STORMTOOLS - High Resolution Inundation Modeling for Narragansett Bay, Mt. Hope Bay, and the Lower Taunton River

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1. Project Background and Objectives

1.1. Abstract

STORMTOOLS is a series of web-based geospatial data layers and applications providing hazard information associated with selected extreme storms events, with and without Sea Level Rise (SLR). The method adopted to define potential storm hazards is based on a state-of-the-art methodology, relying on 2-D numerical modeling of storm surge and waves , primarily for a synthetic design 100-year storm (1% annual probability of occurrence) (Spaulding et al., 2020) . The resulting coastal vulnerability across the shoreline is provided at high discretization (1m) in terms of combined exposure to storm surge and waves, as the predicted Base Flood Elevation (BFE) relative to NAVD88 or predicted total water depth (height above grade).

At the start of this project STORMTOOLS was operational for the entire southern RI shoreline and for the majority of Narragansett Bay; with the exception of Mount Hope Bay and the adjacent Massachusetts shoreline. The present project extends the modeling effort to capture all of Mt. Hope Bay and the adjacent shoreline and re-generates all STORMTOOLS web-based layers and online maps to reflect the newly modeled areas. This effort required a complete re-do of all the numerical simulations using the STORMTOOLS methodology (as defined hereafter) based on a new, combined topographic/bathymetric data set and Mean Higher High Water (MHHW) surface.

1.2. Background

The vision for STORMTOOLS is to provide access to a suite of coastal planning tools, available as data layers and web services, resulting from state-of-the-art numerical modeling, and resulting in widespread accessibility and applicability at high resolution for selected coastal areas of interest.

The initial tool developed under this framework was a simplified flood inundation model, assuming no waves or SLR, developed for a selected storm's return periods. The storm surge was based on a standard extreme value statistical analysis at three NOAA tide gauge stations and subsequent linear interpolation between the gages to generate 2-D maps, consistent with FEMA's methodology (Spaulding et al., 2014, 2015). The interpolation resulted in a near linear spatial scaling fairly consistent with the storm surge predicted using NOAA's Sea, Lake and Overland Surges from Hurricanes (SLOSH) model as well as the US Army Corps of Engineers (USACE) sophisticated suite of models performed as part of the North Atlantic Coast Comprehensive Study (NACCS) (Jensen et al., 2016). Initial simulations were provided for selected return periods of 25, 50, and 100-years, and for selected sea level rises scenarios (1, 2, 3, and 5 ft.). Simulations were also performed for historical hurricane events including the Great New England Hurricane of 1938, Hurricane Carol (1954), Hurricane Bob (1991), and Hurricane Sandy (2012) as well as for nuisance flooding events with return periods of 1, 3, 5, and 10 years. The resulting maps are web-accessible via ArcGIS Online and are widely used in municipal and statewide planning (https://stormtools-mainpage-crc-uri.hub.arcgis.com/).

The scaled methodology, while sufficient for representing smaller episodic events, was insufficient for the 100-year event and was replaced by a more robust approach using FEMA-approved methods and a suite of 2-D models to simulate fully coupled storm surge and wave propagation across the inundated area (Grilli et al., 2017a,b; Spaulding et al., 2017a,b). Following this approach, the storm hazard in the coastal area is defined using the NACCS statistical outputs at local offshore save points (defined by USACE; Nadal-Caraballo et al., 2015), as input to a high resolution coastal wave model. Each specific storm return period (e.g. 100-year) is defined at the NAACS offshore save point by a set of parameters representative of the storm characteristics: storm surge (including astronomical tide and static wave setup) and spectral wave parameters, significant wave height, wave period and wave direction. These storm parameters are used as offshore boundary conditions to a coastal wave model, STWAVE (phase averaged Steady-State Spectral Wave (STWAVE) Model; Smith et al. 2001; Massey et al. 2011), to develop high-resolution (10m) near-shore wave simulations . The new flood surfaces correct major deficiencies with earlier simplified inundation maps by taking into account the shape/orientation of the shoreline including the Narragansett Bay basin and the resulting funneling effects on water levels during storm events. This approach was used to simulate the impact of a 100-year return period storm on the entire Rhode Island shoreline for selected levels of sea level rise (0, 2, 3, 5, 7 and 10 ft). Finally, the approach was refined to simulate the erosion associated to the impact of 100-year storm on the south shore coastal lagoon dune system (Schambach et al., 2018). The method uses the numerical model XBeach (DELTARES; Roelvink, 2009).

Application of the method to RI has demonstrated the ability to generate high resolution flooding maps for use in state and municipal planning and emergency response planning and operation. Access via an online, web-based GIS with an ability to readily access the maps and merge with other data layers has proven critical to the wide spread use of the information. The method used in STORMTOOLS have been fully validated and published (Grilli et al, 2017a,b, Spaulding et al., 2017a,b, Schambach et al., 2018) with products and derivative analyses currently being used statewide for both policy and planning purposes. Applications include:

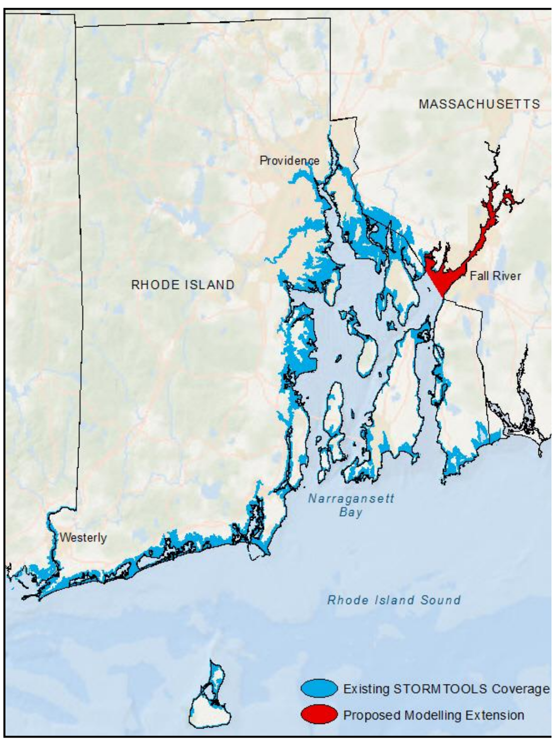

Figure 1: STORMTOOLS modeling extension

1. State Policy - As required by the RI Coastal Resources Management Program (RICRMP), Section 1.1.10.A(4) (Page 64), "...the Council adopts and recommends use of the STORMTOOLS online mapping tool developed on behalf of the CRMC by the University of Rhode Island Ocean Engineering program to evaluate the flood extent and inundation from sea level rise and storm surge. "

2. Municipal Planning - STORMTOOLS is being used in developing local comprehensive plans to meet the requirement of including a Natural Hazards Element into the plan, and to consider long-term adaptation of properties within the predicted flood envelopes.

3. Construction Planning - STORMTOOLS is being used to inform asset management across the state and construction design - the town of Narragansett used STORMTOOLS to increase the height of the berm constructed around the Scarborough waste water treatment facility, the I-195 Commission used STORMTOOLS to increase the elevation of the recently-constructed pedestrian bridge across the Providence River, and Sail Newport used STORMTOOLS to inform the design of their new facility at Fort Adams State Park.

The goal of this effort was to use these proven methods to extend modeling outputs beyond the Rhode Island state line to capture all of Mt. Hope Bay and the Lower Taunton River (Figure 1), allowing for:

a) the development of consistent, bay-wide vulnerability and risk assessments;

b) informed state and municipal planning; and

c) continued public education and outreach.

2. Methods

Analytical methods employed were identical to the approach used in STORMTOOLS and detailed in Section 1.2 of this document. A new elevation model was used to fill the void from earlier work and extend coverage across the study area. Previous STORMTOOLS modeling has been developed upon a custom derived, bare earth topobathy surface; a combination of terrestrial LiDAR elevation points and NOAA NOS hydrographic soundings developed by the University of Rhode Island's Environmental Data Center. The core data for the digital elevation/bathymetric model were bare earth terrestrial LiDAR points collected as part of the 2011 USGS American Recovery and Reinvestment Act, LiDAR for the Northeast project (USGS et al., 2011), and NOAA National Ocean Service (NOS) hydrographic surveys distributed through the NOAA National Centers for Environmental Information (NCEI) Bathymetric Data Viewer (https://maps.ngdc.noaa.gov/viewers/bathymetry/) .

2.1. Extending the TopoBathy Surface

As the underlying topobathy surface is the foundation upon which all modeling is built, a preliminary review was conducted to discover new elevation and bathymetric data sources that had been collected since the original STORMTOOLS products were developed that could potentially be used to extend the surface beyond the RI border. A listing of those data are presented in Table 1.

Table 1. Preliminary data discovery highlighting potential additions to the STORMTOOLS topobathy surface.

<table>
<tr><th>TOPIC</th><th>SOURCE</th><th>YEAR</th><th>DATASET NAME</th></tr>
<tr><td rowspan="5">Hydrographic Surveys</td><td rowspan="5">NOS</td><td>2015</td><td>F00642</td></tr>
<tr><td>2014</td><td>F00643, F00644, H12676, H12677, H12700, H12702, W00352</td></tr>
<tr><td>2013</td><td>H12429</td></tr>
<tr><td>2012</td><td>H12430, H12431</td></tr>
<tr><td>2011</td><td>H11930, H12082, H12296, H12298, H12299, H12324, H12386</td></tr>
<tr><td rowspan="8">Coastal LiDAR</td><td rowspan="5">USACE</td><td>2018</td><td>NCMP Topobathy, East Coast</td></tr>
<tr><td rowspan="3">2015</td><td>NAE Topobathy, MA</td></tr>
<tr><td>NAE Topobathy, RI</td></tr>
<tr><td>NAE Topobathy, CT</td></tr>
<tr><td>2012</td><td>Post Sandy, RI and MA</td></tr>
<tr><td>USGS</td><td>2013-14</td><td>Post Sandy, MA, NH, RI</td></tr>
<tr><td>NOAA</td><td>2014</td><td>NGS Topobathy post Sandy, RI</td></tr>
<tr><td>CT CRCOG</td><td>2016</td><td>Statewide LiDAR</td></tr>
</table>

Rather than develop a custom topobathy surface for this work, based on the preliminary data review, the project team tentatively selected the 2016 USGS Coastal National Elevation Database (CoNED) (https://www.usgs.gov/core-science-systems/eros/coned) for New England as the foundation for the new modeling and inundation surfaces. These data are well documented, incorporate the same 2011

USGS topographic LiDAR data and hydrographic surveys previously used by STORMTOOLS, including many of the additional datasets detailed in Table 1, and are distributed with the same 1 meter horizontal resolution. With additional validation it was expected that these data would provide consistency with earlier work with little deviation from developing a custom solution.

To assess how the CoNED Digital Elevation Model (DEM) equated to earlier STORMTOOLS modeling efforts, a comparison was performed between the CoNED surface proposed for this work and the topobathy model used previously that had been validated against bare earth points from the 2011 USGS topographic LiDAR project and was shown to meet National Standard for Spatial Data Accuracy (NSSDA) requirements. The first test involved placing 5000 random points across the entire study area to obtain an overall quantitative comparison of differences between the two surfaces; the second test placed 1000 points randomly within 1km of the coast to assess differences along the immediate coast where impacts to the surge model would be greatest. Results showed RSMEz difference values of 4.7cm and 7.1cm respectively, with 95% CI values of 9.2cm overall and 13.9cm along the immediate coast. Results from both tests fall well within the USGS Northeast LiDAR collection parameters of RSMEZ values ≤ 15cm with a 95% CI ≤ 30cm. Based on these numbers the CoNED topobathy surface was considered equivalent to the previous DEM and expected to return equally valid results for the updated STORMTOOLS modeling.

2.2. Determining Mean Higher High Water (MHHW)

Just as an updated topobathy surface was required to extend coverage across the study area, so too was an updated MHHW surface. As before, the MHHW surface was developed following the methods outlined in the NOAA whitepaper: *Detailed Method for Mapping Sea Level Rise Inundation (2017).* A seamless base (0 feet) MHHW surface was developed for Narragansett Bay along with companion SLR scenarios of 1, 2, 3, 5, 7, 10, and 12 feet of Sea Level Rise (SLR) using NOAA's VDatum (v4.01) (https://vdatum.noaa.gov/) approach to account for local and regional tidal variability. According to the NOAA methods, there are two primary caveats and one assumption for surfaces generated in this manner:

a) Data developed using these methods are for planning, educational, and outreach purposes only and should not be used for site-specific analysis, navigation, or permitting;

b) MHHW surfaces will assume present conditions will persist and will not reflect future changes in coastal geomorphology; and

c) The digital elevation model used to map sea level rise does not incorporate a hydro-connectivity analysis, and while hydrologically unconnected areas of inundation will still be displayed, they should be symbolized differently to indicate potential uncertainty.

Following these methods two datasets for each SLR scenario are generated; one that shows the extent and depth of flooding, and one that shows adjacent low-lying areas greater than 1 acre that may or may not be flooded. For ease of use and distribution, these datasets have been combined in to a single surface with low-lying areas coded as “999”, and both datasets should be viewed together to provide a complete picture of projected impacts for each scenario. While inundation surfaces display both the extent and maximum depth of water predicted for each event, low-lying areas do not have associated water depths and are merely used to highlight areas of possible concern that require additional investigation.

2.3. Inundation Surfaces

The modeling methodology employed for STORMTOOLS has been extensively published (e.g., Spaulding et al, 2016, 2017a,b; Grilli et al., 2017a,b; Schambach et al. 2018). The method is based on the results of the North Atlantic Coast Comprehensive Study (NACCS) using the coupled storm surge model ADCIRC and Steady State spectral wave model STWAVE to predict the extent of the inundation zone. The NAACS methodology was validated by comparing the results of the coupled models to historical storm events (Bryant and Jensen, 2017). These results were used in boundary conditions to perform high resolution wave simulations in the coastal area (e.g. Narragansett Bay), using the wave model STWAVE and the erosion model XBeach. Both STWAVE and XBeach have been carefully validated against historical storms in different shorelines types and climate environment including the Rhode Island shoreline and wave climate (e.g., Bender et al., 2013; Cialone et al., 2008; Schambach et al., 2018).

This effort leverages previous published STORMTOOLS work without deviating from past methods so no further model validation will be performed for this work. Following the 100-year storm definition and methodology adopted in STORMTOOLS, the model simulates a hypothetical 100-yr synthetic storm event at each specific location (not an actual historical storm). The STORMTOOLS methodology and uncertainties are described in Grilli et al., 2017 and Grilli et al., 2020).

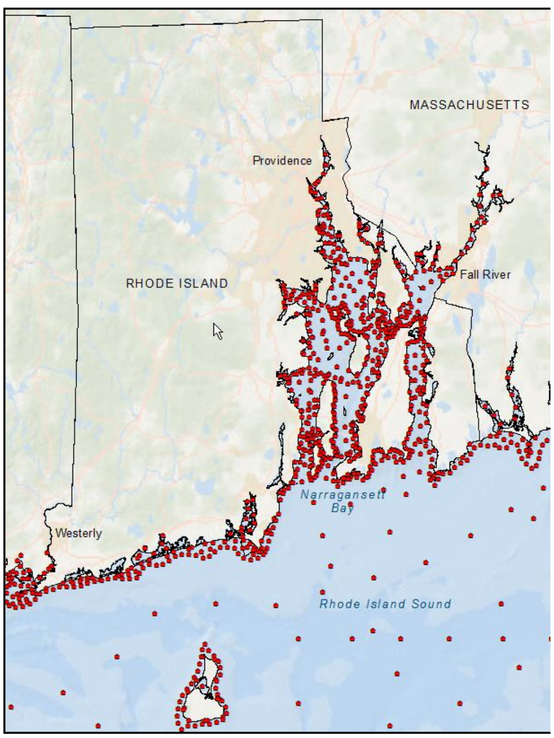

Figure 2: NACCS save point locations.

Storm surge coverage was expanded using the existing NACCS save points within Mt. Hope Bay and the Taunton River (Figure 2). These additional points will be used as initial conditions for numerical wave propagation simulations across the bay for a 100-year event for each of the selected SLR scenarios (0, 2, 3, 5, 7, and 10 ft.). Simulations for all other storm events (1, 3, 5, 10, 25, 50, and 500 years) will include only the effects from surge plus tide including SLR values of 1, 2, 3, 5, 7 and 10 ft.

2.3.1. Surface Modeling and Interpolation

Hydrodynamic modeling for the Mt. Hope Bay extension was completed for the 100yr storm event and outputs were returned as ASCII point files with a 5m resolution. These points were imported into a GIS and interpolated into continuous surfaces for each modeled variable – Base Flood Elevation (BFE) and wave crest height. Using these two values additional surfaces were derived for surge height (BFE minus wave crest height) and total water depth (BFE minus ground elevation). Outputs were merged with existing surfaces for Narragansett Bay and Rhode Island's south shore to create continuous inundation surfaces for all of RI and Mt. Hope Bay.

In addition to the 100yr event, NACCS-scaled surfaces were generated for intermediate/nuisance level storm events with return periods of 1yr, 3yr, 5yr, 10yr, 25yr, and 50yr. For all scenarios other than the 100-year event, inundation surfaces were scaled based on simulations of tropical and extratropical storms using NACCS models. These scaled flood surfaces correct major deficiencies with the widely used bathtub models by taking in to account the shape/orientation of the Narragansett Bay basin and the resulting funneling effects on water levels during storm events (Spaulding, 2014, Simplified flood inundation maps, with sea level rise, for RI). From early STORMTOOLS work, three important points emerge:

1) Surge heights are relatively constant along Rhode Island's south shore;
2) Surge heights increase as one moves north from Newport to Providence, as expected in embayments ; and
3) The relationship between water levels at Newport and Providence is predominantly linear.

Understanding this, as long as the water level is known at the Newport tide gauge, values can be interpolated for any location within the bay. For a complete description of the theory, methods and limitations of this work, users should review both the Scaled Sea Level Rise Summary document and the draft report detailing the methodology employed for the Simplified Flood Inundation Mapping.

Data from the NACCS RI save points were analyzed and spatially scaled to develop a series of projected flood inundation surfaces for coastal RI (Table 2). Mean projections were used for events with a return period of 10 years or less, while the upper 95% confidence interval values were applied to events with return periods 25 years and greater to provide an extra measure of protection.

Table 2. Storm return periods and associated scaling factors and water levels at the Newport tide gauge used for generating inundation surfaces for intermediate and historic storm events.

	RETURN PERIOD	SCALE FACTOR	NEWPORT WATER LEVEL (m)
Periodic Events	1-Year	1.30	1.31
	3-Year	1.30	1.58
	5-Year	1.30	1.75
	10-Year	1.30	1.95
	25-Year	1.30	3.30
	50-Year	1.30	3.62
	500-Year	1.44	4.70
Historic Events	Hurricane of 1938	1.30	3.49
	Hurricane of 1954 (Carol)	1.56	2.67
	Hurricane of 1991 (Bob)	1.30	1.82
	Hurricane of 2012 (Sandy)	1.10	1.89

3. Deliverables and Data Management

3.1. Deliverables

Inundation surfaces were delivered as seamless raster (gridded) surfaces stored within individual Esri® file geodatabases (one for each storm scenario) mirroring existing STORMTOOLS data (Table 3), the only difference being that data outputs will now extend across the state line to include the Massachusetts portion of Mt. Hope Bay and the Taunton River. In addition to the data layers listed, all web services and web mapping applications developed from these layers have been updated to reflect the new modeling work.

Each GIS layer delivered to NBEP contains appropriate metadata including source information for each digital layer (i.e., scale and accuracy, map projection, coordinate system, etc.) and processing methods, data limitations, geographic extent, file format, date of creation, staff contact, and a description and definition of data fields and their contents. As is common with the transfer of geospatial data, this metadata document is an integral part of the data file and is included with each download. IN addition to direct delivery to NBEP, additional repositories for these data will include the Rhode Island statewide Geographic Information System (RIGIS) website (https://www.rigis.org) and the STORMTOOLS project website that is under development as part of a separate effort (https://stormtools-mainpage-crc-uri.hub.arcgis.com/).

To meet the varied needs of users, all GIS deliverables are stored in separate ArcGIS file geodatabases with the following projections:

a) Coordinate system: UTM Zone 19N; Units: meters; Horizontal datum: NAD 1983(2011); Vertical datum: NAVD88; and

b) Coordinate system: RI Stateplane; Units: feet; Horizontal datum: NAD 1983(2011); Vertical datum: NAVD88.

Table 3: STORMTOOLS inundation deliverables

	Event Return Period	Sea Level Rise Scenarios (ft)	Inundation Parameters
	MHHW	0, 1, 2, 3, 5, 7, 10, 12	N/A
Nuisance Events	1-Year	0, 1, 2, 3, 5, 7, 10	Surge + Tide
	3-Year	0, 1, 2, 3, 5, 7, 10	Surge + Tide
	5-Year	0, 1, 2, 3, 5, 7, 10	Surge + Tide
	10-Year	0, 1, 2, 3, 5, 7, 10	Surge + Tide
Major Events	25-Year	0, 1, 2, 3, 5, 7, 10	Surge + Tide @ 95% CI
	50-Year	0, 1, 2, 3, 5, 7, 10	Surge + Tide @ 95% CI
	100-Year	0, 2, 3, 5, 7, 10	Surge + Tide + Waves + Erosion @ 95% CI
	500-Year	0	Surge + Tide

All STORMTOOLS data have also been published as web services that can be freely added to online mapping applications through the REST endpoint (https://maps.edc.uri.edu/stormtools/rest/services/Stormtools2020). The STORMTOOLS Design Elevation Viewer is one such product that has been developed to allow users to intuitively visualize and interact with the data (https://arcg.is/0buDDL).

Web services displaying modeled inundation are provided in a manner that displays both flooding extent and depth for nuisance floods (1, 3, 5, and 10-year return periods) and the larger 25, 50, 100, and 500-year storm scenarios at the 95% confidence interval. Depending on the storm scenario, SLR predictions of 1, 2, 3, 5, 7, 10 feet are also included as shown in Table 3. Inundation maps have also been generated for the largest historic storm events including the hurricanes of 1938 (no name The Great New England Hurricane), 1954 (Carol), 1991 (Bob), and 2012 (Sandy). Each storm scenario (i.e. 100-year event) is served as a single mosaic image service that contains a stack of multiple raster datasets. To work as intended, the display must be "locked" to a specific Image ID limiting the display a single raster at any one time. The following is an example of data organization:

Image ID #	Data Content
1	Storm Event, 0 feet Sea Level Rise (SLR)
2	Including 1 foot SLR
3	Including 2 feet SLR
4	Including 3 feet SLR
5	Including 5 feet SLR
6	Including 7 feet SLR
7	Including 10 feet SLR.

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