Rainfall Runoff and Flood Simulations for Hurricane Impacts on Woonasquatucket River, USA

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***Abstract*—Integrated hydrological and hydrodynamic modeling study has been conducted to investigate hurricane impact on Woonasquatucket River, Rhode Island, USA. Model simulation was conducted for the case study of 2010 storm event. The hydrological model simulates the runoff from the heavy rainstorm, while the river hydrodynamic model simulates the flood waves affected by the interactions of upstream rainfall runoff and downstream storm surge. Results indicate that the river floods was dominant by rainfall runoff in upper river reaches, but dominant by storm surge in the lower river area near the estuary**

***Index Terms*— flood, rainfall runoff, storm surge, storm, hurricane**

I. Introduction

The Woonasquatucket River's headwaters are 300 feet above sea level at Primrose, in the town of North Smithfield. From several ponds there the river flows 19 miles south and east to downtown Providence, at sea level, where it joins the Moshassuck River to form the Providence River, which in turn flows into Narragansett Bay. The lower reaches of the river, up to the Rising Sun Dam near Donigian Park in Olneyville, rise and fall with the tide in Narragansett Bay. The Moshassuck and Woonasquatucket River Basins cover an area of about 24 and 51 square miles, respectively, in north-central Rhode Island (Fig. 1). The Moshassuck and Woonasquatucket Rivers merge about 0.9 miles (mi) upstream from the Fox Point Hurricane Barrier (FPHB) at the northern end of Narragansett Bay in the City of Providence. The flows and WSEs of the Providence River and lower portions of the Woonasquatucket and Moshassuck Rivers can be affected by tides when the barrier gates are open or by the operation of the barrier when the gates are closed. While the river itself is only 19 miles long, the Woonasquatucket watershed covers 50 square miles in the towns of North Smithfield, Smithfield, Johnston, North Providence, and Providence. Nestled between the Blackstone, Moshassuck, and Pawtuxet watersheds, it encompasses all the land where precipitation and groundwater eventually drain to the Woonasquatucket River. Since colonial times, the port of Providence, located at the head of Narragansett Bay and the lower portion of the Woonasquatucket River, has been a vital part of the city's economy. Ocean-going ships regularly dock along the city's waterfront just south of downtown. During the 19th century, the city became a national leader in industrial output and trade. The downtown area is located in a shallow natural basin with an elevation of only 8–12 feet above mean sea level, or 8.22-12.22 ft above NGVD88 datum based on the datum conversion at NOAA tidal gage near Providence.

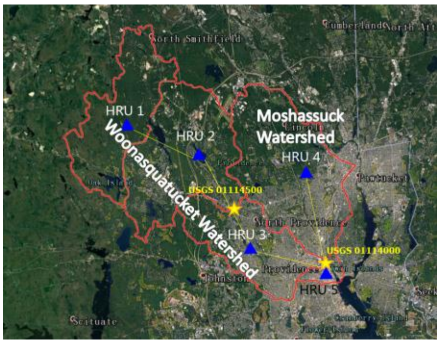

Figure 1. Woonasquatucket river basin

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Because lower portion of the Woonasquatucket passes through heavily urbanized areas, river floods or storm surges may affect the flood area in the area. The primary causes of flooding for the City are prolonged heavy rainfall from large storm systems; torrential short-term rainfall from thunderstorms; snowmelt, often accompanied by heavy rain; and rain, coastal storm surges or both from tropical storms including hurricanes. The City has experienced a variety of damage from flood events that include property damage, loss of life, power outages, and interruption of transportation and communication systems. Coastal storm surges from hurricanes present the single most serious flood threat for the City. Several historical storms or hurricanes have caused flood in the Providence area. The 1938 Hurricane caused devastating storm surges. Hurricane Carol hit Rhode Island on August 31, 1954. Carol also had sustained winds 80 to 100 mph but move only 35 mph and since it hit just after high tide, the tidal flooding was a little smaller. The storm still produced a storm surge between 12 and 14 ft with downtown providence under 12 ft of water. Carol killed 65 people and destroyed 4,000 homes. The Fox Point Hurricane Barrier was constructed between 1960 and 1966 to protect the low-lying downtown area of the city from damaging storm surge and floods associated with hurricanes and other major storm events. The barrier is a 3,000-foot (910 m) long tidal flood barrier spanning the Providence River in Providence, Rhode Island, located 750 feet (230 m) upstream from Fox Point. Hurricane Bob developed in the central Bahamas on August 16, 1991, then steadily intensified and reached hurricane status on the evening of August 17. Bob continued to strengthen during the next 48 hours, as it began an acceleration north-northeastward, paralleling the East Coast. The eye of Hurricane Bob passed over Block Island, Rhode Island at approximately 1:30 PM, and made landfall over Newport, Rhode Island shortly before 2 PM. The heavy rainstorm in 2011 dumped 8.75 inches of rain in East Providence, 7.6 inches in downtown Providence, caused flood in Providence. Flooding has forced some people to abandon cars in Providence (Fig. 2). Although the hurricane barrier can be used to protect the city from storm-surge-induced flood, the barrier may also have a side effect that may block outflow from the river during heavy rainstorms.

Figure 2. Flooding in 2010 forced people to abandon cars this week in Providence, Rhode Island (http://edition.cnn.com/2010/US/weather/04/01/northeast.flooding/index.html)

In this study, a hydrological model was applied to the Woonasquatucket River and Moshassuck River Basins to predict the rainfall runoff from storms and hurricanes. A river hydrodynamic model was applied to the Woonasquatucket River to investigate the interactions of river flow and storm surges along the river, and assess the potential flood conditions under hurricane barrier open or closing scenarios. Simulations for some historical storm events are conducted. In addition, a hypothetical storm characterizing historical storm event is also studied to evaluate the potential flood under extreme condition.

II. Rainfall Runoff Modeling by PRMS Hydrological Model

The 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 stream flow and general watershed hydrology [1]. PRMS's modular design allows users to selectively couple the modules in the module library or even to establish a self-design model. It has been widely applied in the research of rainfall-runoff modeling. It was proved to be a reliable hydrological model. The model simulates the hydrologic processes of a watershed using a series of reservoirs that represent a volume of finite or infinite capacity. Water is collected and stored in each reservoir for simulation of flow, evapotranspiration, and sublimation. Surface runoff, interflow, and groundwater discharge simulate the flow to the drainage network segments, e.g. stream-channel and detention-reservoir. Surface runoff from rainfall is computed using a contributing-area concept. A reservoir routing method is used to compute subsurface flow which is a rapid movement of water from unsaturated zone to stream channel. The groundwater is conceptualized as a linear reservoir and is assumed to be the source of all base flow. Stream flow could be computed directly as the sum of surface runoff, subsurface flow, and groundwater discharge that reaches the stream network. However, a Muskingum flow-routing method computing stream flow to and from individual stream segments is also available in the module. PRMS uses the Muskingum method to calculate the stream flow route. Phase is determined by parameter Kinematic wave coefficient (K_coef) that represents the travel time of flood wave in each segment. PRMS includes climate, plant canopy, impervious-zone interception, surface runoff, subsurface flow, groundwater, streamflow routing, evaporation, and snowpack. Surface runoff is the most outstanding element of streamflow. The most influential elements of surface runoff and infiltration module in PRMS are subbasin area, surface storage depression, impervious area, and type of variable-source area. Subbasin area, impervious area, and type of variable-source area determine the water's transformation from precipitation to surface runoff. Depression parameters provide for water storage during and immediately after precipitation events.

The PRMS model has been successfully applied to some rainfall runoff and snowmelt modeling. Ref. [2]

applied the PRMS model to an integrated decision support system. Ref. [3] used the model to investigate watershed responses to climate change. Ref. [4] applied PRMS to a snowmelt-dominant watershed. Ref. [5] and [6] evaluated climate change impacts on rainfall runoff by PRMS model simulations. Ref. [7] conducted an evaluation of snow water equivalent for mountain basin in the PRMS model. Ref. [8] integrated PRMS model into a ground and surface water flow model GSFLOW. In these studies, PRMS was applied to perform long-term hydrological process in order to provide supports to the local water resource managements. Ref. [9] applied PRMS in flood forecasting.

The hydrological model networks for Woonasquatucket River and Moshassuck River Basins, consisting of sub-basins and channels, were set up based on the geographic characteristics, precipitations, general situation of runoff stations, and the basin distribution. Basin's geographic characteristics such as DEM, land use, and soil type are obtained from EPA's BASINS model database, a multipurpose environmental analysis system developed by EPA, USA. Basin's geographic information (sub-basin's area, slope, aspect, latitude and elevation), reaches' topological structure (stream length, side slope and longitudinal slope) were calculated by EPA's BASINS. After the models were setup, model parameters were calibrated for the storm event in 2010. For the rainfall condition in the storm event in 2010 (Fig. 3), results of stream flow at USGS gage compare well to the observed flow (Fig. 4 and Fig. 5).

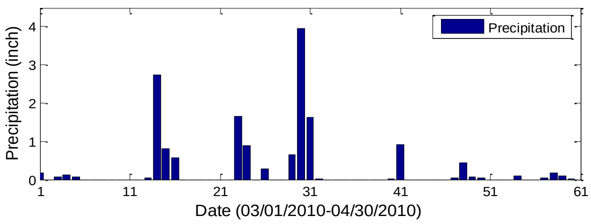

Figure 3. Precipitation during 2010 storm event.

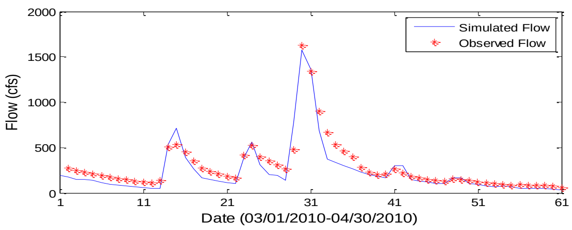

Figure 4. Comparison of modeled and observed flows at USGS gage in Woonasquatucket River

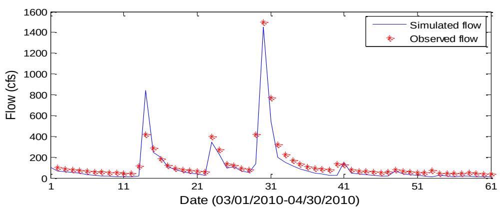

Figure 5. Comparison of modeled and observed flows at USGS gage in Moshassuck River, which will be used as lateral flow to the Woonasquatucket River model.

III. River Hydrodynamic Model Setup by Applying HEC-RAS Model

River flood modeling by using HEC-RAS model was conducted in Woonasquatucket River. 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.

The HEC-RAS model originally setup by Ref. [10] for steady state flow simulations was modified for this study for unsteady flow hydrodynamic simulations. In Zarriello et al.'s HEC-RAS model, river cross section data were obtained from both field surveys and LiDIR data. Field surveys also included dams, bridges, and culverts, which also provided accurate geo-referencing of the structures in the HEC-RAS model. In order to avoid numerical divergence in unsteady hydrodynamic simulations, more river cross sections were added in the revised model for this study. Considering that most urbanized areas with large population are located in the lower river reach, the upstream river inflow boundary in the revised model for hydrodynamic simulations was moved downstream to the location at USGS flow gage. This will also shorten the CPU time because hydrodynamic model simulations for unsteady flow take much longer time than steady flow simulations. For steady simulations, the previous steady model simulations by Zarriello et al. (2014) show reasonable agreement with observed high water mark. The difference between steady simulations of high water marks and observations may be caused by the phase difference of peak flow and elevations at different river cross sections during passage of the flood wave crest. The hydrodynamic model simulations for unsteady flow can show the maximum high water mark at different river cross sections as the results of the interactions of flood wave and storm surge.

IV. Applications of Integrated Rainfall Runoff Model and River Hydrodynamic Model

A. *2010 Storm Event*

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.

B. Boundary Conditions

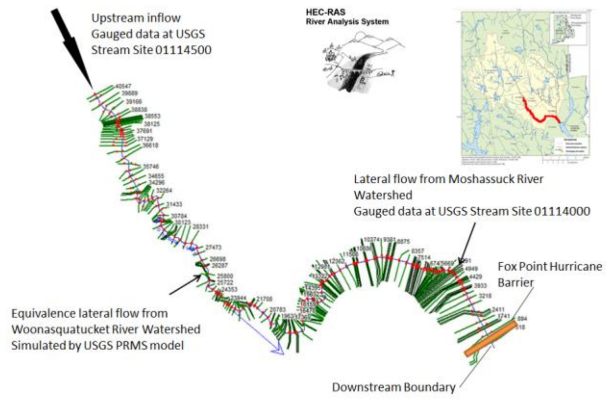

Figure 6. HEC-RAS model for Woonasquatucket River

Rainfall runoff from the hydrological model (Fig. 6) were specified as upstream inflow and lateral inflow. Rainfall runoff from the subbasin above USGS gage is specified at USGS gage as upstream inflow. Rainfall runoff from the subbasin below USGS gage was specified as lateral inflow. Rainfall runoff from Moshassuck River is specified as the lateral inflow to the Woonasquatucket River. Runoff In downstream boundary, storm tides from another coastal storm surge model (ADCIRC model) simulations by David Ullman were specified for the hurricane barrier open condition for unsteady flow simulation. When hurricane barrier was closed, a maximum observed water level was specified for steady flow simulation. Unsteady flow simulation was not performed for hurricane barrier closed condition because we do not have information of the time (hours) that the barrier was closed. Boundary conditions were shown in Fig. 7 and Fig. 8.

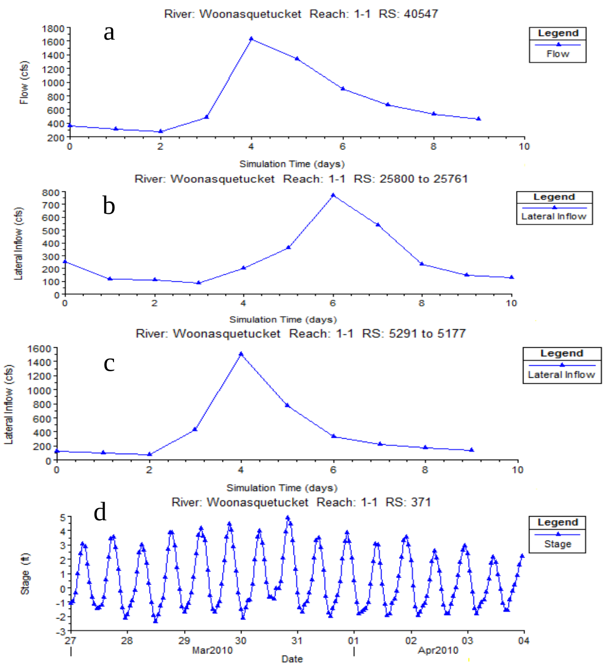

Figure 7. Boundary conditions for 2010 storm event: a) upstream inflow at USGS gage. b) Lateral flow from Woonasquatucket River below USGS gage. c) Lateral inflow from Moshassuck River. d) Tides and surge at NOAA station near Providence for hurricane barrier open condition (datum: NAVD88).

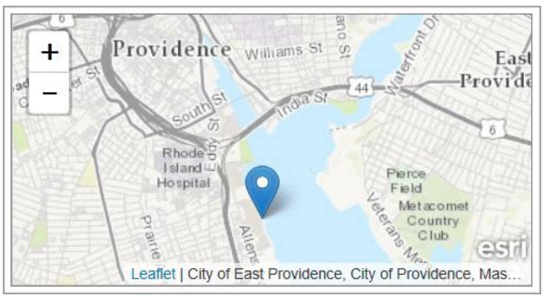

Figure 8. NOAA tidal station near Fox Point Hurricane Barrier in Providence, Rhode Island.

C. Flood Mapping for Open Hurricane Barrier Condition

With the hurricane barrier open, river flow can be discharged out of the river without restriction. Because the storm surge was not very strong during the 2010 storm event, the maximum storm surge elevation was about 5 ft in the downstream boundary at Fox Point Hurricane Barrier. As the result, river simulation shows that river flow was confined within the river banks (red line in the flood area map) in most of areas without causing flood in the flood plain in the Providence (Fig. 9). Because the elevation of the downtown in Providence is about 8-12 ft, there will be no flood in the downtown area the barrier was open. Profile of the of maximum water level along the river for 2010 storm event shows that no flow overtop on bridges and culverts in the river if the hurricane barrier is open to allow the outflow from the river (Fig. 10).

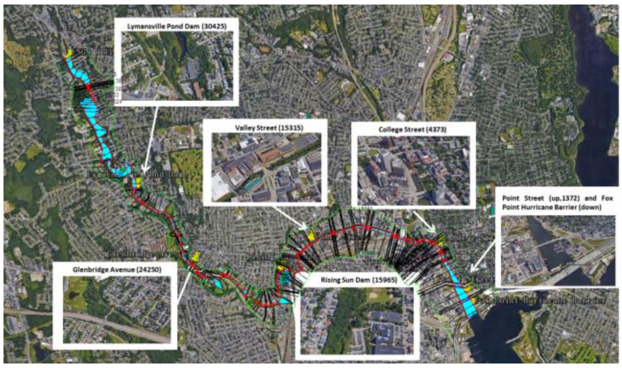

Figure 9. Flood map of maximum water level along the river for 2010 storm event (Hurricane barrier open condition)

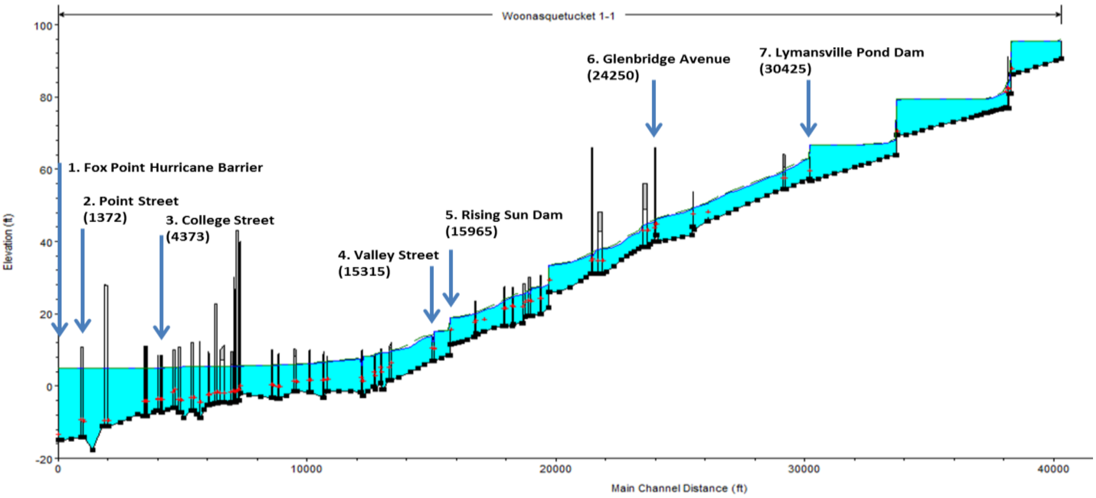

Figure 10. Profile of the of maximum water level along the river for 2010 storm event (Hurricane barrier open condition)

V. Conclusion

Integrated rainfall runoff modeling and river flood modeling have been conducted for the Woonasquatucket River Basin. The USGS's PRMS hydrological model was applied to simulate runoff from the watershed into the river. The HEC-RAS mode, previously developed by USGS (Zarriello, et al., 2014) for steady flow simulations, was modified and improved for unsteady flow hydrodynamic simulations of interactions of rainfall runoff and storm surges. The rainfall runoff model has been validated by satisfactory comparison with observed stream flow at USGS gage in the river. Model simulations were conducted for three storm events: 2010 storm event, Hurricane Calos in 1995, and hypothetic hurricane Rhody. Flood area map from model simulations on top of Google Earth photos are presented for flood area mapping. Profiles of maximum water elevation along the river central line are presented to show the flood over structures in the river. Selected cross sections are also presented to show the details of flood in representative locations or landmarks. Model simulations of water surface elevations were used in flood analysis.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Wenrui Huang and Fei Teng conduct hydrological and hydraulic modeling work. Isaac Ginis and David Ullman provide scenarios for flood analysis. Eren Ozguven provided assistance in preparing the manuscript. All authors have approved the final manuscript.

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