predictions available hourly	• Definitely available in real-time • Good accuracy relative to cost • Can develop fields at resolution of mesh and model time step • Can perturb inputs
Weakness	• Relatively coarse resolution in space (0.25 degrees) and time (hourly) • Difficult to perturb in a physical way, especially the track (due to land masking) • Need to adjust wind/pressure field to focus at storm and blend to background meteorology	• Less accurate than a physics-based model product, no data assimilation

5.2 BASELINE CHARACTERIZATION AND PREPARATION

The total water levels at NSN will first be quantified in a baseline characterization using simulations from ADCIRC, Delft3D FM, and NearCom of storms Isabel (2003), Irene (2011), Sandy (2012), and Michael (2018). These simulations will represent the best-possible predictions of storm-driven waves, surge, and coastal flooding during these events and tailored for the installation. These simulations require several inputs to describe the coastal region and the storm:

Grids: The coastal region is discretized into a grid (or mesh) with a finite number of computational points, where the models solve for water levels and current velocities. Grid resolution varies to emphasize accuracy near the coast and near critical infrastructure like NSN. These grids are developed from DEMs and other datasets that describe the ground surface and characteristics of the coastal region.

ADCIRC: The finite element meshes used in the ADCIRC simulations were developed using OceanMesh2D which requires DEMs, land cover data, coastlines, and floodplain boundaries as inputs. The meshes cover the Atlantic Ocean basin using three DEMs at different resolutions from the 2014 Continuously Updated Digital Elevation Model (CUDEM) and the 2018 Shuttle Radar Topography Mission (SRTM). The first, full-domain DEM spans over the Atlantic Ocean with minimum resolution at 500 m between coordinates 5° N and 101° W to 50° N and 25° W. The second, regional DEM spans over the states of Virginia, Maryland, and Delaware with minimum resolution at 30 m between coordinates 35.4° N and 77.5° W to 39.7° N and 73.5° W. The third, location-specific DEM spans over the southern part of the Chesapeake Bay where the city of Norfolk meets the Atlantic Ocean with minimum resolution at 10 m between coordinates 36.8° N and 76.6° W to 37.2° N and 75.8° W. Some of the DEM pre-processing included clipping the set of raster tiles provided by NOAA Data Access, changing the resolution of the clipped tiles, merging the tiles into one raster dataset, converting the coordinate system to WGS-84 for compatibility with OceanMesh2D, filling null values by interpolating the neighboring cells and converting the output to a netCDF format. The 2016 Coastal Change Analysis Program (CCAP) Regional Land Cover and Change dataset was used for the land cover and land use for the Mid-Atlantic region at 30-m resolution. The CONUS polygon was used for the global coastline with modifications on the east coast to remove barrier islands from all states south of Virginia and north of Delaware. The 10-m floodplain line was used for the global floodplain with modification to include only flooding in Virginia, Maryland, and Delaware.

To develop a mesh that scales in resolution from the city of Norfolk into the Atlantic Ocean, the NSN mesh was built using three stages with a minimum resolution of 20 m, 60 m, and 1 km at the location-specific, regional, and full-domain scales, respectively. In these regions, the resolutions are controlled using the grades of the scale and the maximum resolution. Although a minimum resolution is given for each stage, the maximum resolution is also given nearshore for each. The maximum resolutions were 60 m, 1 km, and 30 km, respectively. The resolution is controlled from the coastlines and scales outward to the limits of the DEM over each vertex in the mesh at a grade of 0.2. Nodal attributes, which are constant in time but vary spatially, are assigned to vertices in the mesh to perform calculations as tides, wind, and wave forcing are applied to the simulation. These nodal attributes include the Manning's *n*, surface directional effective roughness length, canopy coefficient, and primitive weighting factor, which are all assigned from the land use and land cover dataset.

Delft3D: For Delft3D FM, the coupled (D-Flow FM/D-Wave) model domain spanned 460 km (West to East) x 690 km (North to South). D-Flow FM was set up using a single unstructured grid with a stepwise internal refinement by a factor of 2. In this way, the grid resolution varies from 4 km at the most offshore point to 250 m at NSN. D-Wave, on the other hand, was set up using a series of nested structured grids, with resolutions of 5 km, 1 km, 200 m, and 40 m (at NSN). Bathymetric and topographic data were obtained using the Delft Dashboard application (https://publicwiki.deltares.nl/display/DDB/Delft+Dashboard), which merges global (e.g., GEBCO (https://www.gebco.net/)) and local datasets (e.g., the National Oceanographic and Atmospheric Administration's (NOAA) CUDEM (CUDEM)). The datasets were merged and interpolated onto the model grids using the tools within the Delft3D FM integrated modeling suite.

NearCom: For NearCom, the three modules (SWAN, SHORECIRC, SEDIMENT) share the same structured curvilinear or rectangular grid. The grid covers the region of 76.5W - 75.7W, 36.8N - 37.2N and is generated using the NOAA integrated bathymetric-topographic DEM, which combines Coastal Relief Model (CRM; 3 arc-sec) and CUDEM (1/9 arc-sec) datasets. The resolution of the curvilinear grid varies from ~1 km offshore to 10's m nearshore. The water depth values (positive for bathymetry and negative for topography) at grid nodes are obtained by interpolating the CUDEM data nearshore and CRM data offshore.

FUNWAVE: For FUNWAVE, the model domain spanned 7.4 x 8.7 km, centered at NSN, and was discretized using a constant 1 m x 1 m grid spacing. A high resolution (1 m) topo-bathymetric dataset was obtained for the area using the NOAA Digital Coast: Data Access Viewer (Data Viewer) to capture the nearshore beach and dune features for accurate wave runup estimates.

Tides: Tides are forced at the offshore boundaries of the grids, and can also be forced internally for a large-domain simulation. These forcings are prescribed in terms of the tidal harmonic constituents; by specifying the amplitudes and phases of the dominant constituents, the overall tide signal can be reconstructed at points along the boundary and internally.

ADCIRC: For ADCIRC simulations, tides are first prepared by forcing at the boundary vertices of the mesh. For the meshes used in the simulation, the boundary resolution ranges between 10 km to 30 km in the Atlantic Ocean just west of the 50-degree line of longitude connecting Nova Scotia in Canada to Paramaribo, Suriname in South America. The database for the tidal simulation uses the major 8 tidal constituents (K1, O1, Q1, P1, M2, N2, K2, and S2) from the TPXO global model for barotropic tide database (Egbert and Erofeeva, 2002). Forcing for the same eight constituents is also used to calculate the tidal force on the internal vertices of the mesh. Typically, the tidal simulation is set up prior to the wind simulation to establish the tide forcing on the grid before the winds are applied. For Hurricane Irene, a 14-day period beginning on August 6th, 2011 was used. The tides simulation is ramped during its first 2 days and then continued for an additional 12 days to achieve a dynamic equilibrium before atmospheric forcings are applied.

Delft3D: Like ADCIRC, the tide is specified in D-FLOW FM along the open boundaries using the tidal constituents (MN4, MS4, M4, MM, MF, K1, O1, Q1, P1, M2, N2, K2, and S2) from the

TPXO global model for barotropic tide database. The database was downloaded using the Delft Dashboard application.

<u>NearCom</u>: NearCom addresses the nearshore processes only and thus the computational domain is smaller than that used for Delft3D or ADCIRC in a typical tide-surge simulation. The tidal and surge boundary conditions for NearCom are provided by a large-scale model, such as Delft3D or ADCIRC. The data format for the boundary conditions is (time, elevation, <velocity>), where <velocity> represents depth-averaged current velocity components and are optional.

<u>FUNWAVE</u>: The time scale for Class III models like FUNWAVE is typically ≤ 30 minutes. As such, the combined effect of the tide and surge may be expressed as a single water level that does not vary over the course of the simulation. Here, this combined tide and surge level was obtained from the Delft3D FM coupled simulation.

Atmospheric Forcing: During simulations, the coastal ocean is driven by atmospheric forcing in the form of surface pressures and wind stresses. These forcings can be obtained from a variety of sources, ranging from simplistic (e.g. models that use a few storm parameters to develop relatively smooth fields for surface pressures and winds) to complex (e.g. models that represent the full physics of the meteorology). In this demonstration, we will mostly use parametric models (based originally on Holland; 1980; Figure 13) because they can represent the storms with an acceptable level of accuracy, and because they will allow for perturbations (to storm track, to storm intensity, etc.) in later stages of the demonstration. Each model (ADCIRC, Delft3D; NearCom) uses a slightly different form of this parametric model.

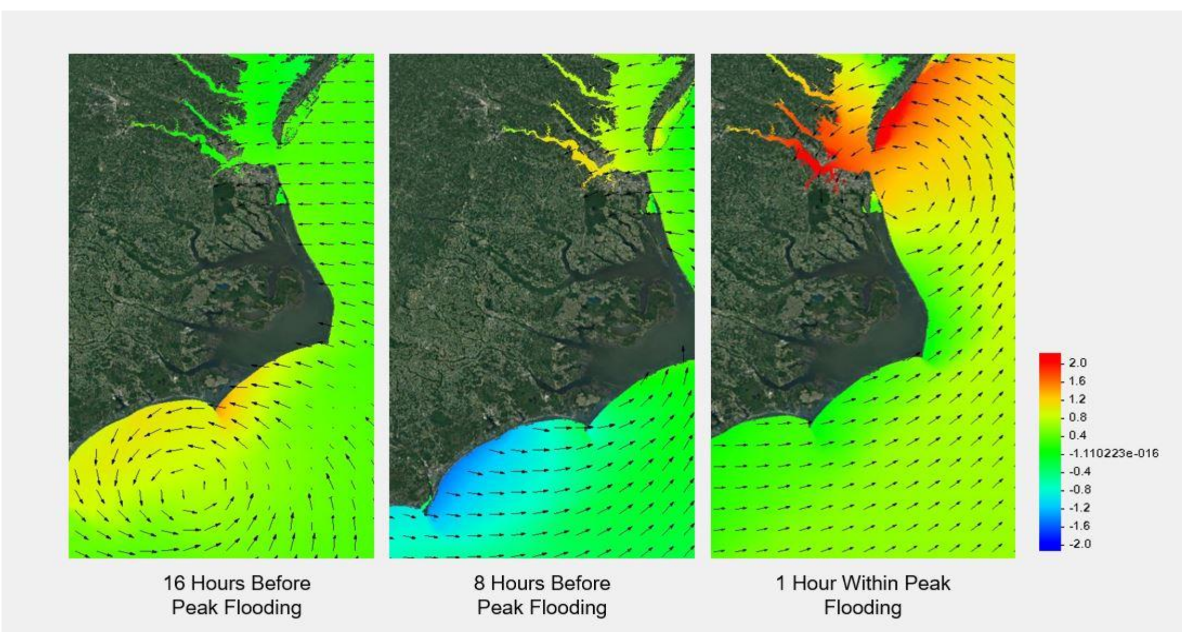

Figure 13. Hurricane Irene (2011) shown by the wind fields of the Holland model. Vectors are wind velocities and contours are water levels (m) as computed by ADCIRC.

We will undertake additional tests using the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The reanalysis dataset combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. The approach is based on data assimilation where model forecasts/hindcasts are combined with observations to produce a new best estimate. The strengths and weaknesses of this approach, compared to the Holland parametric model, are outlined in Table 6.

ADCIRC: A parametric model based on Holland (1980) is embedded within ADCIRC, so that the atmospheric forcing can be developed from just a few storm parameters. The Holland model has been used and extended for forecasting during several recent storms (Forbes et al., 2010; Mattocks and Forbes, 2008), including a different radial profile in each storm quadrant to improve the representation of storm asymmetry (Xie et al., 2006). Hu et al. (2012) improved on the Holland model formulation by removing the cyclostrophic balance assumption and by introducing a piecewise continuous radial wind profile that matched multiple specified wind isotachs in each quadrant of the storm. However, they used only a single scaling parameter in the pressure profile and were limited to satisfying only $V = V_{max}$ at $r = R_{max}$. Thus, their formulation does not force an actual maximum in the radial wind profile at $V = V_{max}$.

ADCIRC was extended to use a generalized asymmetric Holland model (GAHM; Gao et al., 2017), which includes the previous improvements (Hu et al., 2015, 2012; Xie et al., 2006), but reintroduces the two scaling parameters from the original Holland formulation, satisfying both $V = V_{max}$ and $dV/dr = 0$ at $r = R_{max}$ without assuming a cyclostrophic balance at $r = R_{max}$. The cyclostrophic balance is violated by large and weak storms, which is often typical of storms as they approach landfall (Gao et al., 2017; Hu et al., 2012). GAHM is a better representation of the storm described in the parameters, e.g. the best-track and forecast advisories from the National Hurricane Center.

GAHM is implemented within ADCIRC, so the surface pressure and wind fields can be determined dynamically at every point in the computational domain. For the demonstration simulations, we use the best-track analyses provided by the National Hurricane Center; these analyses describe the storm at most every 6 hours and provide parameters about the track, size, intensity, and isotachs in the storm quadrants.

Delft3D FM: Hurricane winds and pressure can be specified in D-FLOW FM using two methods:

1. The wind and pressure fields that vary in both space and time are specified using a curvilinear grid.

2. A cyclone wind/pressure field is prescribed on a polar grid with the center (‘eye’) of the hurricane being the origin of the polar coordinate system. The location of the eye, and the corresponding wind/pressure field, is allowed to vary in time.

With the above methods in mind, two different approaches for atmospheric forcing were considered for the demonstration. Using method 1, the ERA5 hindcast winds and pressures were specified on a regular grid and used as model input. For comparison, the D-Flow FM/D-Wave model was also set up with parametric wind and pressure forcing (method 2) instead of the ERA5 dataset. This approach was achieved in a manner like ADCIRC using the Holland et al. (2010)) model and supporting relations (Holland, 2008; Nederhoff et al., 2019) to replicate wind and pressure generated by Hurricane Irene (2011). The polar grid was generated using the Delft Dashboard application. Similar approaches will be used for the other events of the demonstration.

NearCom: The original Holland model (Holland, 1980) was implemented in NearCom to model wind/pressure forcing in storm surge simulations. The model also has an optional wind/pressure input which can come from large-scale models. In most NearCom applications for storm events, the wind/pressure data are provided by a large-scale model, consistent with the boundary conditions from the same large-scale model.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS

5.3.1 Baseline simulations

Baseline simulations are those using the known hurricane parameters as obtained from ERA5 reanalysis or statistics fed into the Holland model. The baseline conditions generally serve for validation/calibration purposes and as the comparator for forcing and degradation modifications.

5.3.2 Hurricane Irene: Parameter Alteration

A thorough parametric effort will be undertaken to determine the response at NSN and surrounding areas to altering relevant parameters for Hurricane Irene. The baseline simulation will be altered for:

A) SLR. Mean sea level in each model will be modified following Sweet et al. (2022) for "Intermediate-Low" scenarios for the US East Coast: 0.4 m, 0.8 m, 1.3 m, projected for years 2050, 2100 and 2150.

B) Central Pressure Drop. The central pressure will be modified following Mousavi et al. (2011) for sea surface temperature increases of 1.5°, 3°, 4.5° C; leading to central pressure drops of 12%, 24%, and 36% respectively.

C) Hurricane Track. Track changes following Salehi (2018) using multiples of the radius of maximum winds; here 55 NM either side of the present track.

D) Wind Speed. Wind will be modified using changes following Camelo et al. (2020) and Emanuel (1987) where the speed increases by 5% for every degree increase of sea surface temperature. That is, 7.5%, 15%, and 22.5% respectively for the used sea surface temperature increases.

5.3.2 Degradation

Degradation simulations consist of the modifications described in Section 5.1. Only a single parameter is degraded/altered for a particular simulation with a chosen model. A "worst-case" scenario will be simulated following the individual simulations. The worst-case simulation incorporates the largest uncertainties of each of the parameters in Table 5.

5.4 FIELD TESTING

There is no field testing to be conducted as part of this demonstration plan.

5.5 SAMPLING PROTOCOL

No team generated field sampling will be conducted. Model data at each grid point and at relevant locations to available field data will be archived from the simulations.

Anecdotal Data: Beginning in 2010, the City of Norfolk established a System to Track, Organize, Record and Map (STORM) app where residents and city staff can record incidents—such as the location of flooded streets, damaged trees, or disabled vehicles—during and after inclement weather events (STORM Dataset). The STORM dataset for Hurricane Irene (2011) was filtered using the keywords, "flood", "water", "tide/tidal" and "wash", to approximate the extent of flooding using the location of each filtered report. The modeled flood extent was qualitatively compared to the reports for validation.

NOAA Buoys & Tide Gauges: In addition to the community reported flood extent, the coupled D-Flow FM/D-Wave model setup was validated by comparing the modeled wind, waves, and surge to observations at offshore buoys (National Data Buoy Center), tide gauges (NOAA Tides & Currents) and a local wave gauge during Hurricane Irene (2011).

Local Wave Gauge: Long-term data from a wave gauge deployed just offshore of Norfolk was provided by representatives from the City of Norfolk and Moffatt & Nichol. This dataset included wave heights, periods, and directions during Hurricane Irene (2011).

Empirical Approaches: Information (central pressure, latitude, forward speed, angle to coast) needed for the Russo (1998) model will be collected from NOAA updates of each hurricane as they are nearest to Norfolk. Information (beach slope, wave height, wave length) needed for the

Stockdon et al., (2006) model will be collected from a transect offshore of Norfolk fronting the open coast. The beach slope will be taken from the Delft3D bathymetry and identifies across the range from ± 1m about the mean sea level for the simulation. Wave height and wave length will be taken from the simulation result at the 10 m depth contour.

5.6 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

5.6.1 Calibration of Equipment

ADCIRC: Model calibration was achieved by using standard practices for inputs for atmospheric forcing and model dissipation. Wind speeds are converted to surface stresses via a drag coefficient, which varies linearly to wind speeds of about 25 m/s, and then is capped at C_D=2.5×10^{-3} (Dietrich et al., 2011a). Bottom friction is represented with a Manning's formulation with *n* values assigned from land-use/land-cover data, with no lower limit on the bottom friction coefficient. Horizontal eddy viscosity was specified with a value of 50 m^2/s. For model dissipation, ADCIRC uses a weighting factor τ_0 in its modified continuity equation; this factor was also specified with a depth-based scheme with values of 0.03 in shallow waters (resolution finer than 2 km), 0.02 in intermediate waters (depths less than 10 m) and 0.005 in deep waters. These parameter settings are default and have been well-validated in coastal flooding studies with ADCIRC.

Delft3D FM: Model calibration was achieved by varying the wind drag coefficient (C_D) in D-FLOW FM to minimize the error between the modeled and observed surge during Hurricane Irene (2011), as is often done in practice. C_D was set using a piecewise (three-point) linearly varying approach, where C_D is allowed to vary with wind speed (*U*): $C_D^A = 0.5 \times 10^{-3}$ at $U^A = 0$ m/s, $C_D^B = 1.5 \times 10^{-3}$at $U^B = 10$ m/s, and $C_D^C = 6 \times 10^{-3}$ at $U^C = 30$ m/s. The superscripts *A*, *B*, and *C* refer to the three breakpoints based on wind speed.

NearCom: The wind drag coefficient used in NearCoM is consistent with that calibrated in a large-scale model, such as Delft3D FM.

FUNWAVE: No model calibration was carried out due to lack of data. The model was set up using the recommended settings at https://fengyanshi.github.io/build/html/definition.html#input-txt.

5.6.2 Quality Assurance Sampling

No field data are collected as part of this demonstration plan. Validation data are obtained from online data sources and anecdotal records.

5.6.3 Sample Documentation

No field data are collected as part of this demonstration plan. Individual researchers will maintain spreadsheet records of the model simulation being conducted, the clock time required to prepare the model, the model simulation duration, the clock time required to complete the simulation, and the architecture used to complete the simulation.

6.0 PERFORMANCE ASSESSMENT

6.1 General Statistical Analyses

Model accuracy in predicting the magnitude and timing of peak water level (or other parameters) will be evaluated using a variety of statistical metrics:

Root mean square error:	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{N}\left(\psi_{modeled}^{i} - \psi_{observed}^{i}\right)^{2}},$	5
Normalized root mean square error:	$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{N}\left(\psi_{modeled}^{i} - \psi_{observed}^{i}\right)^{2}}}{\left(\max(\psi_{observed}^{i}) - \min(\psi_{observed}^{i})\right)},$	6
Relative Bias:	$RB = \frac{\sum_{i=1}^{N}\left(\psi_{modeled}^{i} - \psi_{observed}^{i}\right)}{\sum_{i=1}^{N}\psi_{observed}^{i}},$	7
Mean normalized bias	$B_M = \frac{\sum_{i=1}^{N}\left(\psi_{modeled}^{i} - \psi_{observed}^{i}\right)}{\sum_{i=1}^{N}\lvert\psi_{modeled}^{i}\rvert},$	8
Coefficient of determination	$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\psi_{modeled}^{i} - \psi_{observed}^{i}\right)^{2}}{\sum_{i=1}^{N}\left(\psi_{modeled}^{i} - \overline{\psi_{observed}^{i}}\right)^{2}},$	9
Sensitivity index	$SI = \frac{\chi_{max} - \chi_{min}}{\chi_{max}},$	10

where ψ represents the parameter being assessed at some station *i*. Increases in RMSE or NRMSE indicate reduced model accuracy. Positive or negative relative bias or mean normalized bias indicate over- and under-predictions, respectively, by the model. These parameters enable us to investigate the overall magnitude differences between predictions and observations. The coefficient of determination and corresponding best fit slope quantify how much the predictions varied from the observations, thereby giving an indication of how well the simulations performed (e.g. a perfect fit would have a slope of unity). The sensitivity of the modelled TWL to the various perturbations (Table 5) will also be assessed using a sensitivity index (SI), defined as the relative difference between the minimum and maximum output values, χ, when a single input variable is changed with the others being constant (e.g. SLR, central pressure, wind speed or track position) over the range considered (Table 5). Larger SI values indicate greater parameter influence.

6.2 Specific Approaches for Each Objective

Objective 1: Each user will document carefully the time required to prepare a model simulation. These times will be tested against those in the performance matrix using a simple differencing algorithm.

Objective 2: Each user will document carefully the time required to prepare a model simulation. These times will be tested against those in the performance matrix using a simple differencing algorithm.

Objective 3: Data from available stations (Section 5.5) will be queried for the time of peak surge. Model output interpolated to the station location will also be queried for the time of peak surge. A simple difference algorithm will be used to quantify the skill in predicting peak surge timing (see Figure 14).

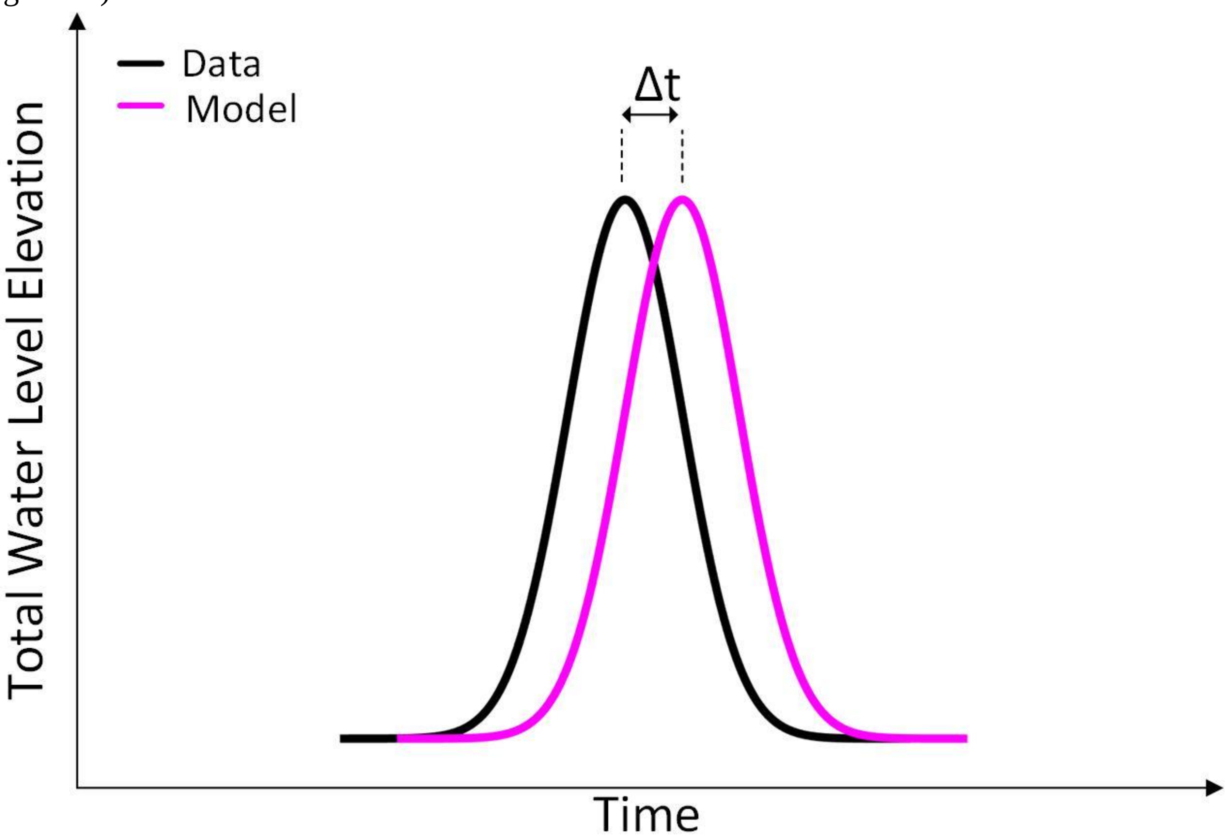

Figure 14. Schematic showing estimate of the timing of model predicted and actual peak surge (Total Water Level Elevation).

Objective 4: Data from available stations (Section 5.5) will be queried for the magnitude of peak surge. Model output interpolated to the station location will also be queried for the magnitude of peak surge. A simple difference algorithm will be used to quantify the skill in predicting peak surge magnitude (see Figure 15).

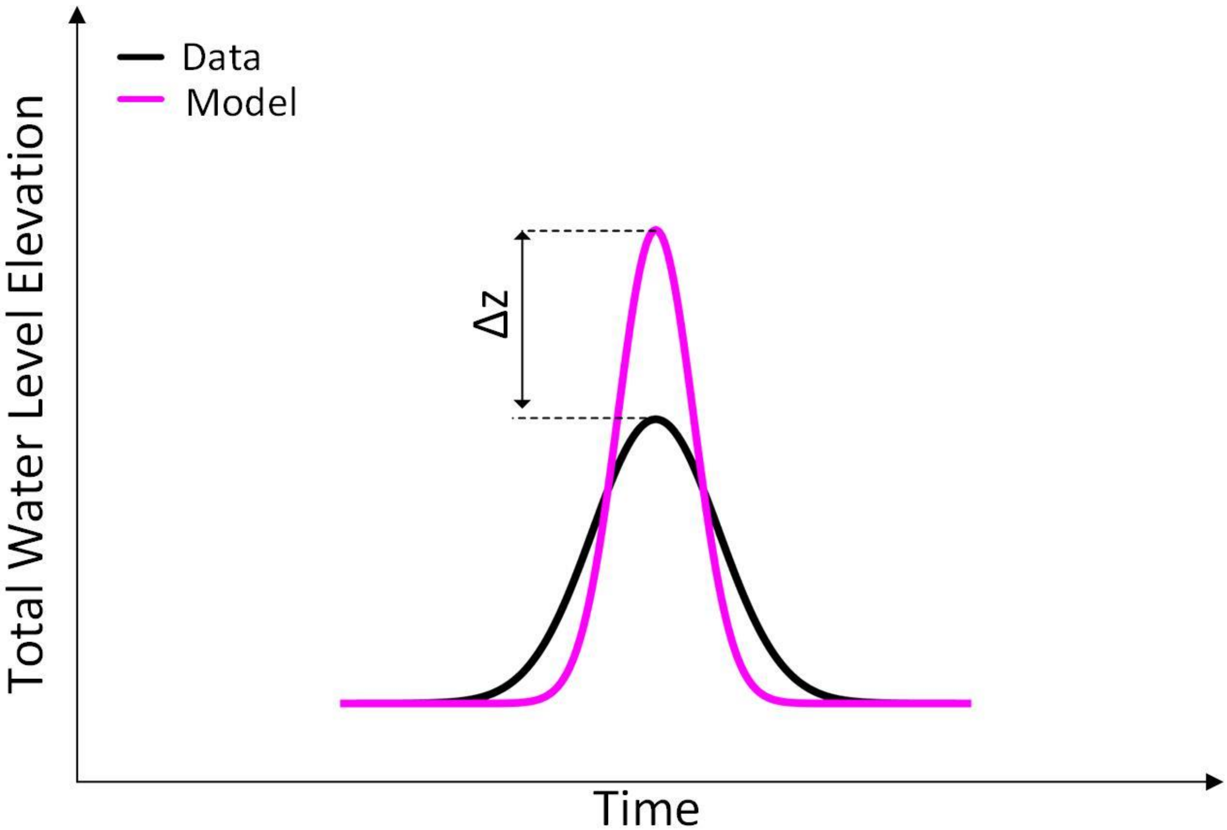

Figure 15. Schematic showing estimate of the maximum amplitude of model predicted and actual peak surge (Total Water Level Elevation).

Objective 5: A range of flooding levels will be selected. Data from available stations (Section 5.5) will be queried for the start and end time that each flooding level was exceeded. Model output interpolated to the station location will also be queried for the start and end time that each flooding level was exceeded. The difference between start and end time for the data or model output yields the flooding duration at a particular flooding level. A simple difference algorithm will be used to quantify the skill in predicting flooding duration at each flooding level (see Figure 16).

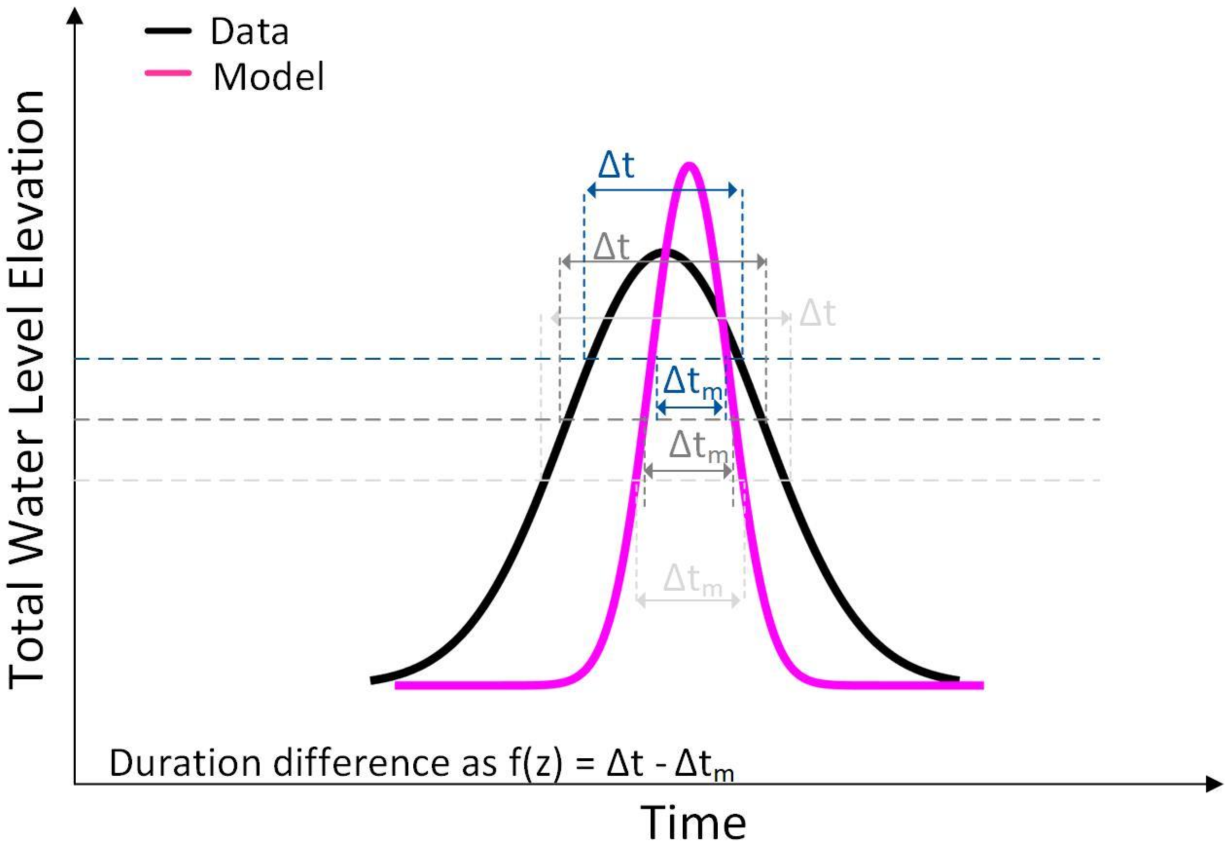

Figure 16. Schematic showing estimate of the duration of model predicted and actual flooding as a function of Total Water Level Elevation cutoff.

<u>Objective 6</u>: We will identify flooded spatial area as a function of time and flooded depth (Figure 17) and compare the results, where possible, to available anecdotal data. The example shown in Figure 17 is meant to provide a description of the approach; here using generic terms such as low, medium, and high with respect to flooding. Actual flood elevations will be determined after conducting the simulation. Subsequently, flooded area will be quantified for each flood elevation level.

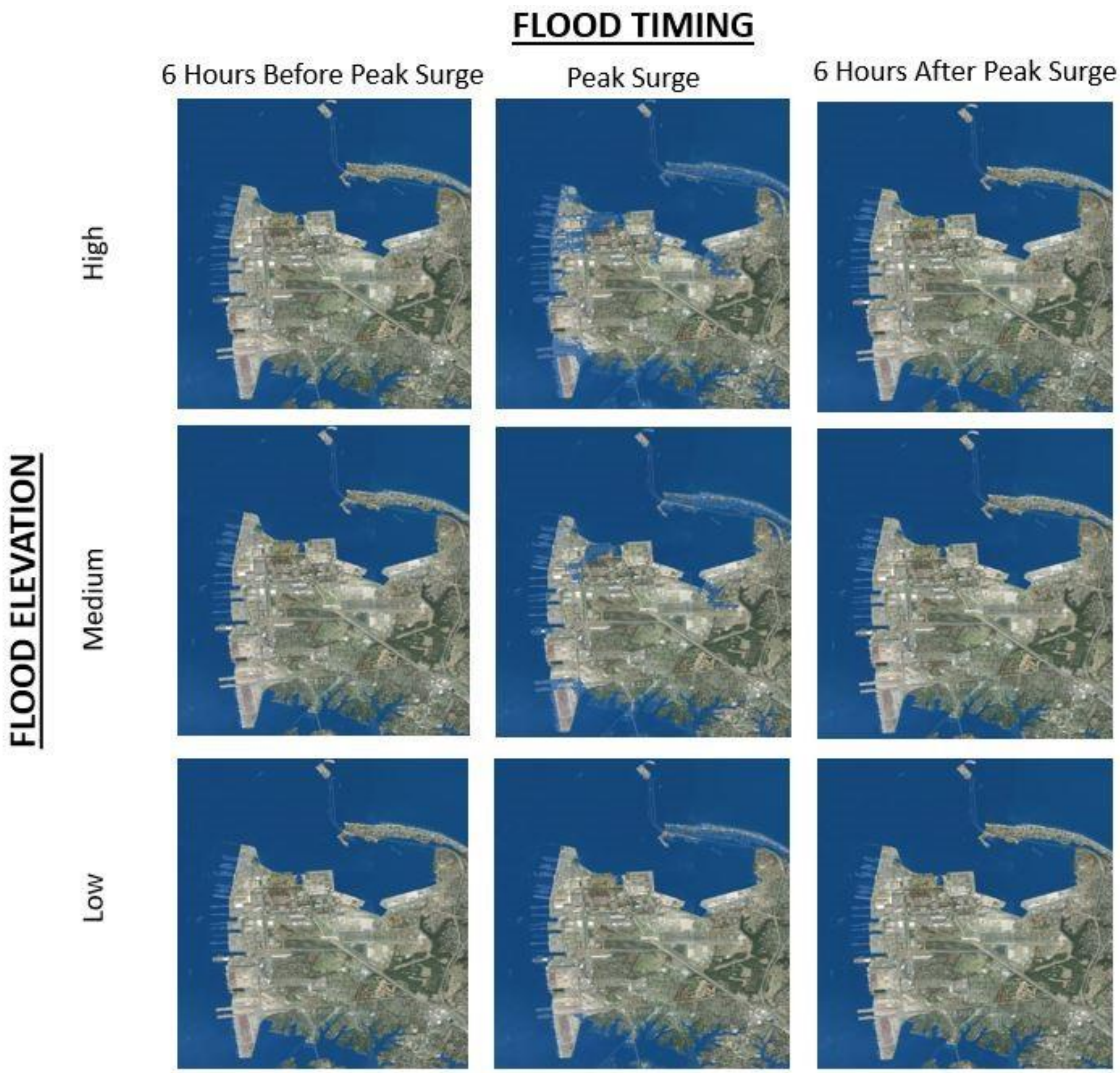

Figure 17. Example maps of inundation area as a function of timing with respect to peak surge.

<u>Objective 7</u>: We will compare the Class III full physics model (FUNWAVE) with the Class II models for the open coast portion of the study to determine the importance of the wave component to TWL. There is no performance metric. However, these simulations provide critical information on whether a Class III model is needed to resolve TWL in a geomorphological setting similar to NSN. This comparison will be carried out by comparing the flood extent predicted using the Class II models (no wave influence) to the flood extent predicted using the Class III model. The contribution of waves to the total flooding, based on the difference in modeled flood extents, can then be expressed as a percentage

<u>Objective 8</u>: We will conduct "degradation simulations" to the base model simulation to quantify prediction error when there is a deficit of information (resolution and/or accuracy). There is no

performance metric. However, these simulations provide critical information on prediction confidence when input and forcing data are imperfect (always the case in a predictive scenario). Model to model comparison will be conducted using the relevant aforementioned parameters (Section 6.1)

Objective 9: Model simulation results will be archived in long-term storage systems with hyperlinks provided on a webpage for program manager review. User-interactive graphic views of model results will be generated using web-friendly interactive mapping techniques, such as the LEAFLET program (Figure 18). Automated programs suitable for multiple computer platforms will be used to transfer data between computational resources and storage systems. The qualitative metric is related to ease of use and ability for technical-level personnel to understand and use the data in a decision-making process.

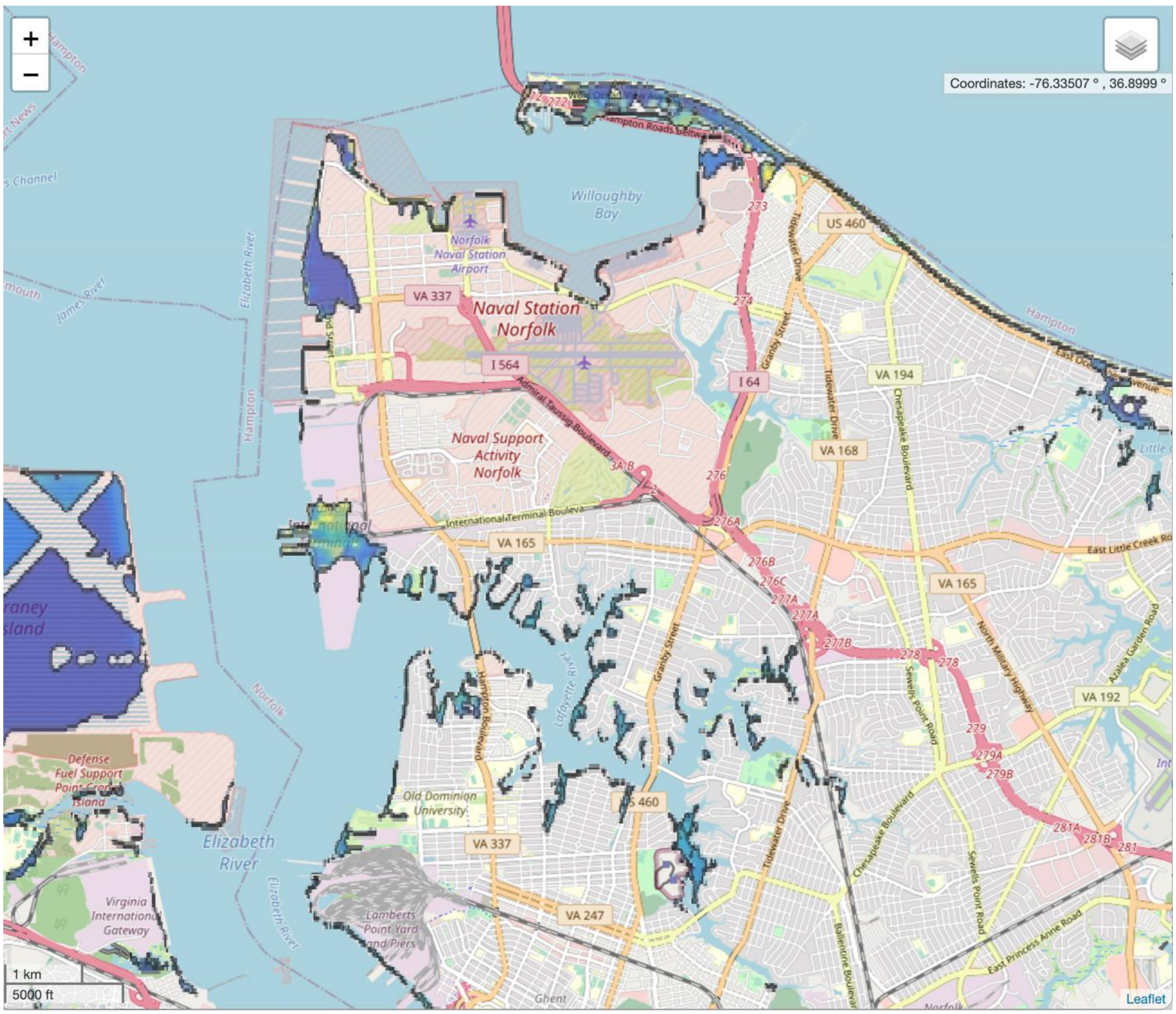

Figure 18. Example snip from the preliminary webpage showing flooded area for a storm event.

7.0 COST ASSESSMENT

In this demonstration, the technologies used are empirical and numerical models for predicting TWL at military installations. We aim to minimize costs associated with model set up and execution. We indicate from the outset that identifying exact costs are inexact. We will produce what we believe are realistic estimates described in the following categories and Table 7.

Model Software: All models in this demonstration are available freely from their developers. ADCIRC is shared freely with academic and government researchers https://adcirc.org, and it is used by DoD staff at the USACE and elsewhere. Delft3D FM is open source and available upon request from Deltares (https://oss.deltares.nl/web/delft3dfm/get-started). A precompiled version with graphical user interface (2023.02 release) was provided free of charge for this study under an academic license. Similarly, NearCom and FUNWAVE are open-source software developed by CACR and are available at https://github.com/fengyanshi/NEARCOM-TVD and https://github.com/fengyanshi/FUNWAVE-TVD, respectively. As such, we will treat the cost associated with these computational tools as $0.

Input Data: As described above, numerical models require data about the coastal environment (configuration of coastline, bathymetry/topography, land-use/land-cover, etc.) and the storm of interest (track, size, intensity, etc.). These data can be obtained freely from public databases. For ground surface elevations and land-cover data, DEMs and geoTIFFs can be obtained from NOAA Digital Coast (https://coast.noaa.gov/digitalcoast/). For storm parameters, forecast consensus and hindcast best-track information can be obtained from the National Hurricane Center (https://www.nhc.noaa.gov) to develop parametric models, and prediction and reanalysis products can be obtained from ECMWF (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5) for the ERA5. These data sets are updated regularly by their relevant agencies, and there may also be additional data for other military installations available to DoD staff. Collecting our own data from sensor installation has a significant cost, but was not feasible for the demonstration at NSN. Thus, for the demonstration at NSN, we will treat data costs as $0 excluding personnel time to retrieve the data which is included in the model setup time computation.

Computational Resources: Another key cost is access to computing resources to run each model simulation. Only empirical simulations for this demonstration are reasonable to run on a desktop computer, all other simulations are feasible only on parallel computing clusters. As an example, in this demonstration, ADCIRC simulations will be run typically on 128 or 256 CPUs at the high-performance computing center at North Carolina State University, with additional simulations on a national cluster at Purdue University via the NSF ACCESS program. Delft3D, NearCom and FUNWAVE simulations are run typically on a NSF-supported University of Delaware high performance computer (HPC) called DARWIN. Simulation using Delft3D or NearCom can take roughly 12 hours on 4 CPUs. 2D FUNWAVE simulations require a day on 784 CPUs. 1D

FUNWAVE simulations require only 15 minutes on 28 CPUs. Researchers and military personnel may have similar access to clusters locally (at their home institutions) or nationally (via ACCESS and similar programs).

Costs for computing resources can be significant, especially for parallel computing. Local HPC access may exist at universities having been acquired over years of other project support. Typical costs are approximately $20k per core or approximately $325 per CPU; not including additional/ongoing costs for operation and maintenance of computing resources. These costs are likely similar for parallel computing clusters at other institutions and at DoD sites. For this demonstration we estimate the total computational resource "cost" $250k (a rough estimate for 10 nodes, 640 CPUs, and maintenance). Note, that this is not a recurring cost for each model setup or each simulation.

Researcher Effort – Model Setup and Simulation: A major cost for model implementation is the time required for the researcher/user to set up, calibrate, and validate each model at each military installation. As described above, we will track the time requirements as part of this demonstration, with goals for implementation of each model/class. We make a distinction between expert user and non-expert user in terms of personnel costs. Here, an expert is defined as a PhD student, Post Doc or Professor with extensive experience using a particular model. Personnel hourly rates including fringe benefits and facilities and administrative costs are estimated at $62, $100, and $250, respectively. Table 2 indicated expected time to set up the different types of models. We expect an additional 20 weeks per model type to address the performance objectives and model simulation variations. These time frames are used to generate a cost estimate for this demonstration (Table 7). For ease of calculation we use a rough estimate of $150/hr. It is important to note that future simulations at other installations may or may not require this amount of time as the wide range of variations in model simulation may not be necessary.

For this demonstration, we assume that these researchers are available already (at our home institutions) and do not need to be hired specifically for simulations of coastal flooding at military installations. For adoption by the DoD, simulations could be conducted by DoD staff who are already trained experts in coastal modeling, or offsite contractors with the required expertise. For this demonstration, we will track the person-power requirements (time for model setup, etc.) for each model/class, but we will not attempt to quantify the costs for other personnel conducting the simulations. It is important to note that costs for model setup and simulation efforts for non-model experts will be significantly more than the estimates for the personnel funded on this ESTCP project.

Researcher Effort – Webpage Development: Project personnel will manipulate the model output into graphs and data overlain on charts or aerial imagery for project manager perusal. These data products will be displayed on a dedicated web page with menus for selecting different scenarios enabling managers to rapidly infer the effect of altering model parameters. We estimate the expert researcher time to generate the web interface at 40 hours total.

Each researcher will maintain a time spreadsheet that will be collated and recorded to indicate total effort.

Table 7. Cost estimates for NSN model simulations.

Cost Category	**Cost ($k)**
Model software: Delft3D, FUNWAVE, ADCIRC, NearCom are freely available from internet repositories	0
Data products: Data for model calibration/validation (e.g. water level, waves) are freely available from numerous data sources	0
HPC: We estimate a one-time cost for a cluster consisting of 10 nodes (640 CPUs) to conduct model simulations (noting that the HPC needs for this project were provided by existing University resources)	250
Personnel time – model set up: Total model set up time is estimated at 16 weeks for the 5 personnel involved in the demonstration	96
Personnel time – simulations: Total estimated time to conduct simulations, investigate output, re-run simulations as needed, and produce useable model output is estimated as a total of 20 weeks for the 5 personnel involved in the demonstration	120
Personnel time – webpage: Total estimated time to take useable model output to generate easily understood figures/graphs is estimated at 1 week	6
TOTAL	**472**

8.0 SCHEDULE OF ACTIVITIES

The schedule of activities is presented in a Gantt chart (Figure 19) where gray shades indicate months of expected activity

Task	SubTask	YR23								YR24		
		Month										
1. Demonstration plan		5	6	7	8	9	10	11	12	1	2	3
	1.1 Submission											
	1.2 Approval											
2. Baseline simulations												
3. Irene variations												
4. Degradation simulations												
5. Parameterized vs modeled wind fields												
6. Quantitative performance objectives												
7. Qualitative performance objectives												
8. Web interface - feedback												
9. Demonstration report												

Figure 19. Gantt chart of demonstration activities.

9.0 MANAGEMENT AND STAFFING

Demonstration plan efforts are distributed across the various researchers on the project as shown in the flow chart (Figure 20). Puleo is responsible for the overall project coordination and empirical estimates. Other researchers are responsible for model simulations using software that they have developed and/or are experts on: Lashley (Delft3D and FUNWAVE); Shi (NearCom and FUNWAVE); Dietrich and Knowles (ADCIRC).

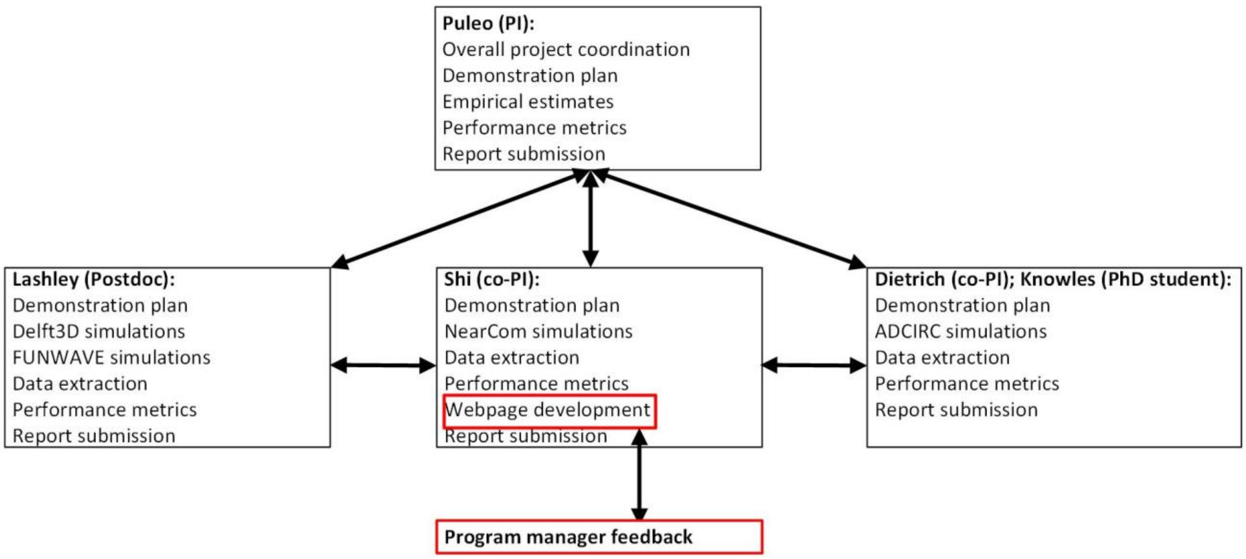

Figure 20. Flow chart showing organization of researchers for the demonstration.

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APPENDICES

Appendix A: Health and Safety Plan (HASP)

Researchers are not conducting field work nor working with hazardous materials as part of this demonstration plan. The effort is solely numerical modeling focused. As such, any risks or physical requirements are commensurate with those of a standard "desk" job and do not comport additional risk. Only a single user is required for simulating any of the models described in the demonstration plan.

Appendix B: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Jack Puleo	University of Delaware 259 Academy Street Newark, DE 19716	302-339-0343 302-831-1228 jpuleo@udel.edu	PI, project lead
Chris Lashley	University of Delaware 259 Academy Street Newark, DE 19716	clashley@udel.edu	PostDoc, Delft3D lead, FUNWAVE lead
Fengyan Shi	University of Delaware 259 Academy Street Newark, DE 19716	fyshi@udel.edu	Co-PI, NearCom lead, FUNWAVE lead
Casey Dietrich	North Carolina State Univ 915 Partners Way Raleigh NC 27695	919-515-5277 jcdietrich@ncsu.edu	Co-PI, ADCIRC lead
Jenero Knowles	North Carolina State Univ 915 Partners Way Raleigh NC 27695	jsknowle@ncsu.edu	PhD student