Application of STORMTOOLS's simplified flood inundation model, with and without sea level rise, to RI coastal waters

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ABSTRACT

The vision for **STORMTOOLS** is to provide access a suite of coastal planning tools (numerical models, etc.), available as a web service, that allows wide spread accessibly and applicability at high resolution for user selected coastal areas of interest. The first tool developed under this framework was a simplified flood inundation model, with and without sea level rise, for varying return periods. The methodology is based on using the water level vs return periods at a primary NOAA water level gauging station and then spatially scaling these values to generate a map. The spatial scaling was performed using predictions of high resolution storm simulations performed by NOAA using their Sea, Lake and Overland Surges from Hurricanes (SLOSH) model for various hurricane categories and by the US Army Corps of Engineers (USACE) ADCIRC/WAM/STWAVE numerical hydrodynamic/wave model predictions performed as part of the North Atlantic Coast Comprehensive Study (NACCS) for synthetic tropical storms, to estimate inundation levels for varying return periods for coastal waters.

The mapping methodology follows the NOAA sea level rise protocol and is applicable to any coastal region. The scaling for the RI application used Newport, RI water levels as the reference point. The predicted flooding based on NACCS model predictions were comparable and within the range of uncertainty to that based on the SLOSH - NOAA based method. Predictions are provided for once in 25, 50, and 100 yr return periods (at the upper 95% confidence level), with sea level rises of 1, 2, 3, and 5 ft. Simulations were also performed for historical hurricane events including: 1938, Carol (1954), Bob (1991), and Sandy (2012) and nuisance flooding events with return periods of 1, 3, 5, and 10 yr. The maps are web accessible via ArcGIS and being widely used in municipal and state wide planning (http://www.beachsamp.org/resources/stormtools/).

INTRODUCTION

The vision for **STORMTOOLS** is to provide access a suite of coastal planning tools (numerical models, maps, etc.), available as a web/app service, that allows wide spread accessibly and applicability at high resolution for user selected coastal areas of interest. The initial tools are models to predict winds, water levels, waves, and currents in coastal areas. The models and associated data bases would reside on the web server site and run or accessed remotely via web based, user requests (Figure 1). The system could either be hosted by a government agency, a regional collaborative organization, an educational institution, or reside on the cloud. The system would allow new embedded study domains, with high resolution grids to be developed for areas of particular interest. The approach is well suited for classic downscale modeling approaches used to investigate the impact of climate change on coastal and riverine processes and can readily take advantage of rapidly evolving cloud computing resources.

In the present application, the method is employed to generate flooding maps for varying return periods for the RI coastal waters based on use of the NOAA SLOSH simulations for varying storm categories (http://www.nhc.noaa.gov/surge/slosh.php) or alternately ADCIRC/WAM/STWAVE numerical hydrodynamic/wave model predictions performed by the US Army Corps of Engineers (USACE) as part of the North Atlantic Coast Comprehensive Study (NACCS) for synthetic tropical (1050) and historical (100) extra tropical storms (Cialone et al, 2015). Simulations were performed with and without sea level rise. The strategy employed in this application is to use extremal analysis at a primary water level station to determine the water levels for varying return period and then hydrodynamic model simulations to determine the spatial scaling of peak water levels for storms/return periods referenced to this primary gauging station.

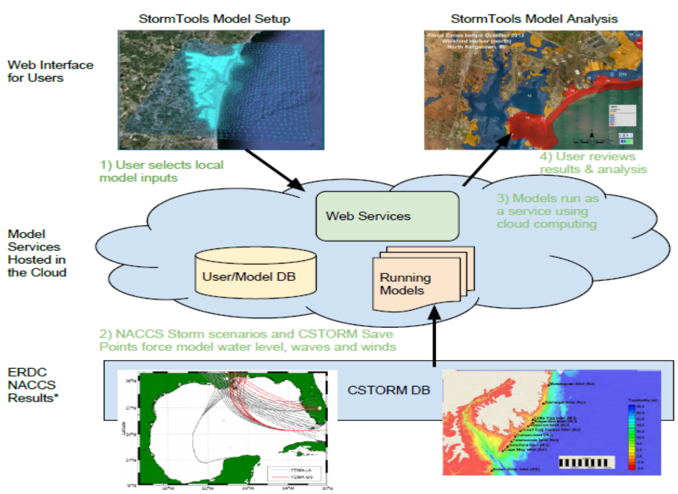


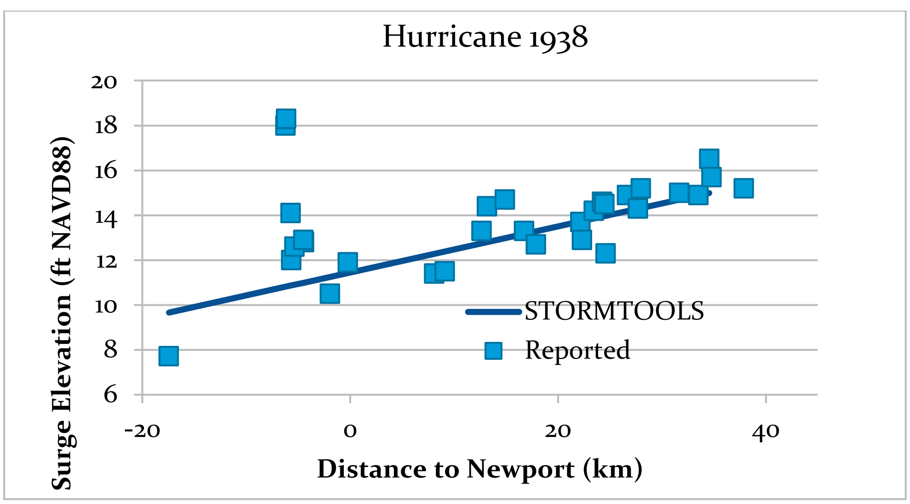
Figure 1 **Vision for STORMTOOL system showing access to NACCS surge model predictions from the CSTORM Data Base.**

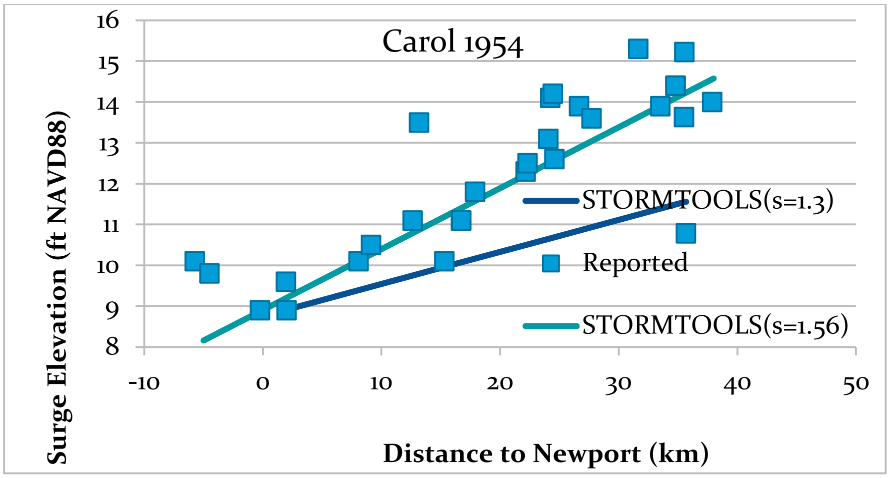
ANALYSIS OF HISTORICAL DATA

The peak water level data at Providence and Newport, RI (the only two primary NOAA NOS water level gauges in RI), when data are simultaneously available from both locations, is shown in Table 1, rank ordered by peak water level. The table also shows the ratio of the two. Storm levels are shown to be amplified at the head of Narragansett Bay (Providence) compared to the value at the mouth (Newport), with an average value of 1.3 and a range of 1.1 to 1.4. To investigate the spatial trend more closely peak water level data from 1938, 1954, and 2012 tropical storms were analyzed using historical data (FEMA, 2012) and plotted vs distance along the central axis of Narragansett Bay in Figure 2. The data clearly show that the storm surge amplification is linear with distance up the bay but the scale factor depends on the storm. While data were not available for Providence for hurricane Carol (1954), the figure clearly shows that its scale factor, determined by a fit to the existing data at other locations, is on the order of 1.56, much larger than the mean value (1.3) shown in Table 1. The differences in scale factors can be explained by the storm track (Figure 3) and forward speed, with the largest amplifications for tracks to the west of Narragansett Bay with the highest forward speed. Both contribute to maximizing the northward winds along the central axis of the bay.

Table 1 Water levels (MHHW and NAVD88) for peak storms impacting RI from NOAA NOS Newport (#8452660) and Providence(#845400), RI gauging stations.

Scaling of peak storm water level							
			MHHW levels (m)		NAVD88(m)		Ratio
Storm	Storm Name	Storm Type	Newport	Providence	Newport	Providence	PVD/ NPT
		Tropical/Extratropical					
9/21/1938	1938	Cat 3	2.88	3.86	3.49	4.62	1.32
10/29/2012	Sandy	Cat 1-2	1.28	1.33	1.89	2.09	1.10
8/19/1991	Bob	Cat 2	1.21	1.57	1.82	2.33	1.28
9/14/1944	Great Atlant	Nor'easter	1.21	1.79	1.82	2.55	1.40
1/9/1978	Great Blizzar	Nor'easter	1.10	1.50	1.71	2.26	1.32
11/30/1963	Helena	Tropical storm	0.99	1.42	1.60	2.18	1.36
						Average	1.30
				MHHW (NAVD88)			
			Newport	0.61			





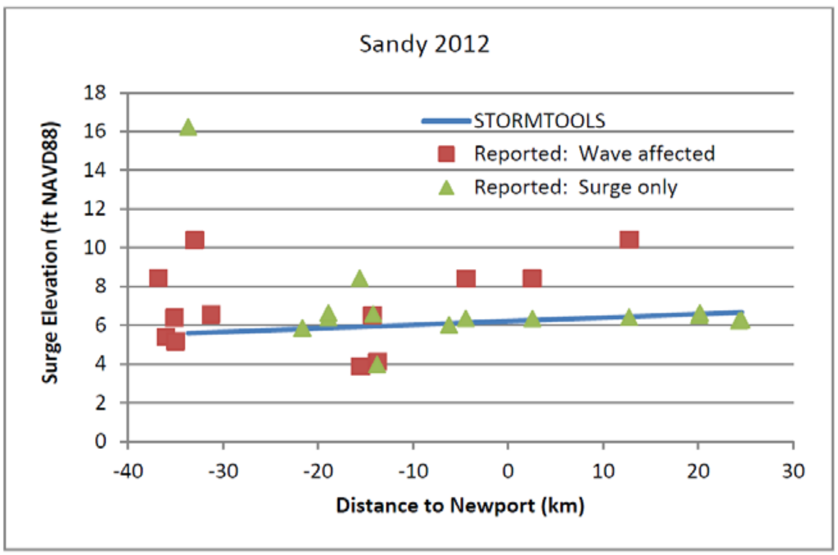


Figure 2 **Peak storm surge water levels (FEMA,2012) for 1938, 1954, and 2012 hurricanes vs distance up the bay referenced to Newport, RI. The data are fitted using a straight line with distance along the central axis of Narragansett Bay. Negative distances are to the west following the southern RI shoreline.**

FLOOD MAP GENERATION

In the interest of space only the flooding maps based on NACCS predictions are described here. Those using SLOSH simulations followed a similar protocol with the exception that the spatial structure was obtained from analyzing the various category storms in the data base and scaling the return period surge levels at Newport, RI based on the NOAA extreme value analysis (Generalized Extreme Value, GEV) of historical data. NACCS performed simulations 1050 synthetic tropical storms using a fully coupled ADCIRC/WAM/STWAVE with a very high resolution grid primarily covering the Mid Atlantic study area. The grid resolution was as high as 50 m in flood inundated areas in Narragansett Bay and along the southern RI shoreline and associated coastal ponds. Simulations were performed for surge only and surge plus tidal cases. Model predictions were saved at 18,000 grid locations; 1,000 in RI. Return period analyses were performed by USACE for each save point. Values for the mean and upper and lower 95% confidence intervals were provided. In the present effort, the data from the RI save points for selected return periods were analysed and spatially interpolated to develop a flooding map for the state. As an example, Figure 4 shows the map for the surge plus tide case for the 100 yr return period, upper 95% confidence interval. The figure shows that the peak water levels along the coast are very similar but amplified with distance up the bay. Details on this application and validation of the results are provided in Spaulding et al (2015). Hashemi et al (2015) have used the model predicted peak water level for the synthetic storms to develop an Artificial Intelligence (AI) neural network based storm prediction model. The model training, testing, and validation were all very good with $R \geq 0.92$. Performance was equally good when the AI method was applied to the largest tropical storms impacting RI with a root mean square error (RMSE) equal to 30 cm.

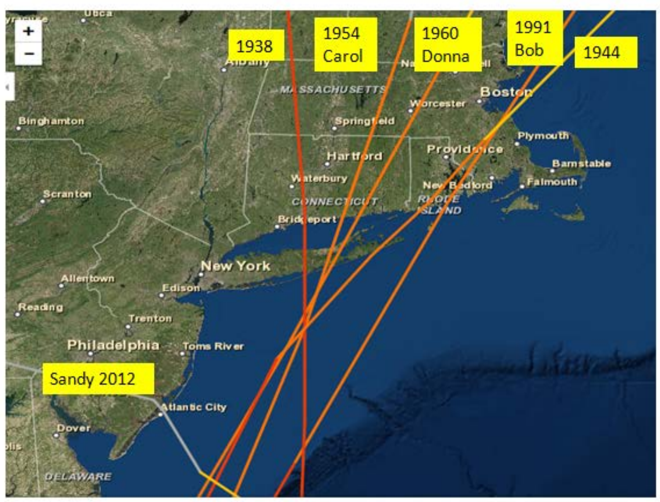


Figure 3 **Storm tracks for 1938, 1944, 1954, 1960, and 2012 storms (NOAA NHC data base). The color of the storm track indicates strength (red- Cat 3, orange- Cat 2 and yellow- Cat 1).**

Figure 5 shows the amplification of the peak water level vs distance along a transect from New London, CT; along the southern RI coast line, and finally up the central axis of Narragansett Bay. These three locations were selected, since they are closest NOAA primary water level stations for RI. Results are based on simulations for various category hurricanes from NOAA SLOSH simulations (Cat 1-4 with 2(0.6 m) and 5 (1.52 m) ft of water level increase) and from NACCS simulations for the surge and surge plus tide, mean and upper 95% confidence interval cases. A straight line, with two segments is fit through the data for the SLOSH and

NACCS cases. The scaling estimate used by FEMA in the most recent Washington County Flood Insurance Study (FIS)(FEMA, 2012) is shown for reference.

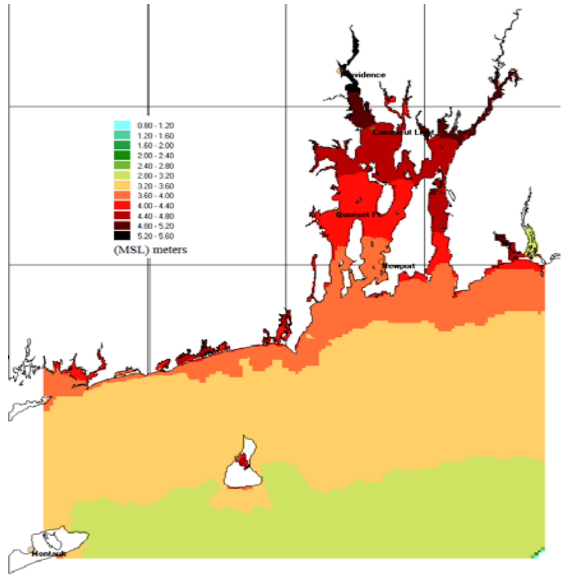


Figure 4 **Contour map (meters, relative to MSL) of the upper 95% confidence interval, 100 yr peak water level, for the tide plus surge case, based on NACCS simulations.**

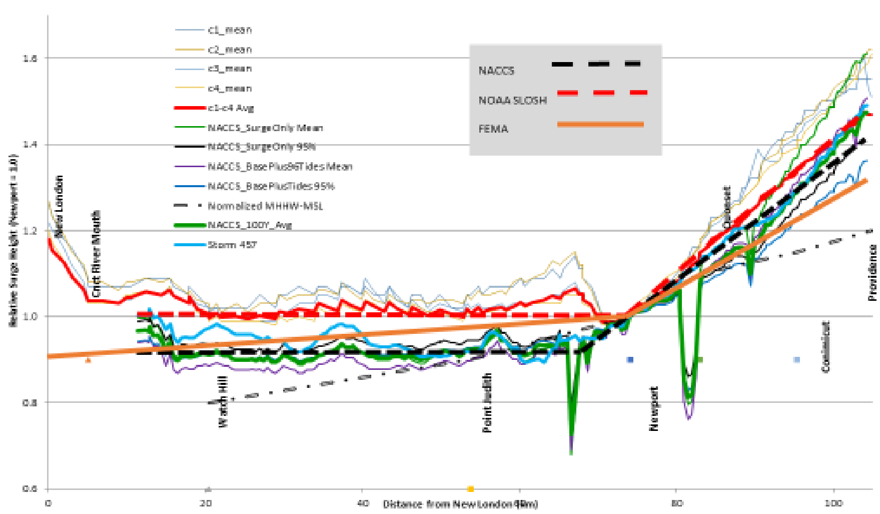


Figure 5 **Peak surge water level vs distance from New London , CT along the southern RI coast line, and up the central axis of Narragansett Bay relative to Newport, RI for NOAA SLOSH and ACOE NACCS simulations. Results are**

provided for SLOSH Category 1 to 4 storms means and for NACCS for surge only and surge plus tides for the mean and upper 95% confidence interval fits to the 100 yr return period predictions. Approximate values (straight dashed lines) for SLOSH and NACCS predictions and the FEMA (straight solid line) analysis are provided. The normalized MHHW- MSL is also provided for reference.

It is clear from the figure that, in a broad sense, there is little difference in water level along the southern RI coastline for the SLOSH and NACCS simulations, but a linear amplification with distance up the bay. It is noted that the SLOSH simulations suggest at hinge point at Newport, while those from NACCS predict that the hinge point should be at the mouth of the bay (slightly south of Newport). The difference may be due to the much higher resolution of the NACCS model simulations and the inclusion of detailed representation of the flood inundated areas.

Table 2 shows a summary of the results for water levels from NACCS (surge + tides, surge only), NOAA, and FEMA FIS for the 100 yr water levels (meters, referenced NAVD88) for Providence, Newport, and New London. Mean and upper 95% confidence interval values are given if available. FEMA does not provide confidence intervals.The amplification in the bay is 1.3 based on FEMA. (Note that FEMA performed an L-Moment analysis of historical water level data at the three stations to determine the 100 yr return period and simply linearly interpolated between them). This compares to 1.66 and 1.44 for the mean and upper 95% confidence intervals for the NACCS surge only case, respectively with similar values of 1.55 and 1.4, for the surge plus tide case. Values based on NOAA NOS historical water level data show scaling of 1.41 for the mean and 1.6 for the upper 95% confidence interval. For the present effort the NACCS scaling for the upper 95% confidence interval for the surge plus tide case (1.4) is used. The reasons for its selection are that it is the highest resolution model available for the area, use of the upper 95% is conservative and accounts for likely uncertainties in the modeling and extermal analysis efforts, and the return period analysis does not have limitations associated with approaches based on limited historical data. The later is a well known issue at the Providence station for the 1938 hurricane.

Table 2 Water levels(m) for 100 yr return period for Providence, Newport, RI and New London, CT from the NOAA, NACCS, and FEMA.

	NACCS Surge+ Tide		Surge		NOAA		FEMA FIS
Station	Mean	Upper 95%	Mean	Upper 95%	Mean	Upper 95%	
Providence	4.29	5.49	4.01	5.17	3.48	5.56	4.2
Newport	2.76	3.93	2.42	3.58	2.47	3.47	3.21
New London	2.86	4.37	2.78	3.92	2.31	3.17	2.87

Scaling Relative to Newport							
Providence	1.55	1.40	1.66	1.44	1.41	1.60	1.31
Newport	1	1	1	1	1	1	1
New London	1.04	1.11	1.15	1.09	0.94	0.91	0.89

SLOSH simulations were performed for selected water level offsets of 2(0.6 m) and 5 (1.52 m) ft, nominally noted as tides, but can also be considered a proxy for sea level rise (SLR). The average amplification for the SLOSH simulations for all category storms (Cat 2 to 4) is 1.57. The value decreases to 1.45 for 2 ft (0.6 m) of SLR and 1.37 for 5 ft (1.52 m). Similar results were found from the NACCS study. Use of amplification factors without SLR are hence conservative and have been adopted in the present study. This assumption allows one to simply add SLR to the corresponding flooding maps for any selected return period. For present study values of 1, 2, 3, and 5 ft of SLR have been used based on the Army Corp of Engineers SLR calculator (http://www.corpsclimate.us/ccaceslcurves(superseded).cfm) for the high rate for Newport and Providence, RI.

Maps were generated following the NOAA sea level rise mapping protocol (NOAA, 2012) with all elevations given referenced to NAVD88. The maps use the statewide 2011 LIDAR Digital Elevation Model (DEM) with a horizontal resolution of 1 m and seamless cover the entire state. The DEM has a vertical root mean square error(RMSE) of approximately ±15 cm. The base maps can be selected from a variety of alternatives. With a focus on meeting the varied needs of municipal and state planners, emergency responders, coastal engineers and the general public, maps were generated for the 25, 50 and 100 yr return periods with 1, 2, 3, and 5 ft of sea level rise, nuisance flooding events with 1, 3, 5, and 10 yr and hurricanes 1938, 1954, 1991, and 2012. Access to the flooding maps is via a web based, map viewer (Arc GIS) (http://www.beachsamp.org/resources/stormtools/. The GIS structure of the map viewer allows overlays of additional relevant data sets (roads and highways, wastewater treatment facilities, schools, hospitals, emergency evacuation routes, etc.) as desired by the user. The simplified flooding maps are publically available and are now being implemented for state and community planning in response to climate change impacts.

As an example, Figure 6 shows the 25, 50, and 100 yr return period flooding (left panel) and mean high high water (MHHW) plus SLR (right panel) for the Port of Providence. The figure shows the level of detail provided by the maps and their ability to visualize areas impacted by progressive levels of flooding and SLR. Maps for various return periods and SLR are also available. Figure 7 shows the ability to overlay the locations of critical infrastructure on the flooding maps to assist in emergency response planning and operation. In this case, the issue is that the fire station closest to Warwick Neck would be unable to reach the local residents in a 25 yr event. One can also interrogate the critical infrastructure symbol to provide details on the facility including its location and contact information. These types of maps can be made to support user needs to integrate flooding information with the location of other assets and infrastructure as well including highways, bridges, waste water treatment facilities, and communications systems.

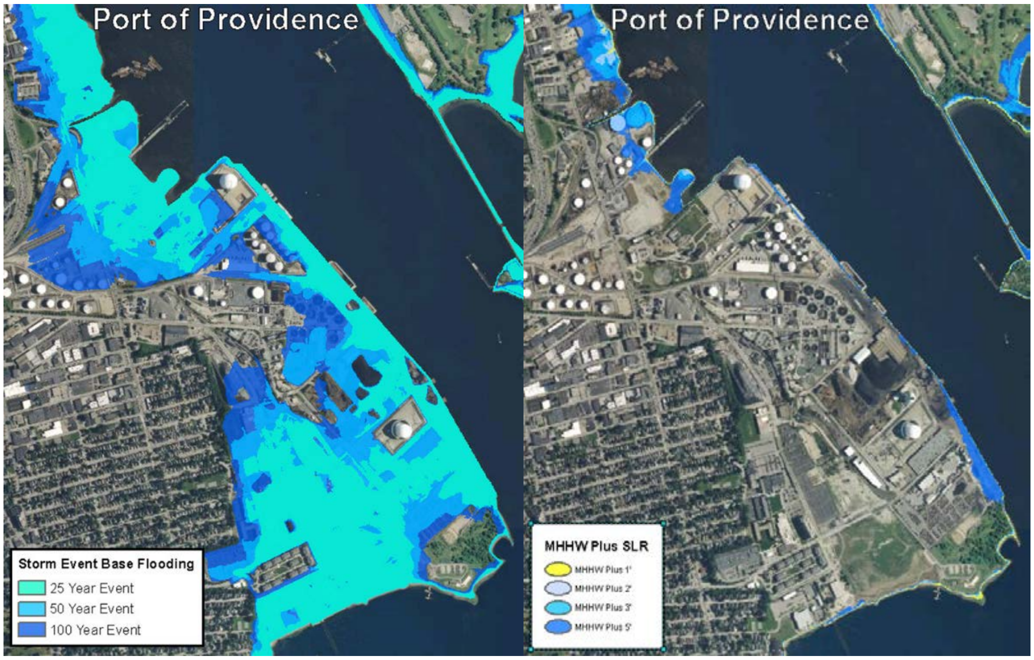


Figure 6 **Flooding maps for the Port of Providence for the 25, 50, and 100 yr return period (left) and for 1, 2, 3, and 5 ft of sea level rise, relative to Mean High High Water(right).**

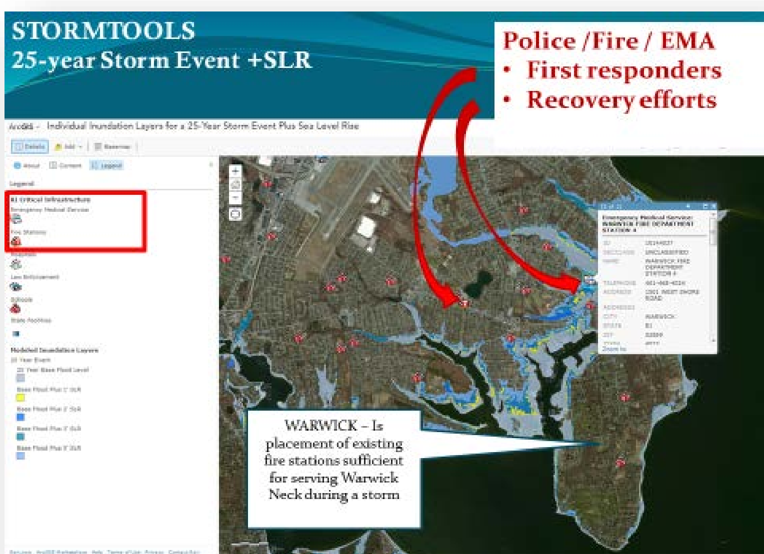


Figure 7 **Flooding map for Warwick Neck, RI showing flooding from the 25 yr return period storm with SLR. The location of critical infrastructure are provided**

as well. The insert demonstrates the ability to link to an underlying table which provides details on critical facilities.

CONCLUSIONS

The vision for **STORMTOOLS,** is to provide access a suite of coastal planning tools (numerical models, etc.), available as a web service, that allows wide spread accessibly and applicability at high resolution for user selected coastal areas of interest. The approach has been implemented to develop simplified maps of coastal flooding for RI, including the effects of sea level rise. The application employed SLOSH and ADCIRC/WAM/STWAVE (NACCS) simulations to determine the spatial variability of the surge relative to a reference location and the return period analysis at the reference location to develop inundation maps for varying return periods. Inundation maps for any return period can be then be determined by scaling the water level at the reference location by the spatial maps. The NACCS method was selected for the present application given the very high resolution of the state of the art, fully coupled models (includes wave current interaction), and the use of a representative population of synthetic storms, which do not suffer the limitation of historical data with their short record lengths.

Application to RI has demonstrated the ability of the approach to generate high resolution flooding maps for use in state and municipal planning and emergency response planning and operation. Access via an on line, web based GIS with an ability to readily access the maps and merge with other data layers has proven critical in the wide spread use of the system. Efforts are in progress to provide the same functionality for an app that provides the user with detailed information on the location of interest.

ACKNOWLEDGEMENT

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