GINIS, URI

DHS Coastal Resilience Center

Annual Project Performance Report

Covers reporting period January 1, 2016 – June 30, 2016

1. **Project Title:**

   Modeling the combined coastal and inland hazards from high-impact hypothetical hurricanes

2. **Principal Investigator / Institution:**

   Isaac Ginis, University of Rhode Island, Professor

3. **Other Research Participants/Partners:**

   Co-PIs:
   - Chris Kincaid, University of Rhode Island, Professor
   - Tetsu Hara, University of Rhode Island, Professor
   - Lewis Rothstein, University of Rhode Island, Professor
   - David Ullman, University of Rhode Island, Marine Research Scientist
   - Pam Rubinoff, University of Rhode Island, Senior Coastal Manager
   - Wenrui Huang, Florida State University, Professor

   Key Partners:
   - NOAA/NWS/NCEP Environmental Modeling Center
   - NOAA/NWS Northeast River Forecast Center
   - NOAA/OAR Geophysical Fluid Dynamics Laboratory
   - Rick Luettich and Brian Blanton, University of North Carolina at Chapel Hill
   - U.S. Army Corps of Engineers
   - Daniel Cox, Oregon State University

4. **Short Project Description:**

   This project advances modeling capabilities for assessing the potential impacts of landfalling hurricanes on critical infrastructure and communities, exacerbated by the effects of climate change. The primary focus is on extreme real and hypothetical, yet plausible high-impact hurricane scenarios in the Northeastern United States by combining multiple hazard impacts, including coastal flooding due to storm surge and inland flooding due to rainfall. This project will allow DHS and other agencies to better understand the consequences of coastal and inland hazards associated with extreme high-impact landfalling hurricanes in specific regions and to better prepare the coastal communities for future risks.

5. **Abstract:**

   The major goal of this project is to comprehensively investigate the hazards in the focus region using the most advanced coupled hurricane-ocean prediction, coastal ocean circulation/storm

surge, wave, climate, and hydrological models. To attain this goal, the following specific tasks will be accomplished: 1) Creating physically consistent, hypothetical high-impact scenarios that combine widespread, multiple hazard impacts (e.g. storm surge and rainfall-induced flooding); 2) using a multi-model ensemble approach to integrate 2-3D coastal models with watershed and 1D river models to provide the best possible coastal and inland flood guidance; 3) implementing the URI air-sea coupling module developed for NOAA operational hurricane models to coupling storm surge/wave models; 4) providing hazard model output in format suitable for HAZUS or other risk modeling software and tools used by DHS and other agencies; 5) utilizing the most advanced tools for sharing, visualizing and communicating the hazard model simulations with end users; and 6) account for the impacts of natural and anthropogenic stressors, including climate change, on the focus region by using nested-grid regional 'down-scaling techniques.

6. End users:

- NOAA/NWS Northeast River Forecast Center (NERFC),
  Provided data for historic hurricanes in RI for model validation and will participate in the analysis and adoption of model results and implementing the improved model capabilities into operations at NERFC.
- NOAA/NWS/NCEP Environmental Modeling Center (EMC), Head of Marine Modeling and Analysis Branch.
  Assisted in the implementation of the WAVEWATCH 3 wave model in Narragansett Bay and Rhode Island coastal waters and will participate in the analysis and adoption of model results and implementing the improved model capabilities into operations at NCEP.
- US. Coast Guard, R&D Center: Met and provided briefing of the Disaster Dynamics project and explored potential intersections with Coast Guard Missions. Specific discussion focused on end-user interest in enhanced hurricane modeling and the benefits for Coast Guard decision making - specific reference was made to the use of ADCIRC by Coast Guard Atlantic Area a critical element of their decision matrix that led to relocating the Atlantic Area Command & Control to St. Louis ahead of an approaching hurricane. So continued improvement of the hurricane prediction tools was well received. Additionally, the R&D Center team was interested in the wind, wave and storm surge modeling and prediction aspects associated with this work and how it could support improved Search and Rescue Modeling/Prediction (specific reference made to the cargo ship El Faro case noting that the influence of wind and waves on the current and subsequent drift predictions would have helped locate the vessel more quickly), hind-casting storm impacts after hurricane landfall to assist with resource deployment (pollution response, assistance, etc.) as well as helping NOAA's Navigation Response Teams and USCG in reconstituting operation of key/priority waterways.
- Rhode Island Emergency Management Agency (RIEMA), Jessica Stimson, State Hazard Mitigation Officer and Stephen Conard, Training Exercise Coordinator
  Updates of this project are provided at quarterly meetings of State Hazard Mitigation Planning and Silver Jackets meetings. The research will provide input to their planning efforts, and training exercises, planned for FY2017.
- RI Flood Mitigation Association (RIFMA)

As a state association of floodplain managers, they have been briefed on the project and will track the outcomes so that they can collaborate on outreach and training as appropriate

- FEMA Region 1, Federal Coordinating Officer and Disaster Recovery Manager: Provided verbal overview of the Disaster Dynamics project and had initial discussions about how best to integrate FEMA Coordinating Officer and Disaster Recovery Managers into the discussion and how these modeling and predication capabilities could be used to benefit FEMA's efforts. Landry was going to see if he was the right person to be involved, or to identify an alternate contact. Although not discussed, it follows from the US Coast Guard end-user discussions that both improved forecasting and hind-casting capabilities would add another key element to FEMA's decision matrix for resource deployment strategies ahead of and after hurricane landfall. More discussion will follow.
- Narragansett Bay Commission, Tom Uva, Director of Planning, Policy and Regulation: Chris Kincaid, Co-PI met with members of the Narragansett Bay Commission's (NBC's) Environmental Monitoring Division, and presented research goals of the project at the annual NBC board meeting. Based on discussions with NBC staff one potential benefit to their planning strategies that our modeling could impact was the effect on surge levels that could be expected at their campus (just south of the Fox Pt. Hurricane Barrier) given different storms and management responses. As an initial test, the ROMS model, with wetting and drying capabilities turned on, was run with and without the hurricane barrier closed for Hurricane Bob conditions. Results were presented at a professional meeting and will be shared at a meeting with NBC officials in Fall, 2016.
- Port of Providence, Stephen Curtis, Facility Manager - FY2017 participation anticipated
- Association of State Flood Managers, Chad Berginnis, Executive Director- FY2017 participation anticipated

7. Explanation of Changes:

As the research component of this project progressed some adjustments were made to the work plan, primarily to accelerate the implementation of the ADCIRC storm surge model in Narragansett Bay and Rhode Island coastal waters. The effort was facilitated by our UNC partners and led by Rick Luettich. In addition, we accelerated the implementation of the WAVEWATCH 3 wave model due to the assistance we received from our NOAA/NWS/NCEP/EMC partners led by Arun Chawla.

Given the multiple activities occurring in Rhode Island, the team modified our strategy to engage end-users in different venues, rather than one workshop as initially planned. This is reflected in the table and milestones below with activities planned in the coming months.

8. Unanticipated Problems:

N/A

9. Project Outcomes:

This project will deliver physically consistent, yet plausible high-impact hurricane scenarios for RI and Southern New England areas and a comprehensive multi- model analysis of the coastal and inland hazards. A new air-sea coupling module (ASCM) for coupling storm surge/wave models will be implemented into ADCIRC and the Regional Ocean Modeling System (ROMS). ASCM will be transitioned to NOAA's Environmental Modeling Center (EMC) for possible implementation into the operational hurricane prediction models and U.S. Army Corps of Engineers to improve their storm surge prediction models. We will take advantage of our multi-year collaboration with EMC to facilitate this transition. In addition, detailed mapping and analysis of the inland and coastal flooding from different hurricane scenarios will be generated and provided to NOAA NWS Forecast Office in Taunton, MA and DHS regional stakeholders.

We held a meeting at URI with the DHS Office of Cyber and Infrastructure Analysis and several scientists supported by DHS/OCIA to discuss how the coastal and inland hazard modeling results of this project may be applied for simulating the impact on critical infrastructure and developing risk analysis for decision-makers. Based on these discussions, we are currently developing a coordinated work plan that will include ingesting the URI hazard analysis (wind fields, inundation, and other storm parameters at landfall) into infrastructure impact models. The outcome of this effort could take several forms, depending on what kind of final product we intend to produce (e.g., text-based reports, graphical products, presentations).

We will collaborate with Prof. Dan Cox (OSU). Initially, this will involve a series of Skype/WebEx sessions to discuss how to efficiently combine our expertise into a next round of work, where a nested-grid modeling approach will link models of flow/surge energy in our simulated storms to Professor Cox's models on the response of critical infrastructure. In this second stage, our two groups will join efforts on establishing linkages from the large-scale circulation modeling at URI to the fluid-structure work at OSU.

10. Research Activity and Milestone Progress:

Research Activities and Milestones: Progress to Date

Reporting Period 1/1/2016 – 6/30/2016			
Research Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not reached, and when completion is expected
Simulate historic storms and generate *Hurricane Rhody* scenario using the HWRF and GFDL hurricane models.	5/30/2016	50%	This activity will be completed during the period 7/01/16-12/31/16. Instead, we prioritized implementation of the WAVEWATCH III wave model and ADCIRC storm surge model during this time period (see below)
Configure ROMS with wetting/drying (4/30) and increased model spatial resolution (2/29), coastline and bathymetry. Initial model validation.	6/30/2016	100%	
Initial set up of the HEC-HMS and HEC-RAS for Narragansett Bay and Wood-Pawcatuck River Watersheds, collecting and processing hydrological, soil, land cover data,	6/30/2016	100%	
Implement and configure high-resolution WAVEWATCH III wave model in Narragansett Bay and Rhode Island coastal waters.	11/30/16	100%	This activity is accomplished ahead of schedule
Implement and configure high-resolution ADCIRC in Narragansett Bay and Rhode Island coastal waters.	11/30/16	100%	This activity is accomplished ahead of schedule

Research Milestone			
Simulation of historic storms and generation of *Hurricane Rhody* hypothetical storm scenario	50%		Summary is provided in Appendix
Implemented and configured ADCIRC and ROMS storm surge models in Narragansett Bay and Rhode Island coastal waters	100%		Summary is provided in Appendix
Implemented and configured WAVEWATCH III wave model in Narragansett Bay and Rhode Island coastal waters	100%		Summary is provided in Appendix
Initial validation and calibration of the storm surge and wave models was done for Hurricane Bob (1991)	100%		Summary is provided in Appendix
Implemented and configured in Taunton River Basin two hydrological models HEC-HMS and PRMS and tested and compared the model performance against available observations.	100%		Summary is provided in Appendix
Implementation of HEC-RAS and HEC-HMS models and inland flood modeling in the area of Taunton City for the 2010 flood event	100%		Summary is provided in Appendix

11. Transition Activity and Milestone Progress:

Transition Activities and Milestones: Progress to Date

Reporting Period 1/1/2016 – 6/30/2016			
Transition Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not reached, and when completion is expected
Organize a workshop with end users to discuss the objectives and	3/31/16	50%	Team changed strategy to engage end-users in different

outcome of this project and to determine what types and forms of products are most useful for meeting their short and long term goals.			venues, rather than one workshop. Meeting with RI Emergency Mgmt team will take place within next 6 weeks. Implementation of a break-out workshop at annual RI EMA sponsored "Rhody Ready" event of local, state and regional emergency managers will highlight the research and applications, together with a facilitated discussion with end-users to gain input and feedback. Meetings with USCG, RI Silver Jackets (Fed-state partnership with RIEMA, FEMA, USACE etc), and others individually have been most effective.
Transition Milestones			
Meetings with USCG, RI Silver Jackets (Fed-state partnership with RIEMA, FEMA, USACE etc),	4/13/16	100%	Learned of advances by RI-DEM and RIEMA in mapping pollution hotspots within the flood zones of Narragansett Bay and major RI Rivers. Developed plan for model simulations of risk analysis during extreme storm events. Pam Rubinoff joined the Board of the RI Silver Jackets. USCG has informed us that they specifically need early reads on predicted storm impacts in order to choose response/staging sites that enable resources to be close to the storm for fast deployment, but not so close as to suffer damage.

Meeting with Dr. Chris Landsea, National Hurricane Center	5/4/16	100%	Informed NHC about the scope and ongoing efforts of this project and discussed potential applications for improving hurricane coastal impact forecasting
Meeting with David Vallee, NOAA/NWS Northeast River Forecast Center, Taunton, MA Robert Thompson, NWS Weather Forecast Office, Taunton, MA	5/4/16	100%	Informed NOAA/NWS Northeast forecast center about the scope and ongoing efforts of this project and discussed potential applications for improving regional forecasts of coastal and inland flooding
Narragansett Bay Commission Board meeting	3/15/16	100%	Identified a need to investigate potential hazards associated with co-location of floating objects and holding tanks of environmentally sensitive fluids (oil, LNG, etc) within the flood zone of the primary waste water treatment plant at the Port of Providence and developed a plan to conduct a number of process simulations for various combinations of storm parameters
The PI has joined the RI Scientific Support for Environmental Emergency Response (SSEER) Team.	5/1/16	100%	The DHS URI team will be available to provide scientific support for environmental emergency response to the Department of Environmental Management

12. Interactions with education projects:

Pam Rubinoff, Co-PI, presented for the Natural Hazards Resilience UNC's graduate certificate program, as well as a public lecture on March 30, 2016. Both presentations provided an overview of resilience practice (RI, US, and International), tools, and lessons learned in a talk *Natural Hazards Risk Management: Outreach & Extension*. The presentation elicited rich discussion between students and the speaker related to practitioner experiences from the 2 decades in this field.

Chris Kincaid, Co-PI delivered a lecture on DHS Project Science as part of OCG 110 – The Ocean Planet, URI General Education Oceanography Course.

13. Publications:

Gao, K. and I. Ginis, 2016: On the equilibrium-state roll vortices and their effect in the hurricane boundary layer. *J. Atmos. Sci.*, 1205- 1222.

Gao, K., I. Ginis, J.D. Doyle, Y. Jin, 2016: Effect of boundary layer roll vortices on the development of the axisymmetric tropical cyclone *J. Atmos. Sci.*, submitted, June 2016.

Huang, W., F. Feng, and I. Ginis, 2016: Evaluations of two hydrological models for storm runoff modeling in Taunton River Basin, *Natural Hazards*, to be submitted in September 2016.

Liu, Q., L. M. Rothstein, Y. Luo, D. S. Ullman, and D. L. Codiga, 2016. Dynamics of the periphery current in Rhode Island Sound, *Ocean Modelling*, 105, 13-24.

Liu, Q., L. Rothstein, and Y. Luo, 2016. Dynamics of the Block Island Sound estuarine plume. J. Phys. Ocean., Accepted for publication.

Reichl, B. G, D. Wang, T. Hara, I. Ginis,, T. Kukulka, 2016: Langmuir turbulence parameterization in tropical cyclone conditions. *J. Phys. Oceanogr.*, 46, 863-886.

Reichl, B. G., I. Ginis, T. Hara, B, Thomas, T. Kukulka, and D. Wang, 2016: Impact of sea-state dependent Langmuir turbulence of the ocean response to a tropical cyclone, *Mon. Wea. Rev*, (in press).

Sun, Y., C. Chen, R. C. Beardsley, D. Ullman, B. Butman, and H. Lin, 2016. Surface Circulation in Block Island Sound and Adjacent Coastal and Shelf Regions: A FVCOM-CODAR comparison, *Progress in Oceanography*, 143, 26-45.

Whitney, M. M., D. S. Ullman, and D. L. Codiga, 2016. Subtidal Exchange in Eastern Long Island Sound, . *J. Phys. Oceanogr*. (in press).

14. CRC Performance Metrics:

CRC Performance Metrics			
Metric	**Research**	**Education**	**Center**
Courses/certificates developed, taught, and/or modified		See Table	
Enrollments in Center-supported courses/certificates			
HS-related internships (number)	0		
Undergraduates provided tuition/fee support (number)	0		
Undergraduate students provided stipends (number)	0		
Graduate students provided tuition/fee support (number)	2		
Graduate students provided stipends (number)	2		
Undergraduates who received HS-related degrees (number)	0		
Graduate students who received HS-related degrees (number)	0		
Certificates awarded (number)			
Graduates who obtained HS-related employment (number)	0		
SUMREX program students hosted (number)	0		
Lectures/presentations/seminars at Center partners (number)	1		
DHS MSI Summer Research Teams hosted (number)	0		
Journal articles submitted (number)	2		
Journal articles published (number)	7		
Conference presentations made (number)	15		
Other presentations, interviews, etc. (number)	12		
Patent applications filed (number)	0		
Patents awarded (number)	0		
Trademarks/copyrights filed (number)	0		
Requests for assistance/advice from DHS agencies (number)	0		
Requests for assistance/advice from other Federal agencies or	5		
Total milestones for reporting period (number)	11		
Accomplished fully (number)	9		
Accomplished partially (number)	2		
Not accomplished (number)	0		
Product/s delivered to end-user/s (description and recipients)	See Table		
External funding received	See Table		
Leveraged support			
Articles on Center-related work published on website			
Coverage in media, blogs (number)			
Social media followers (number)			
Posts to social media accounts (number)			
Events hosted (number)			
Website hits (number)			

Table for Documenting External Funding and Leveraged Support

External Funding			
Title	PI	Total Amount	Source

Improving NOAA's HWRF Prediction System through New Advancements in the Ocean Model Component and Air-Sea-Wave Coupling	Ginis	$260,000	NOAA
GFDN operational tropical cyclone model maintenance and support	Ginis	$134,000	Navy
Advancing tropical cyclone models through explicit representation of boundary layer roll vortices	Ginis	$260,000	ONR-Navy
Langmuir turbulence under tropical cyclones	Hara, Ginis	$376,000	NSF
Airflow separations over wind waves and their impact on air-sea momentum flux	Hara	$355,000	NSF
4D physical models of migrating mid-ocean ridges: Implications for shallow mantle flow	Kincaid	357,000	NSF
Collaborative Research: 3D Dynamics of buoyant diapirs in subduction zones	Kincaid	442,000	NSF
NOAA/RISG: Quahog Larval Dispersion and Settlement in Narragansett Bay	Kincaid Ullman	199,000	RI Sea Grant/NOAA
Authentic Data and Visualization Experiences and Necessary Training (ADVENT): An undergraduate model for recruiting students to STEM careers in the U.S. Navy	Pockalny Kincaid	750,000	ONR-Navy
Numerical Circulation Modeling in Support of Hypoxia Studies in Narragansett Bay	Ullman	60,000	RI DEM
Pushing to New Limits for Models of Rhode Island Bays and Sounds	Ullman Kincaid Rothstein	68,000	Rhode Island Science and Technology Advisory Council
CHRP: Observations and Modeling of Narragansett Bay Hypoxia and its Response to Nutrient Management	Ullman and Co-PIs	660,00	NOAA

Leveraged Support

Description	Estimated Annual Value
Returned Indirect Cost [1]	$10,000
Graduate Student tuition	$15,000
Project Coordination and Management (Thomas Miller)	$3,000

[1] The University of Rhode Island's Coastal Institute (CI) has generously agreed to return 66% of their share of indirect cost return back to the project. The CI obtains 17% of the indirect cost, so roughly 11.3% of indirect cost is being returned to the project.

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Project Title: Modeling the combined coastal and inland hazards from high-impact hypothetical hurricanes

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Appendix

In this Appendix we provide some details of the project main accomplishments during this time period.

1. Implementing high-resolution ADCIRC-SWAN coupled system in Narragansett Bay and Rhode Island coastal waters

During the first 6 months of the project, we have run storm surge and wave simulations using ADCIRC-SWAN for several historical storms that impacted Rhode Island. These include hurricanes Carol (1954), Bob (1991), and Floyd (1999). The objective was to evaluate, using observational data, the various choices that need to be made when performing numerical simulations of storm surge. These simulations, forced with several different wind products, were compared with available observations of water level, wind, and waves to assess the skill of the model simulations. Because the modeled storm surge is quite sensitive to the magnitude of the surface drag coefficient used, we compared the model results using several different parameterizations for the surface drag coefficient.

Model setup and historical storm simulations

The ADCIRC/SWAN storm surge/wave modeling efforts were greatly facilitated by the provision by our UNC partners (R. Luettich and colleagues) of a basic finite element model grid. This grid covers the North Atlantic west of longitude 60_o W and features fine resolution (of order 50-100 m) within Narragansett Bay. The advantage of this grid is that the open boundary is sufficiently far from the region of interest such that at these boundaries one need only apply tidal forcing which is obtained from a data assimilating global tidal model (the tides must be correctly simulated since the water levels during a storm are a superposition of the tidal and storm effects). The storm surge is a local effect in this grid, requiring no open boundary forcing. The model is run in 2-dimensional, depth-averaged mode, with wetting and drying of elements enabled, allowing simulation, not only of water elevation, but also of inundation of the land surface in the hurricane impact region.

Two types of wind forcing were used for the historical simulations. The first, used for all the storms, was a time series of parameterized wind fields at 10 m height, generated using the Best Track hurricane data (e.g. location of eye, minimum central pressure, radius of maximum winds). The second type of wind forcing, produced for Hurricane Bob only, was derived from a high-resolution dynamic model of the hurricane surface boundary layer forced by parameterized winds at the top of the boundary layer (3 km height). The hurricane wind fields produced by this model include the effects of land, which become important as hurricanes near landfall.

Comparison of model water levels with observations from long-term NOAA tide gauges at Newport and Providence was performed to evaluate model fidelity in simulating storm surges in Narragansett Bay. Observations from both stations were available for hurricanes Bob and Floyd, while for hurricane Carol only observations at Newport were available. Comparison of the predictions of the SWAN wave model, which is coupled to ADCIRC, with observations was performed at 3 National Data Buoy Center buoys in the mid-Atlantic Bight. These sites are not in the immediate vicinity of Narragansett Bay, but they do provide a check on the wave predictions under tropical storm conditions.

Evaluation of surface drag coefficient parameterizations

A key element of a storm surge/wave model when simulating the effects of hurricanes is the parameterization of the surface drag coefficient. The ADCIRC default parameterization is the linear function of 10-meter wind speed described by Garratt (1977), but with a limit on the drag coefficient magnitude of 3.5×10^{-3}. We tested an alternative formulation in which the limit was set at 2.0×10^{-3} as well as a different parameterization that is used by the Ginis group for their hurricane forecasts. The drag coefficient using this formulation initially rises with wind speed, but then peaks and drops off a moderately high wind speeds (see Figure 1.1). Comparisons of storm surge simulations using these parameterizations with observations from Hurricane Bob indicate that the default ADCIRC formulation results in a severe over-prediction (by about 1 m) of the surge magnitude (Figure 1.2). For Hurricane Bob, the Garratt formulation with the 2.0×10^{-3} limit produced the lowest surge in Narragansett Bay, with the Ginis parameterization producing a surge intermediate in height, but both were high relative to the observations. Because we could not rule out the fact that overestimation of the hurricane winds could produce a surge that is too high, we decided to use the Ginis parameterization going forward, since that formulation produces optimum hurricane track and intensity forecasts.

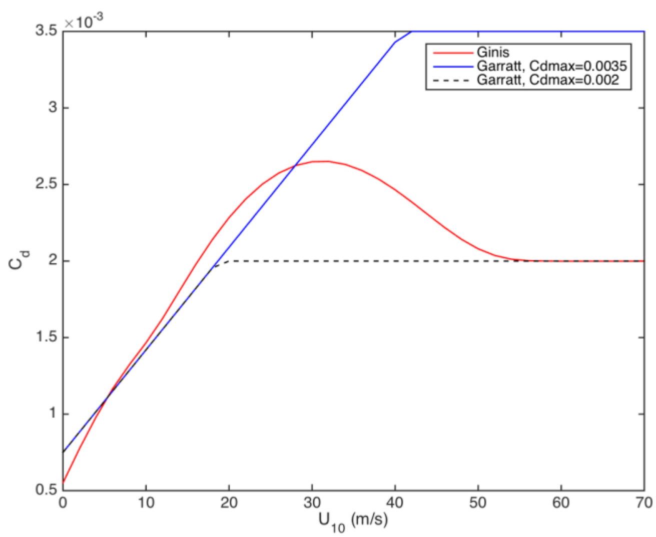


Figure 1.1. Surface drag coefficient parameterizations as functions of 10-meter wind speed.

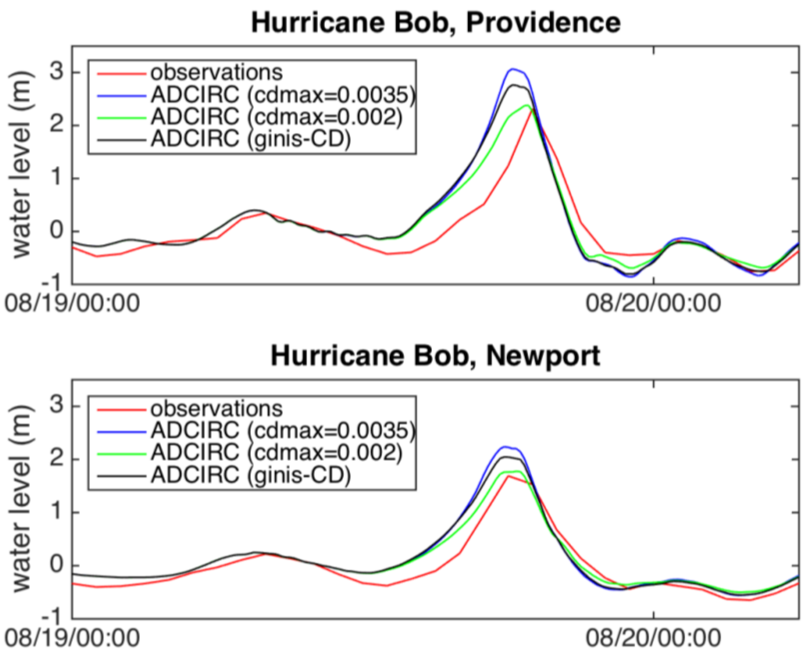


Figure 1.2. Comparison of water level observations with model predictions at Newport (bottom) and Providence (top) for Hurricane Bob. The blue and green lines show respectively the model water level time series using the Garratt drag coefficient parameterization with a limit of 3.5×10^{-3} and 2.0×10^{-3}. The black line shows the model response using the Ginis parameterization.

Effect of waves

Shoaling surface gravity waves can induce a change in the water surface elevation from so-called wave radiation stresses. The coupling of the ADCIRC circulation model and the SWAN wave model occurs via the radiation stresses (as well as the coupling of the wave field to the circulation field via the instantaneous water depth and currents). For Bob, the comparison of simulated significant wave height with observations yielded the conclusion that waves were over-predicted in height at locations to the left of the eye, while they were correctly predicted at the (one) station to the right of the eye (Figures 1.3 and 1.4). The reason for this discrepancy is still under investigation by the project team. Comparison of the storm surge with wave effects (coupled ADCIRC-SWAN) with the ADCIRC-only simulation indicates that for Bob, the presence of waves adds approximately 0.5 m to the predicted storm surge (Figure 1.5).

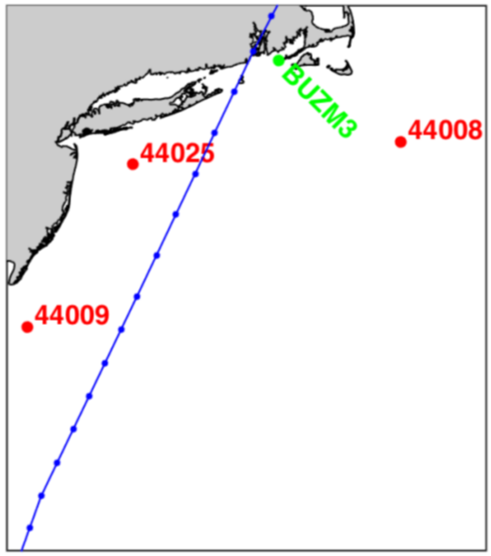


Figure 1.3. Track of Hurricane Bob (blue) in relation to the NDBC buoys with observations of wind and waves (red) and wind only (green).

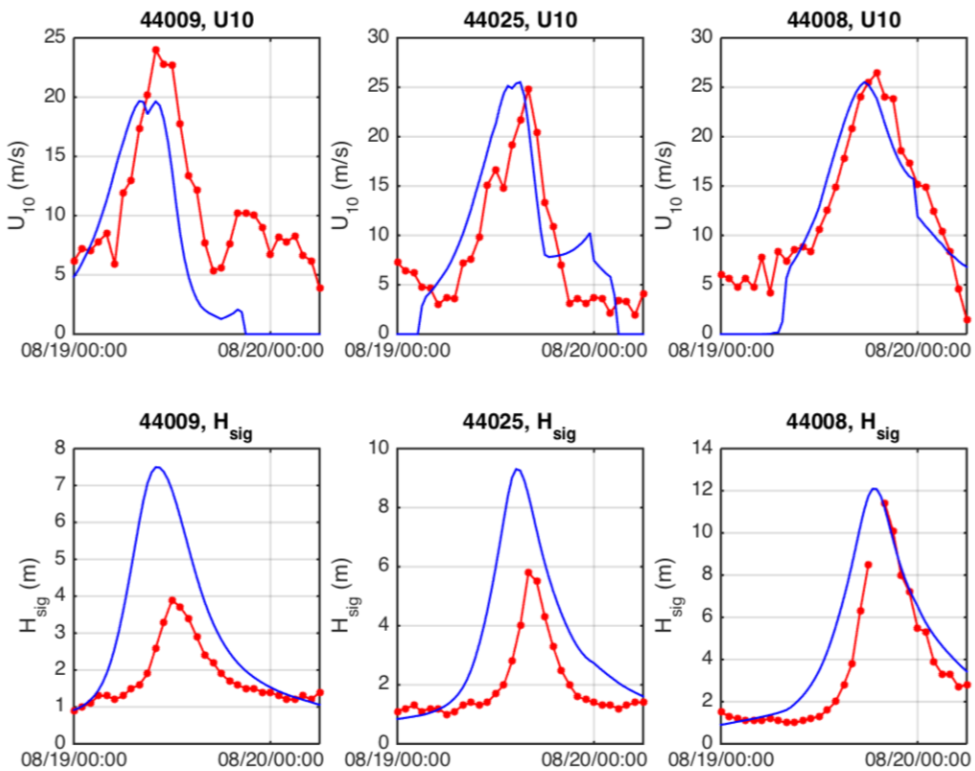


Figure 1.4. Comparison of observed wind speed at 10 m height (top) and significant wave height (bottom) with coupled ADCIRC/SWAN model predictions at the three buoy locations shown in Figure 3. Observations are in red and model predictions are in blue.

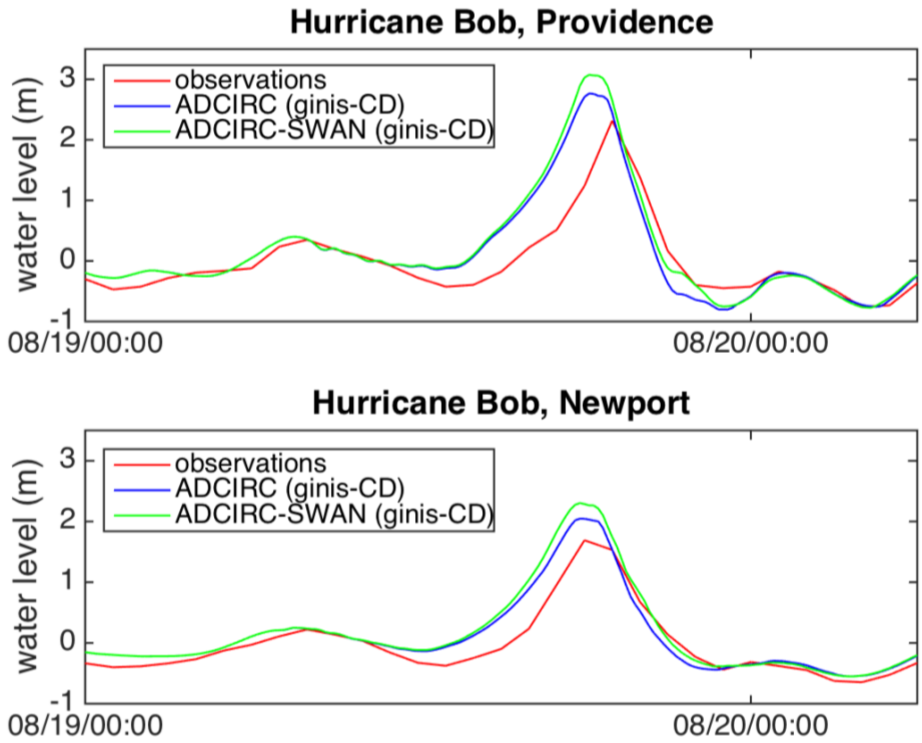


Figure 1.5. Comparison of water level observations with model predictions at Newport (bottom) and Providence (top) for Hurricane Bob, showing the effect of waves on the storm surge. The red line is the observations, the blue line is the ADCIRC simulation without waves, and the green line is the coupled ADCIRC/SWAN simulation.

Effect of different wind forcing fields

We compared the predicted (coupled ADCIRC-SWAN) storm surge with observations at the Narragansett Bay tide gauges using a number of wind forcing products. The first wind product, which was used for the results described above was the simple vortex parameterization of 10-meter wind based on hurricane best track information (blue line in Figure 1.6). The other wind fields were produced by the hurricane boundary layer model (with different assumptions about the wind at the top of the surface boundary layer). In general, the over-prediction of storm surge during Bob persists regardless of the wind product used (figure 6). However, the timing of the surge is better simulated using the boundary layer model winds. The range of variability in the maximum storm surge elevation arising from the uncertainty in the wind field is approximately 0.5 m for Hurricane Bob (Figure 1.6).

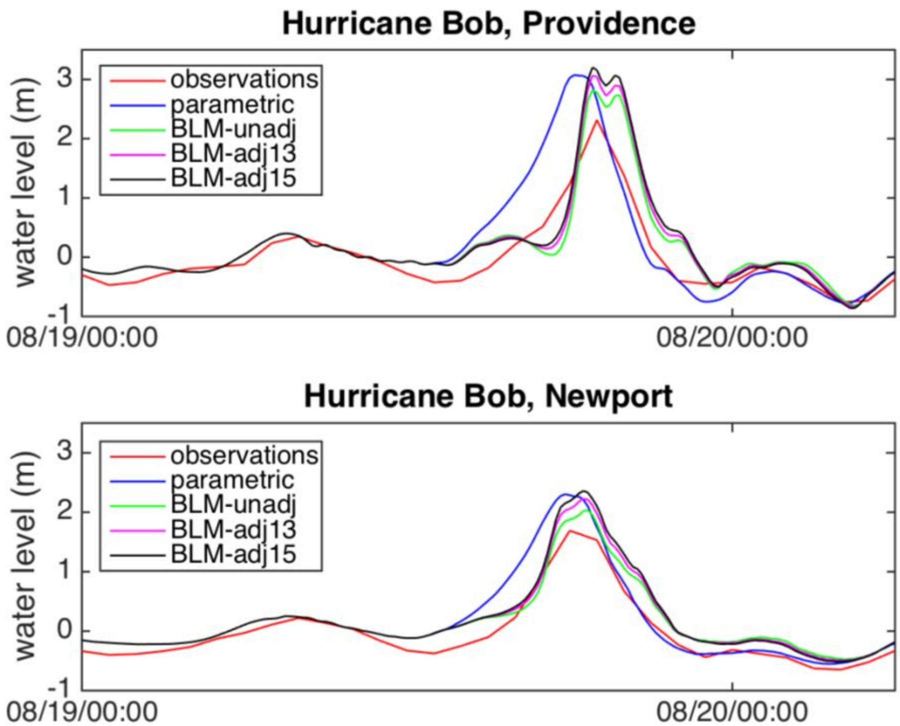


Figure 1.6. Comparison of water level observations with model predictions at Newport (bottom) and Providence (top) for Hurricane Bob, showing the effect of different wind forcing products. The red lines show the observed water levels while the blue, green, magenta, and black lines show respectively the model (ADCIRC/SWAN) water levels using the parametric wind model and the BLM for 3 different parameterizations of the winds at 3 km height.

Visualization of results

In order to provide compelling visualization of our storm surge simulations to potential stakeholders, we have been working with several groups to improve the presentation of results. We have provided sample output from Hurricane Bob to Carola Kaiser (Louisiana State University) for inclusion into her web-based ADCIRC visualization tool. We have also shared our results for Hurricane Carol with Peter Stempel (URI Marine Affairs graduate student) who will perform visualizations of infrastructure impacts from this storm.

2. Implementing high-resolution ROMS model in Narragansett Bay and Rhode Island coastal waters

The Regional Ocean Modeling System (ROMS) is a free-surface, terrain-following, primitive equation solver used to study the effect of storm surge in Narragansett Bay and surrounding areas. The ROMS model is used with wetting and drying scheme having a critical depth value of 0.1 meter. This allows for the inundation of normally dry areas under storm surge conditions.

Our study area covers Narragansett Bay and extends into Rhode Island Sound (Fig. 2.1). We use a numerical grid containing 750 by 900 by 7 nodes. The grid is curvilinear with increasing grid spacing to the south. The resulting resolution is highest at the head of Narragansett, Bay around 30 m and lowest in Rhode Island Sound around 150 m. Bounded on the east by the mouth of Buzzards Bay and extends south of Martha's Vineyard. To the west the grid extends into Long Island Sound and as far south as Montauk, NY.

The bathymetry is interpolated from three elevation and bathymetry data sets. For inside Narragansett Bay we use NOAA 30 meter resolution bathymetry obtained from hydrographic soundings. The datum is mean lower low water and is adjusted to mean sea level (MSL). For bathymetry outside of Narragansett Bay we use NOAA Coastal Relief model with resolution of 90 meters. Elevation was interpolated from USGS National Elevation Dataset with resolution of 30 meters. Both the 90 m bathymetry and 30 m elevations used a NAVD 88 datum. Once the three data sets were sampled at the grid locations, we use a Shapiro filter to smooth data and remove any jumps created by adjoining different data sets.

To study the effect of storm surge we have to include many forcing conditions. The two most important are meteorological forcing and boundary conditions. Initially we focus on modeling the effect of hurricane Bob, as there are observations to compare with. For hurricane winds we apply parametric winds at 10 meters every 15 minutes. This dataset was developed from URI/GSO hurricane Bob simulations. Other meteorological forcing include long wavelength radiation, solar shortwave radiation, surface relative humidity are based on normal year of the Weather Research & Forecasting Model (WRF) in the model area. Air temperature, precipitation and air pressure were obtained from atmospheric station USC00370218 in Adamsville, RI recorded daily during hurricane Bob. All meteorological time series were applied uniformly to the entire grid, expect for winds. Winds are applied on a course grid and vary spatially.

Due to the small spatial extent of the model, boundary conditions are very influential in terms of storm surge. We use surface elevations as well as barotropic estimates of flow interpolated from a Regional Advanced Circulation Model (ADCIRC). This model covers the majority of the United States East Coast and is run by URI/GSO team for hurricane Bob and includes. The boundaries of our ROMS model are forced every half hour.

To verify our model we use available hourly observations at NOAA tide gauges located at Newport, RI and Providence, RI (Fig. 1). Specifically, we use the Willmott skill to quantify our comparison (Willmott, 1982) :

$$\text{Willmott skill} = 1 - \frac{\frac{1}{N}\sum_{i=1}^{i=N}(m_i - o_i)^2}{\frac{1}{N}\sum_{i=1}^{i=N}(|m_i - \bar{o}| - |o_i - \bar{o}|)^2},$$

where o_i is an observation, m_i is a model observation and N is the total number of observations.

A value of 1 would be a perfect score and the model would completely reproduce the data. We compute the skill for both time periods before the storm, to obtain validity of tidal estimations, and during the storm. The skills are 0.95 and 0.96 for the tidal component and storm surge respectively. Time series of sea level are plotted in Figure 2. Output from the model is output every 3 minutes at a higher temporal resolution than the hourly tide gauges. The peak amplitude corresponds well with the timing of the observed peak but the model over estimated surge at both Providence and Newport (Fig. 2.2). The maximum surge at Providence tide gauge was 2.3 m and 3.0 m for observations and the model results respectively. The maximum surge at Newport tide gauge was 1.6 m and 2.0 m for observations and the model results respectively. In general with a high overall skill, the storm surge appears to be well modeled but the response after the hurricane has passed on August 20th is only moderately well predicted. Spatially, the maximum observed surge was around 3 m over MSL in the Providence area. A map of the maximum observed surge is displayed in Fig. 2.3.

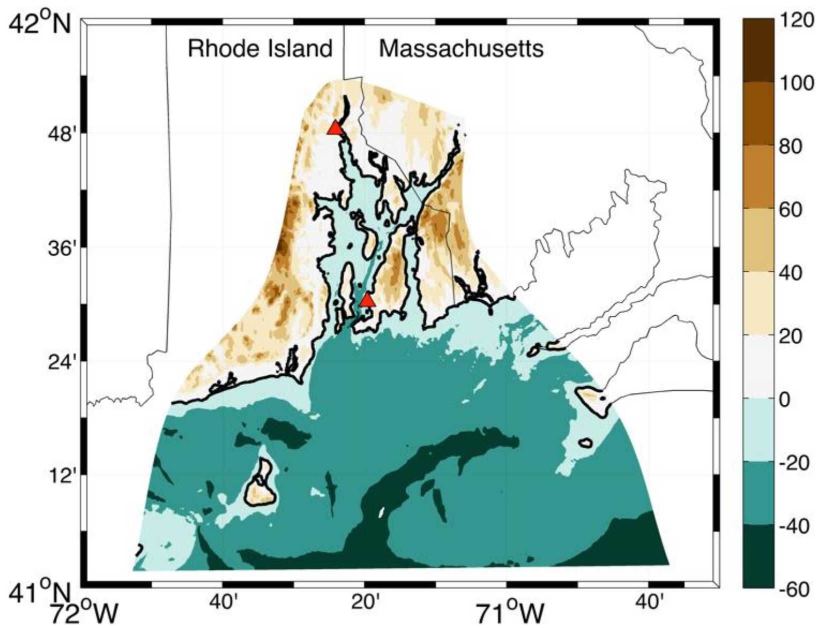


Figure 2.1: Map of ROMS domain. Color bar indicates elevation in meters. Red triangles indicate locations of Providence (north) and Newport (south) tide gauges. Mean sea level denoted with black line.

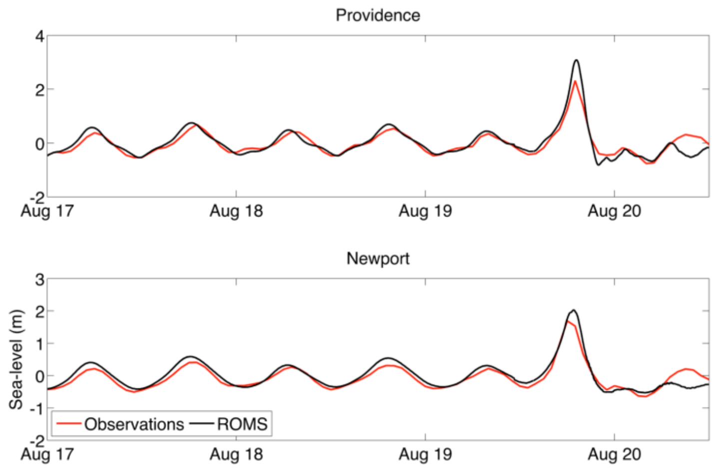


Figure 2.2: Sea-level observations (red) and modeled estimations (black) are displayed for Providence, RI (above) and Newport, RI (below).

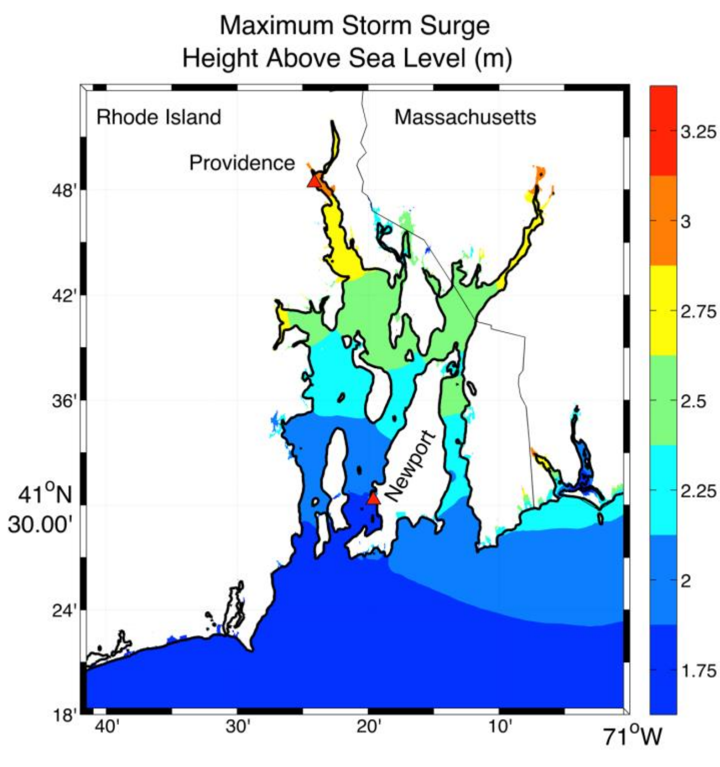


Figure 2.3: Maximum estimated storm surge in meters above mean sea level modeled by ROMS. Black line indicates mean sea level in the model. Tide gauge locations marked by red triangles.

3. Validation of wave models under hurricanes in coastal regions.

One of the main objectives of this project is to couple ocean wave models and storm surge models in order to properly account for the surface wave impacts on storm surge. We employ multi-model (ensemble) approaches by combining different wave models (WAVEWATCH III, SWAN, STWAVE) and different storm surge models (ADCIRC, ROMS).

During this report period, we carried out a validation study of the three wave models in coastal regions. First, we simulated the surface wave field under Hurricane Bob (1991) using both WAVEWATCH III and SWAN, forced by parametric wind field generated from the TCvital (Figure 3.1). In both models the drag coefficient was capped at 2.5×10^{-3} for high wind speeds (exceeding 25 m/s). The figure shows that SWAN predicts higher significant wave height than WAVEWATCH III when the same wind forcing is applied.

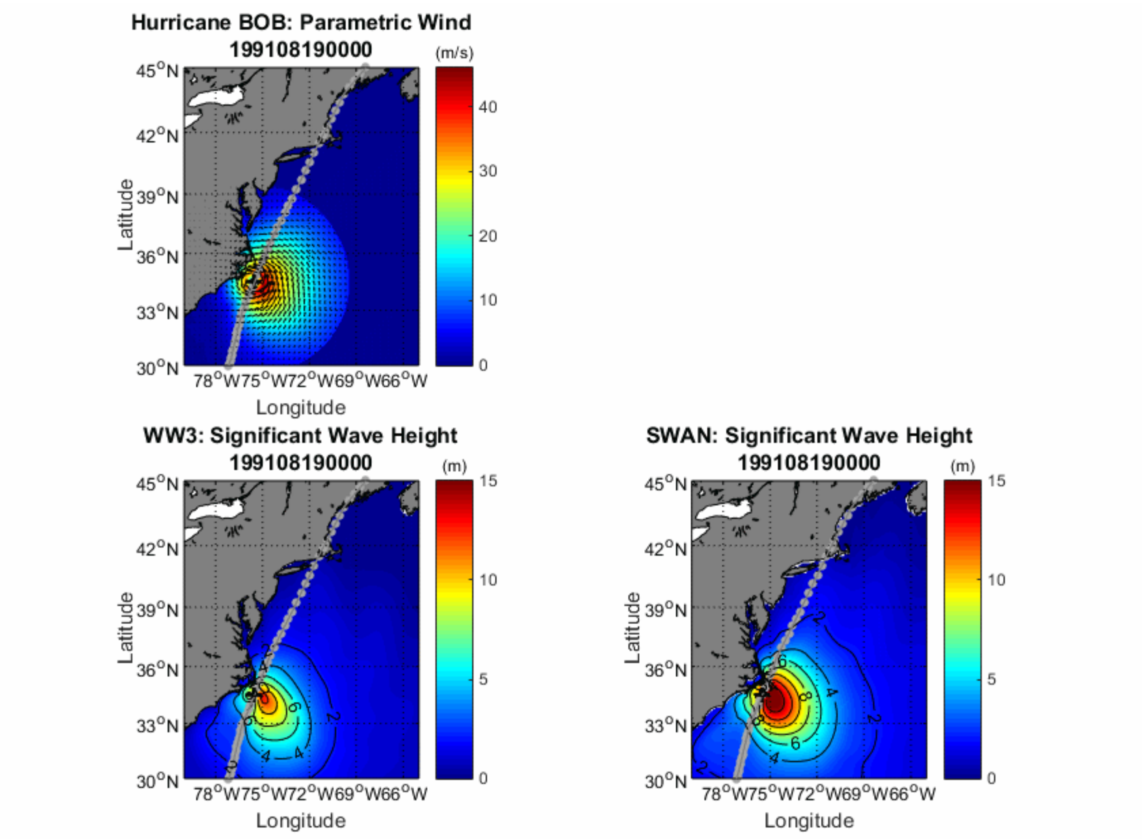


Figure 3.1. Top panel shows the parametric wind field. The bottom panels show the significant wave height simulated by WAVEWATCH III (left) and SWAN(right).

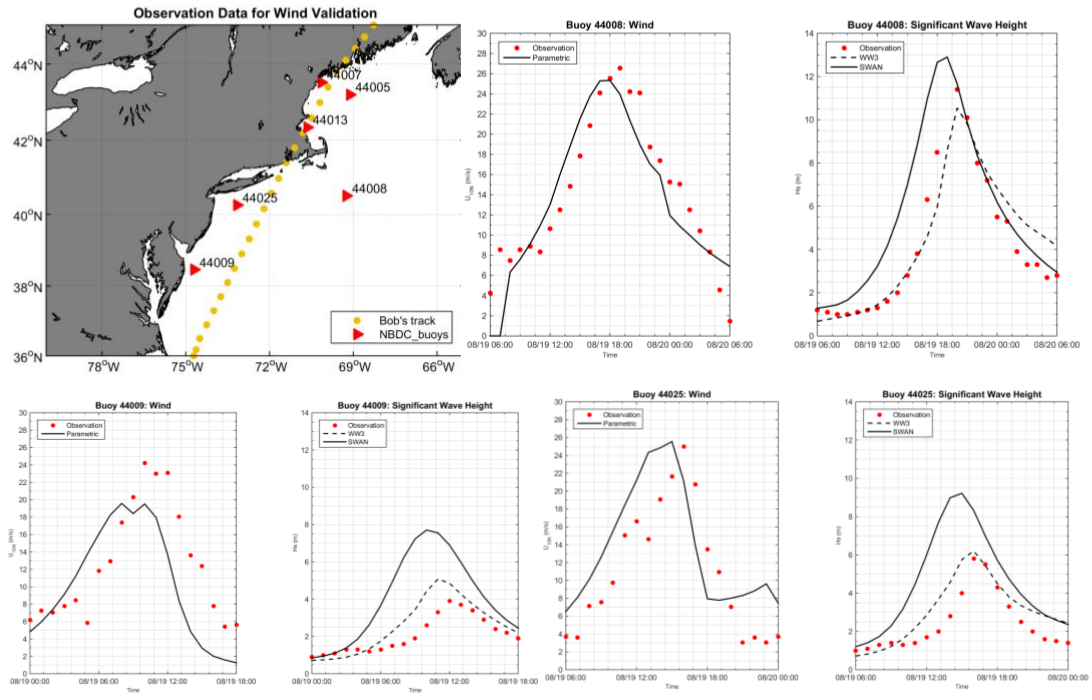


Figure 3.2. Comparison of predicted and observed wind speed and significant wave height at

The parametric wind and wave simulation results were compared against observations from three coastal buoys (Figure 3.2). The wind speed compaison shows that the parametric wind speed is consistent with the observation at the offshore location (44008), but it is not as consistent with the observaition near the coast (44009 and 44025). This is possibly because the real wind field becomes more complex as a hurricane approaches a coast and the simple parametric wind field becomes less accurate.

The significant wave height comparison shows that the WAVEWATCH III results (dashed lines) generally agree with the observation. This is consistent with our earlier finding (Fan et al. 2010) that the WAVEWATCH III is skillful in predicting the hurricane wave field if the drag coefficient is capped at high wind speeds. The SWAN results (solid lines), however, always overestimate the significant wave height, suggesting that the forcing terms (wind input and/or dissipation) of the model need to be adjusted before the model is coupled with the storm surge models.

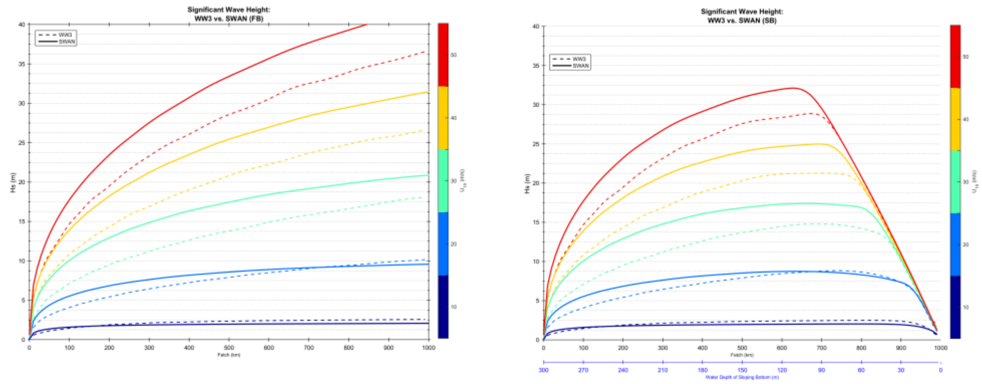


Figure 3.3. Fetch dependent wave field (significant wave height) under constant wind speeds (10, 20, 30, 40, and 50 m/s). Left panel shows results in deep water. Right panel shows results with shoaling (depth decreasing with fetch).

Next, we investigated the wave field in shallow water, where bottom dissipation and breaking reduce the significant wave height, using idealized experiments of steady state (fetch dependent) wave fields under constant wind speeds (Fig. 3.3). The deep water results show that both WAVEWATCH III (dashed line) and SWAN (solid line) produce similar wave fields at 10 m/s wind speed, but the results diverge (SWAN predicts higher waves) as the wind speed increases. When the wave field encounters decreasing depth, both models predict almost identical reduction of the significant wave height. We also investigated the reduction of the significant wave height due to decreasing depth using the STWAVE. The STWAVE result is consistent with the WAVEWATCH III and SWAN results at 10 m/s wind speed. However, as the wind speed increases, the STWAVE results deviate from the other two model results.

In summary:

1. WAVEWATCH III is skillful in hurricane conditions in deep and intermediate waters. (We need to validate WAVEWATCH III results in shallow waters.)
2. SWAN results are not as consistent with observations as WAVEWATCH III results, if wind forcing (drag coefficient) and bottom dissipation are identical. Forcing terms of SWAN need to be retuned in order to achieve a comparable skill as WAVEWATCH III.
3. With constant wind speed SWAN waves grow faster at high wind speeds.
4. SWAN and WW3 WAVEWATCH III behave similarly in shoaling regions but STWAVE results differ at high wind speeds.

4. Rainfall runoff and river flood modeling in Taunton River Basin

Taunton River Watershed

The Taunton River Watershed is one of the sub-basin of the Narragansett Basin (Fig. 4.1). It is the second largest watershed in the state of MA at 562 square miles and contains 94 square miles of wetlands and 221 lakes or ponds. 700,000 people call the watershed home. The Taunton River starts in the Town of Bridgewater and receives discharge waters from 18 river systems as it courses through ten communities before ending at the State of Rhode Island's Mount Hope Bay, which is part of Narragansett Bay. Tidal influences reach 18.0 miles inland and a salt-water intrusion reaches 12.6 miles inland, providing unique habitat for fresh and salt-water aquatic, terrestrial, and biological species. The river systems support the most productive river herring spawning grounds in the Commonwealth.

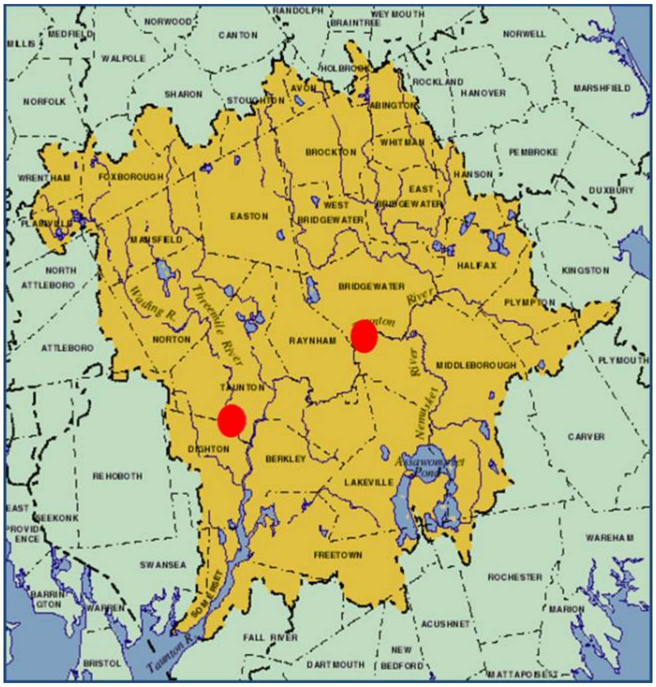


Figure 4.1. Taunton River Basin.

2010 Storm and flood Event in Taunton River Basin

The widespread flooding that occurred in central and eastern Massachusetts during mid to late March 2010 was caused by a series of moderate to heavy rainfall events over a 5-week period which started in late February. The successive and unrelenting nature of these moderate to heavy rainfall events saturated soils and limited opportunities for rivers and streams to recede, making the state vulnerable to flooding. The first major flood event in March occurred during the 13th to the 15th. Low pressure systems over the Gulf Coast and Midwest combined to form a potent, slow moving low pressure system that slowly tracked from Virginia to south of Long Island. A deep plume of tropical moisture fed into the system. Heavy rains affected a large portion of the Northeast but the heaviest precipitation fell over eastern portions of southern New England. With the mid-March event, a swath of 7 to 10 inch rains fell across east coastal Massachusetts from Methuen and Gloucester southward through Plymouth and Brockton. Totals of 4 to 6 inches fell just to the west, generally in the vicinity of the I-495 corridor and west into the Worcester Hills. Notably lower totals occurred over the Connecticut River Valley area of Massachusetts, where totals ranged from 2 to 3 inches. Flood impacts were minimal in this area. Widespread flooding occurred along the eastern half of Massachusetts in mid-March. These sites included the Concord River at Lowell, the Taunton River at Bridgewater, the Shawsheen River at Wilmington, and the Charles River at Waltham. Impacts were severe. This rain event produced widespread flooding along numerous rivers and streams in eastern Massachusetts. Basement flooding was rampant. The Taunton River at Bridgewater, which had broken its record flood crest only 2 weeks prior, set a new record flood crest with the late March event. An unusual aspect of the late March floods was the lake flooding that occurred in southeast Massachusetts. Some of this lake flooding extended well into April 2010. Locations affected by lake flooding included Norton Reservoir and Lake Winnecunnet in Norton; West Pond, Big Sandy Pond and Kings Pond in Plymouth; Assawompset Pond in Lakeville; Long Pond in Freetown and Lakeville; Forge Pond in Freetown; and South Wattupa Pond in Westport. In total, 8 of the 30 long term United States Geological Survey network gages in Massachusetts broke previous record crests during the period of March to early April 2010. Monthly rainfall records also were exceeded for March.

Figure 4.2. Floodwaters from the Taunton River flood in Taunton during 2010 flood event: source, NWS.

Rainfall Runoff Modeling

Hydrological rainfall-runoff modeling studies were conducted to simulate rainfall runoff in Taunton River Basin for the storm event in 2010. Two hydrological models, HEC-HMS and PRMS, were used in this study to evaluate their performance for rainfall runoff modeling. HEC-HMS (Hydrologic Modeling System) is a watershed hydrological model developed by Hydrologic Engineering Center, US Army Corp of Engineers (USACE). The HEC-HMS model has been widely used and tested worldwide. The program is a generalized modeling system capable of representing many different watersheds. Hydrologic elements are connected in a network to simulate a rainfall runoff process. Available elements are sub-basin, reach, junction, reservoir, diversion, sources and sinks. Computation proceeds from upstream elements to the downstream direction. A classification of different methods is available to simulate infiltration losses. Options for event modeling include SCS curve number, Gridded SCS curve number, Exponential, Green Ampt, and Smith Parlange. The one-layer deficit constant method can be used for simple continuous modeling. The five-layer soil moisture accounting method can be used for simple continuous modeling of complex infiltration and evapotranspiration environments. Unit hydrograph method includes the Clark, Synder, and SCS techniques. The modified Clark method, ModClark, is a linear quasi-distributed unit hydrograph method that can be used with gridded meteorological data. An implementation of kinematic wave method with multiple planes and channels is also included. Another popular hydrological model, the Precipitation-Runoff Modeling System (PRMS), is a deterministic, distributed-parameter, physical process based modeling system developed by USGS to evaluate the response of various combinations of climate and land use on streamflow and general watershed hydrology.

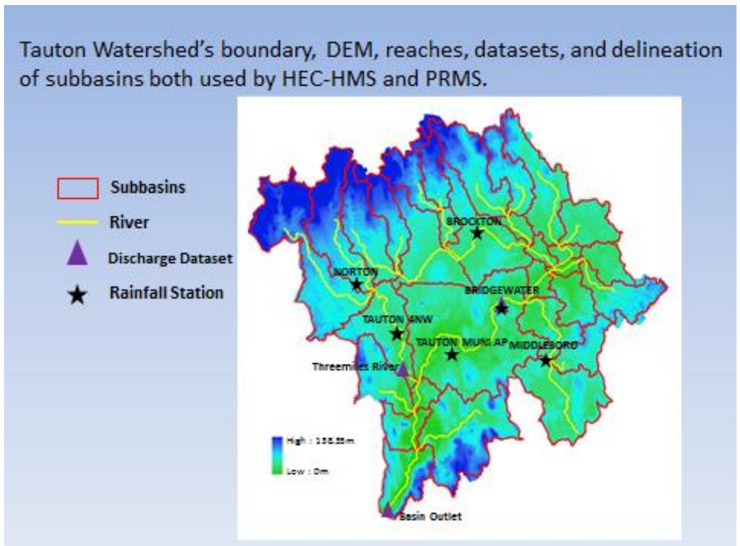


Figure 4.3. Watershed elevations, sub-basins, and data station locations.

Results of model simulated rainfall runoff by HEC-HMS model
Rainfall runoff modeling by using HEC-HMS for the year of 2010 are given in Fig. 4.4 a,b. Results indicate that the model is able to provide reasonable predictions of storm-induced runoff. However, over a year period, there are some errors for the period between July and September. In addition, for snow condition, the HEC-HMS model seems over estimates runoff.

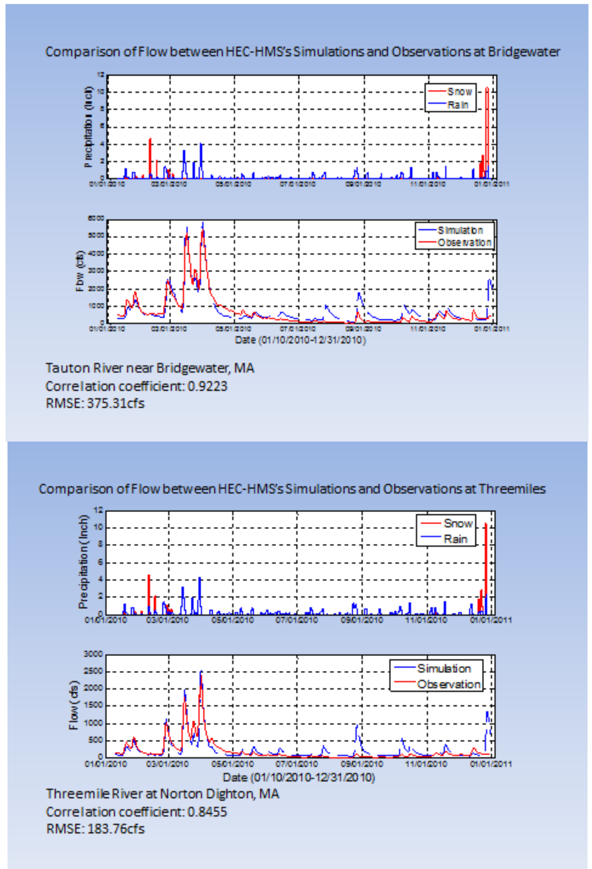
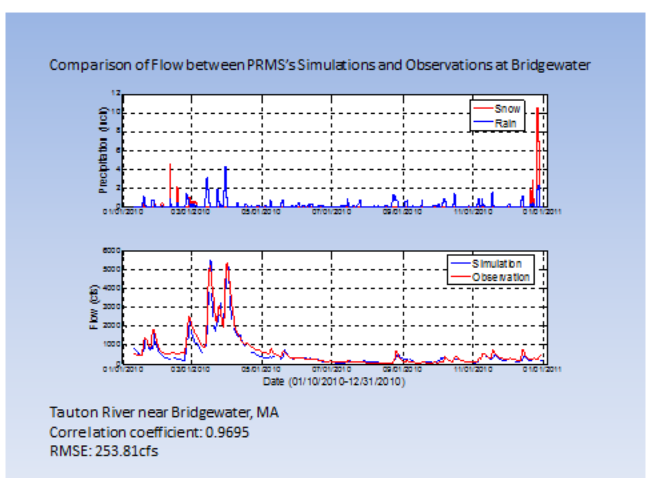


Figure 4.4. Comparison between HEC-HMS model simulated and observed flows at USGS gages.

Results of model simulated rainfall runoff by PRMS model

Rainfall runoff modeling by using PRMS was conducted. Comparison between PRMS model simulated and observed flow at USGS gages are presented in Fig. 4.5. Results indicated that PRMS can handle well for not only rainfall runoff in March and April but also the snowfall event in December.



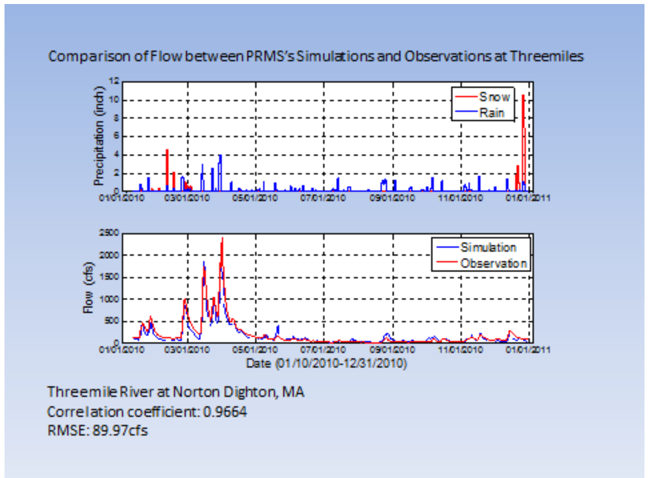


Figure 4.5. Comparison between PRMS model simulated and observed flows at USGS gages.

Comparison of performance between HEC-HMS model and PRMS model

Statistical comparison between hydrological model simulations and observations for 2010 are given in Table 1. Results indicated that, over a year period, HEC-HMS model show correlation values of 0.89 at Bridgewater and 0.85 at Threemiles Stations, and PRMS model show correlation values of 0.96 at Bridgewater and 0.96 at Threemiles Stations. At both stations, PRMS model show lower root-mean-square errors. The satisfactory calibrations of hydrological models for Taunton River Basin provide a very good reference for studies in the remaining sub-basins in Narragansett Watershed.

Table 1. Statistics between model simulations and observations

Comparisons between observations and simulations by HEC-HMS and PRMS

Data Set	Model	Peak Runoff (Simulation) cfs	Peak Runoff (Observation) cfs	Error of Peak Discharge (%)	Correlation coefficient	RMSE cfs
Bridgewater	HEC-HMS	5904.59	5388.69	9.57	0.8929	860.43
	PRMS	5503.92	5388.69	2.13	0.9695	253.81
Threemiles	HEC-HMS	2537.10	2399.29	5.74	0.8455	183.76
	PRMS	2354.11	2399.29	1.88	0.9664	89.97

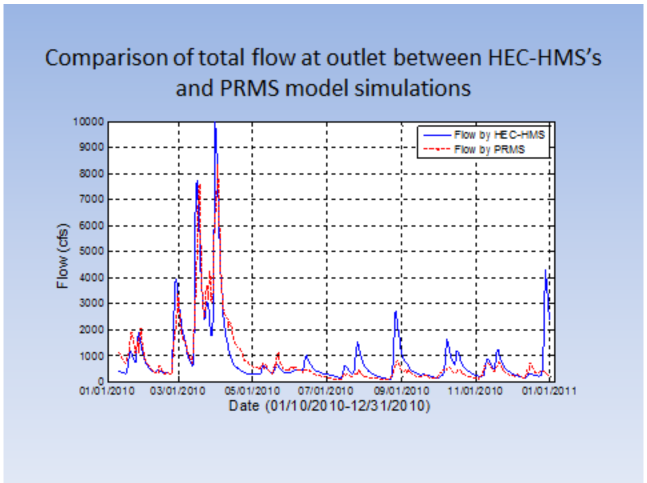


Figure 4.6. Comparison between rainfall runoff predicted by HEC-HMS and PRMS

River Flood Modeling in the Area near Taunton City

River flood modeling by using HEC-RAS model was conducted in the area of Taunton. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The HEC-RAS system contains four one-dimensional river analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; (3) movable boundary sediment transport computations; and (4) water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design and analysis features that can be invoked for evaluations of hurricane impacts such as breaks, sediment scour around bridge piers and abutments, backwater flood caused by culverts and bridge causeways; and effects of storage area such as detention ponds and lakes on flood mitigations. Based on the topo map and literature review, river cross sections were obtained in the selected river locations as shown in Fig. 4.7. Manning coefficient was selected based on the general range of values for open channels. For the rain storm event in 2010, upstream river inflow was specified from hydrological model simulations by PRMS model as shown in Fig. 4.8. Downstream boundary condition was specified as normal slope.

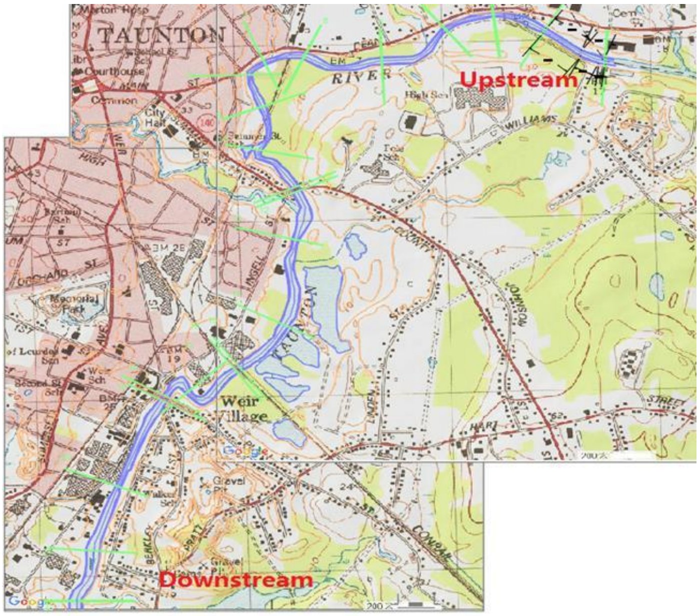


Figure 4.7. Area map and river cross-section locations for HEC-RAS model near Taunton City.

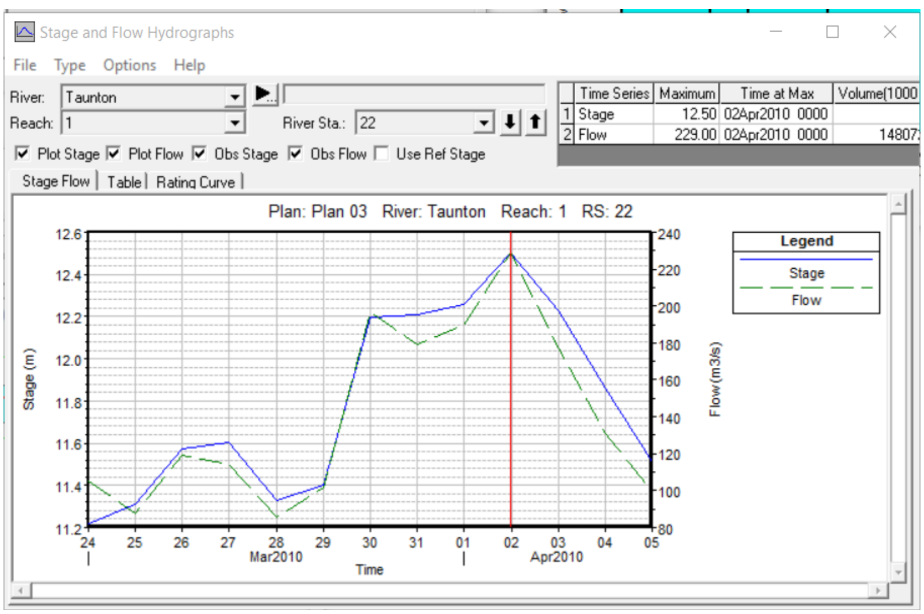


Figure 4.8. Upstream inflow predicted by hydrological model

Hydrodynamic modeling was conducted for the flood event from March 24- April 05, 2010. For the peak flow condition, flood area is shown in Fig. 4.9 in the HEC-RAS model plot. For convenience view, flood area has been mapped to the topo map as shown in Fig. 4.10.

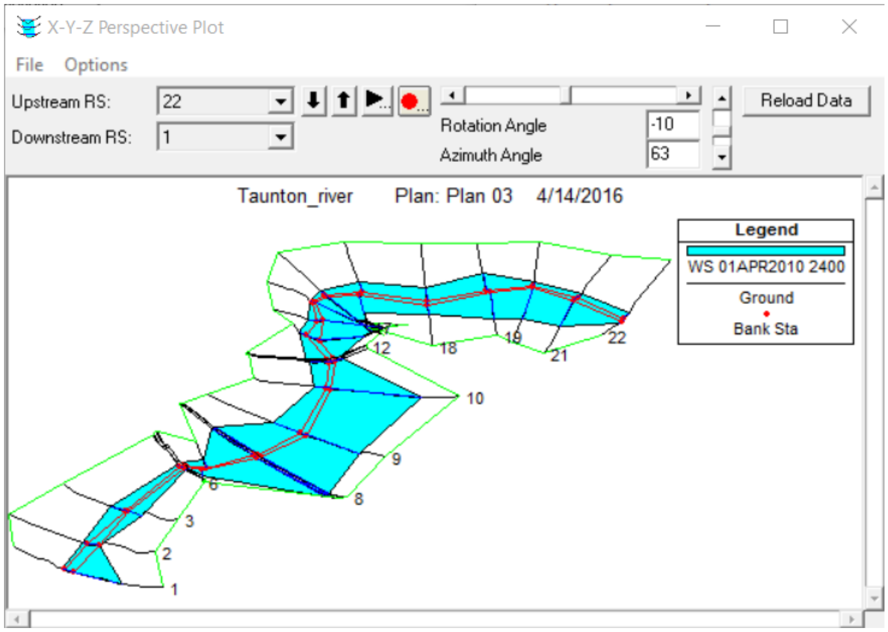


Figure 4.9. HEC-RAS model simulated flood at peak flow.

Figure 4.10. Flood area on top map as predicted by HEC-RAS model

References:

Garratt, J. R., 1977. Review of drag coefficients over oceans and continents, Monthly Weather Review, 105, 915-929.

National Geophysical Data Center (1999), U.S. Coastal Relief Model, Northeast Atlantic. National Geophysical Data Center, NOAA. doi:10.7289/V5MS3QNZ *http://www.ngdc.noaa.gov/mgg/coastal/crm.html*

NOAA (1998), Raster Digital Data, Narraganset, RI (M020) Bathymetry Digitial Elevation Model (30 meter resolution) Derived From Source Hydrographic Survey Soundings, NOAA's Ocean Service, Special Projects (SP), Silver Spring, MD. <http://estuarinebathymetry.noaa.gov>

U.S. Department of Commerce, (1991). Record of Climatological Observations- GHCND: USC00370218, NOAA/NCEI/NESDIS, Asheville, NC.

U.S. Geological Survey (2015), USGS NED 1/3 arc-second n42w072 1 x 1 degree ArcGrid 2015: U.S. Geological Survey: Reston, VA, http://ned.usgs.gov/, http://nationalmap.gov/viewer.html.

Willmott, C.J., 1982. Some Comments on the Evaluation of Model Performance. Bull. Am. Meteorol. Soc. 63, 1309–1313. doi:10.1175/1520-0477(1982)063<1309:SCOTEO>2.0.CO;2