Combined Effect of Storm Surge and Overland Flow on Flooding in a Coastal Urban Area

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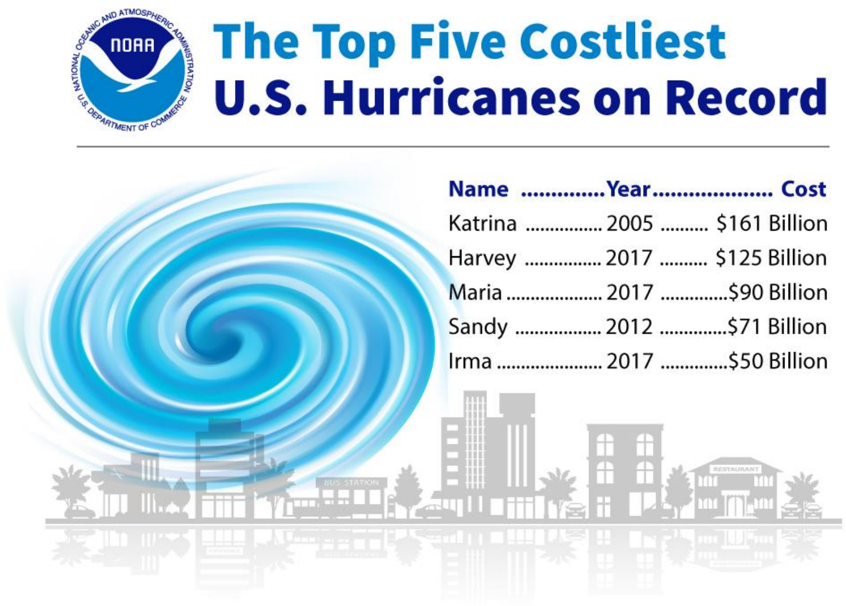
Introduction

Hurricanes are four out of five costliest natural disasters in U.S. history:

1. Hurricane Katrina, 2005
2. Hurricane Harvey, 2017
3. Hurricane Sandy, 2012
4. Hurricane Andrew, 1992
5. Los Angeles earthquake, 1994

Source: Enki Research Group

Three out of five costliest hurricanes occurred in 2017



Coastal Storm Impacts on Infrastructure

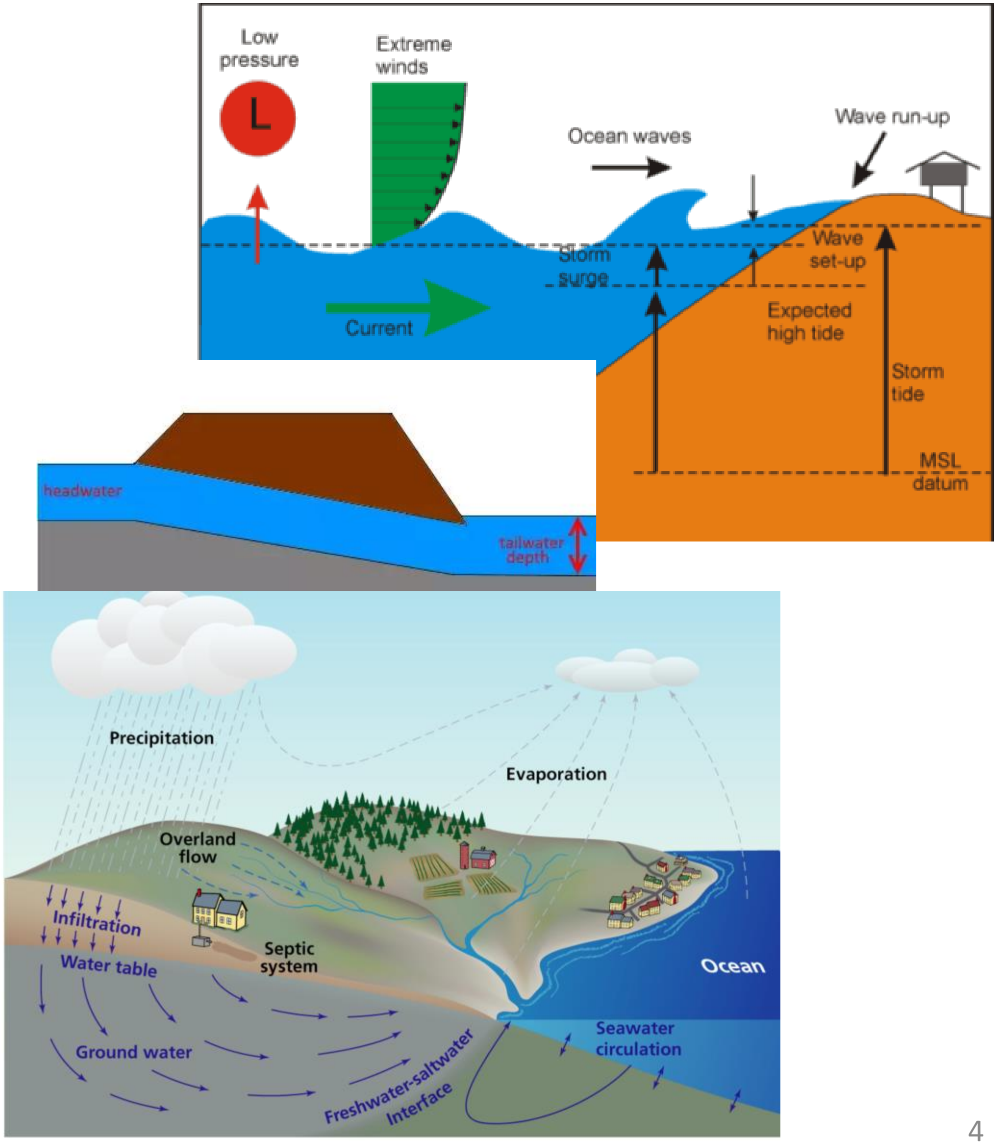
Strom Surge Flooding
Hurricane Ike (2008),
Galveston, TX

Structural Damage due to Waves
Hurricane Ike (2008), Galveston, TX

Precipitation-driven flooding
Hurricane Harvey (2017),
Houston, TX

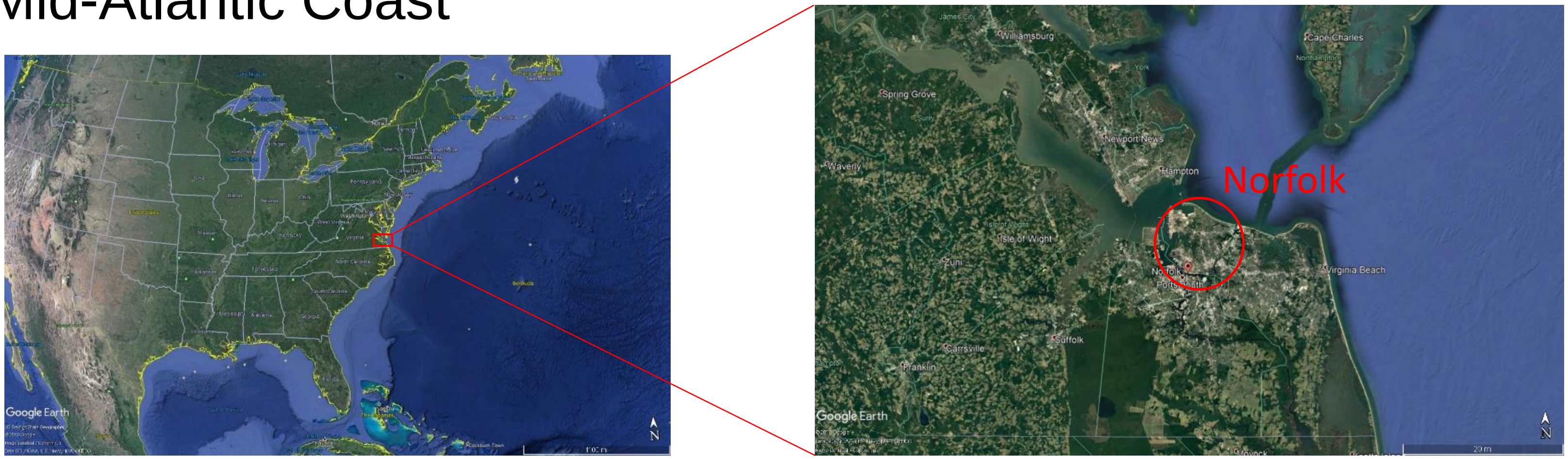
What processes affect urban flooding?

- Storm tide levels
  - Wind stress
  - Wave setup
  - Current tides
  - Tide level
- Tailwater level in stormwater infrastructure
- Precipitation intensity
- Infiltration



Study Area

- The low-lying region of Hampton Roads, Virginia in the U.S. Mid-Atlantic Coast



  - Highest rate of relative sea level rise (SLR) in U.S. East Coast (~7 mm/yr, Boon et al. (2010))
  - Highly urbanized with population 1.7 million
  - 10th in the world in terms of assets vulnerable to SLR
  - Largest naval base in the world

- Number of recurrent flooding events has been increased due to relative sea level rise (SLR) and regional ocean dynamics

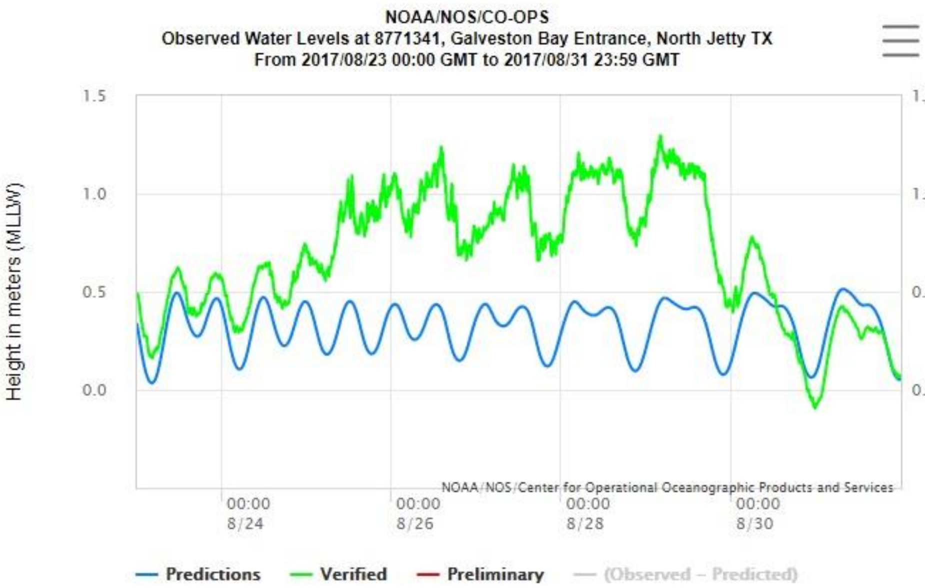
Study Area

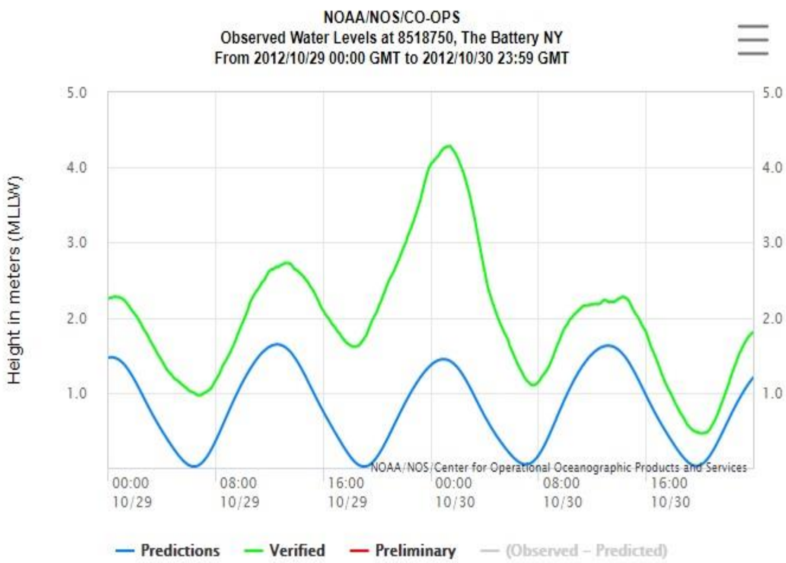
Hurricane Joaquin (2015)
Storm Surge at Norfolk: 1.1 m

Introduction

Hurricane Harvey (Texas, 2017)
Maximum Storm Surge at Galveston, TX: 0.81 m

Hurricane Sandy (2012)
Maximum Storm Surge at Battery, NY: 2.86 m



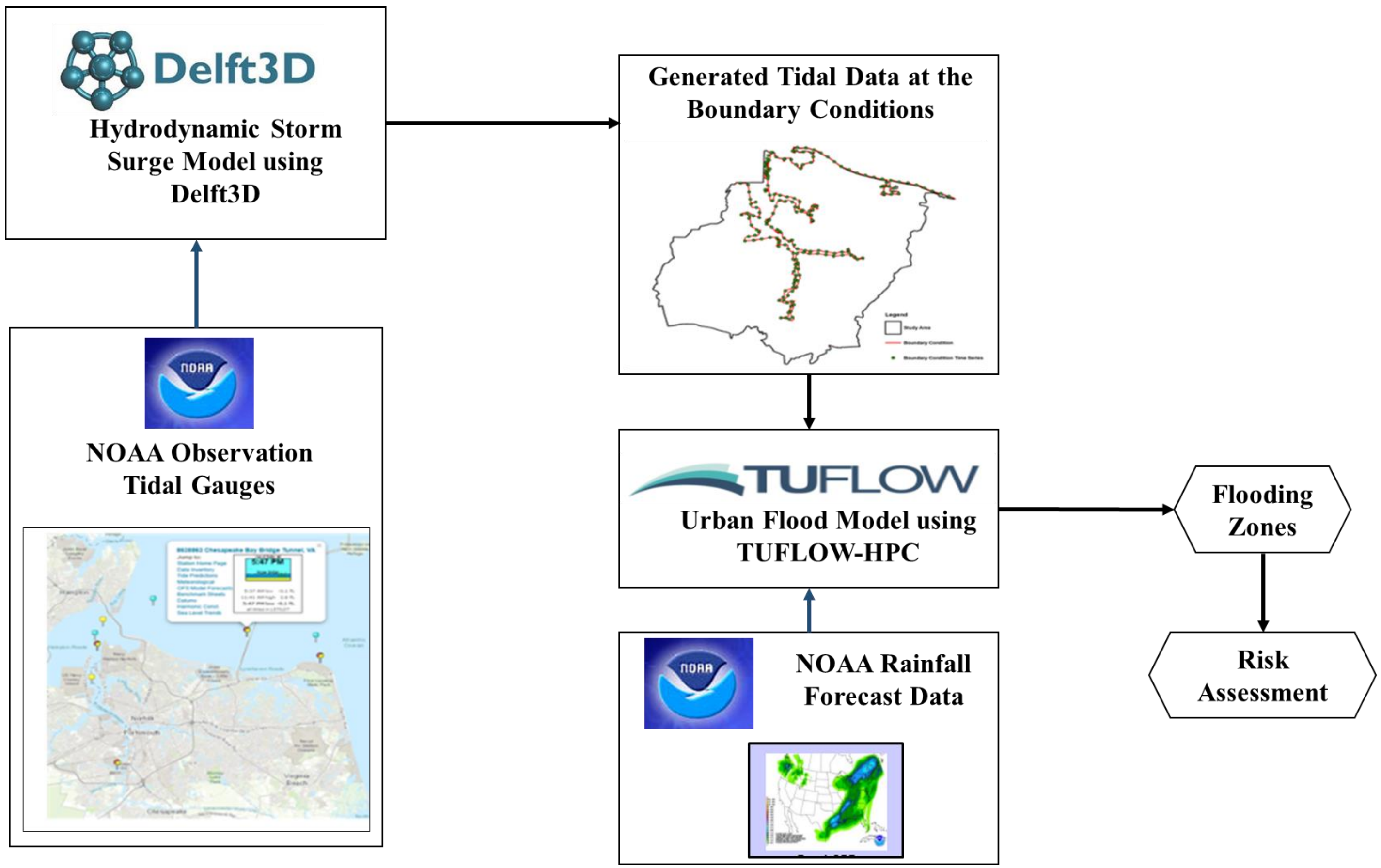


Storm Surge flooding was dominant during Sandy while precipitation-driven flooding was dominant during Harvey

Coupling Workflow

Storm Surge Model: Hydrodynamic+Wave Model
Delft3D Modeling suite (D-Flow+SWAN)

Urban Flooding Model: 2D Hydrodynamic TUFLOW model



Governing Equations-Storm Surge Model

Delft3D-FLOW:

Depth-Averaged Continuity and Navier-Stokes Equations:

$$\frac{\partial \xi}{\partial t}+\frac{\partial\left[d+\xi\right]U}{\partial x}+\frac{\partial\left[d+\xi\right]V}{\partial y}=Q$$ Continuity

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+fV=-\frac{1}{\rho}P_u+\frac{\tau_{sx}-\tau_{bx}}{\rho(d+\xi)}+F_u$$ X Momentum

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}-fU=-\frac{1}{\rho}P_v+\frac{\tau_{sy}-\tau_{by}}{\rho(d+\xi)}+F_v$$ Y Momentum

Delft3D-Wave (SWAN):

Evolution of wave action density (*N*) spectrum is solved.

$$\frac{\partial N}{\partial t}+\frac{\partial c_x N}{\partial x}+\frac{\partial c_y N}{\partial y}+\frac{\partial c_\sigma N}{\partial \sigma}+\frac{\partial c_\theta N}{\partial \theta}=\frac{S}{\theta}$$

The two modules are dynamically coupled.

Governing Equations-Urban Flood Model

TUFLOW:

2D Depth-Averaged Shallow Water Equations:

Continuity

$$\frac{\partial \xi}{\partial t}+\frac{\partial \left(HU\right)}{\partial x}+\frac{\partial \left(HV\right)}{\partial y}=0$$

X Momentum

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}-c_f V+g\frac{\partial \xi}{\partial x}+$$

$$gU\left(\frac{n^2}{H^{4/3}}+\frac{f_1}{2g\Delta x}\right)\sqrt{U^2+V^2}-\mu\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial x}=F_x$$

Y Momentum

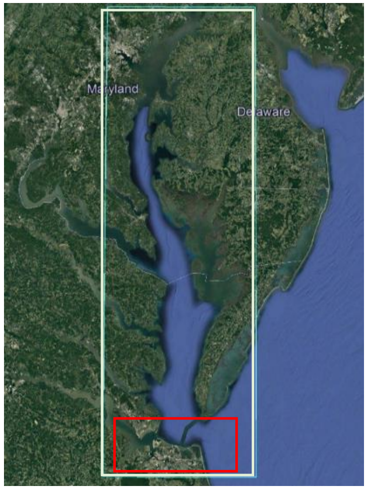
$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+c_f U+g\frac{\partial \xi}{\partial y}+$$

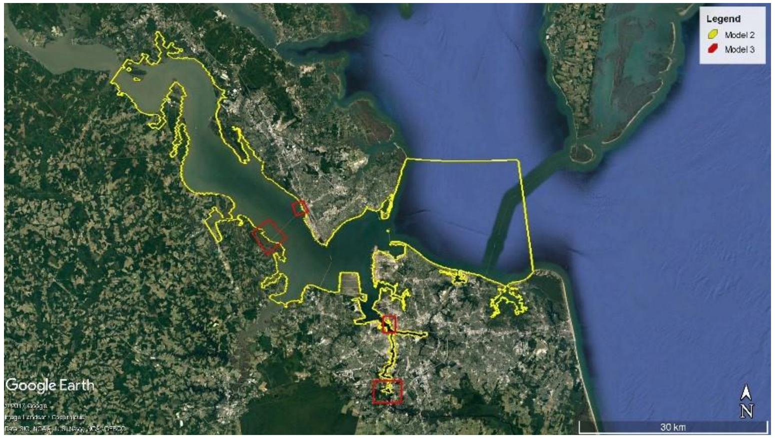
$$gV\left(\frac{n^2}{H^{4/3}}+\frac{f_1}{2g\Delta y}\right)\sqrt{U^2+V^2}-\mu\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial y}=F_y$$

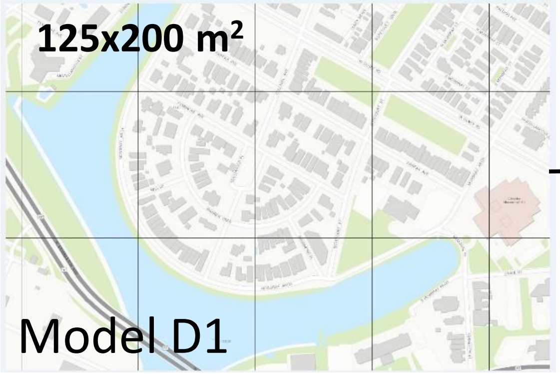
Computational Grid-Storm Surge Model

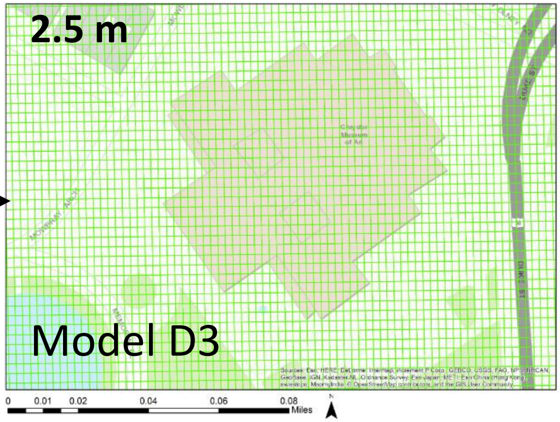
Nested Model Approach:

Output of the low-resolution model is used as the boundary condition in a high-resolution model







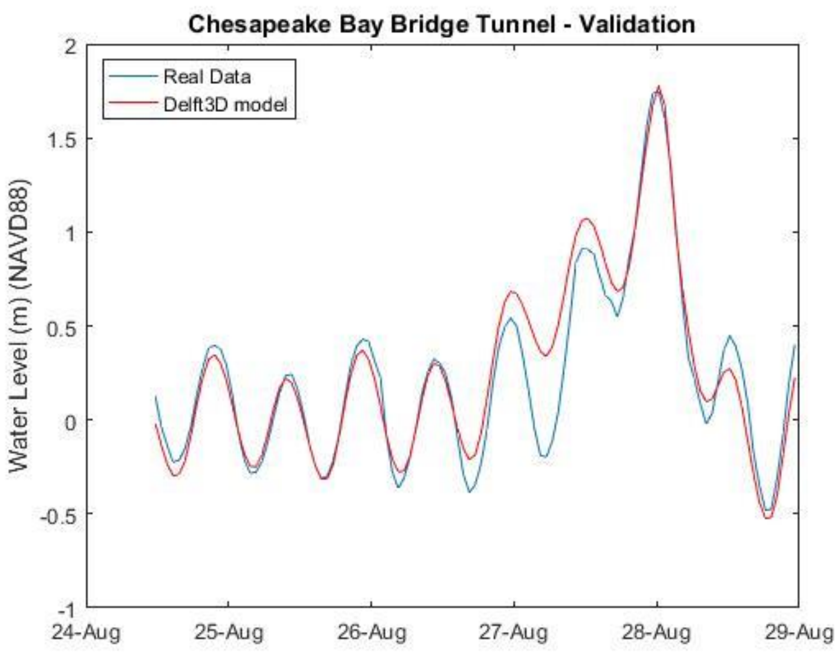


Castrucci and Tahvildari, MTS Journal (2018)

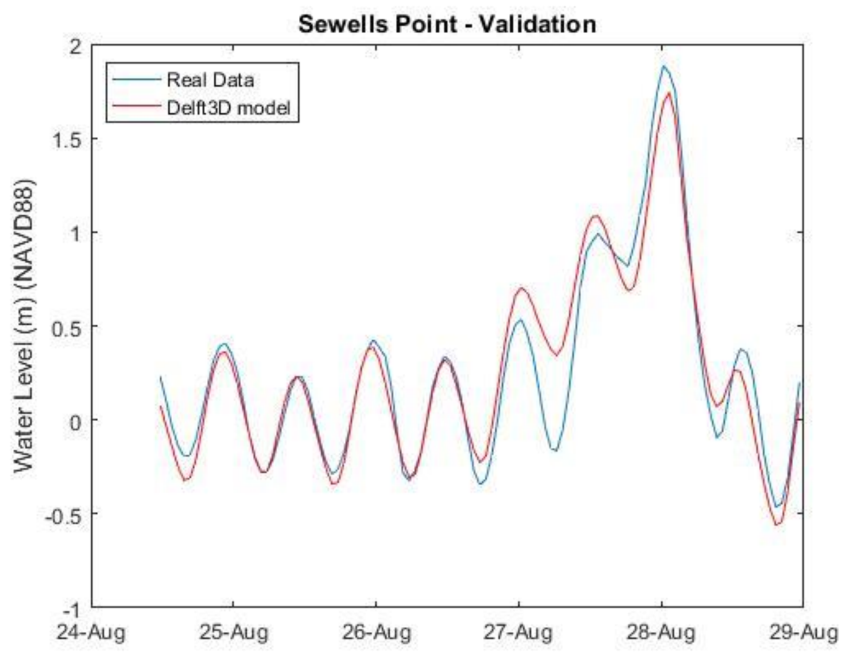
Storm Surge Model Validation

Hurricane Irene (2011):

Model D1



Model D2



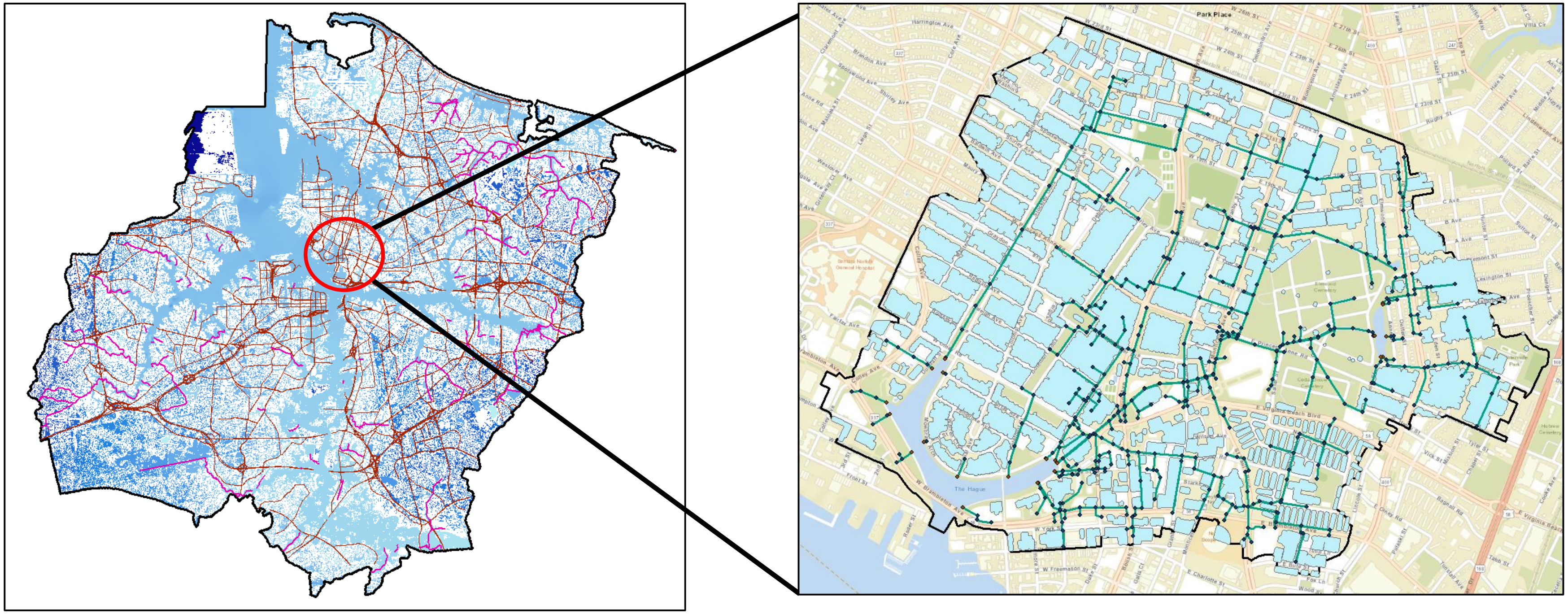
Model 3: No tide gage within the domain in 2011

***Castrucci and Tahvildari, MTS Journal* (2018)**

Urban Flood Model Domain

Model T1: Coarse grid (~10 m resolution), City scale

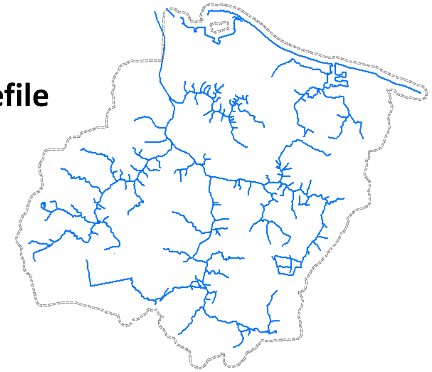
Model T2: Fine grid (~2 m resolution), Neighborhood scale



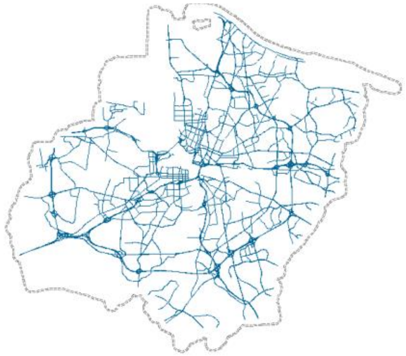
Urban Flood Model Domain

Main Components

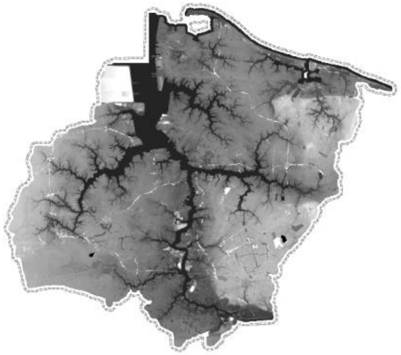
Flowline Shapefile



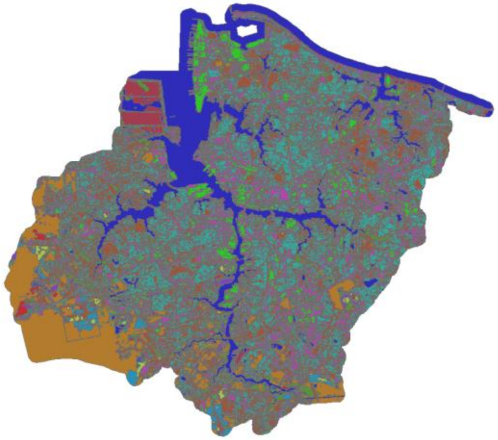
Road Network



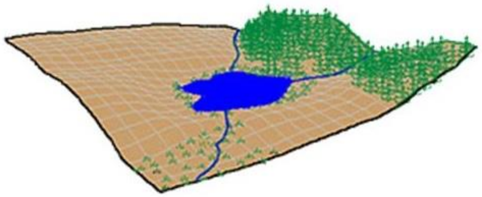
1m DEM topography and bathymetry



Impervious Ratio



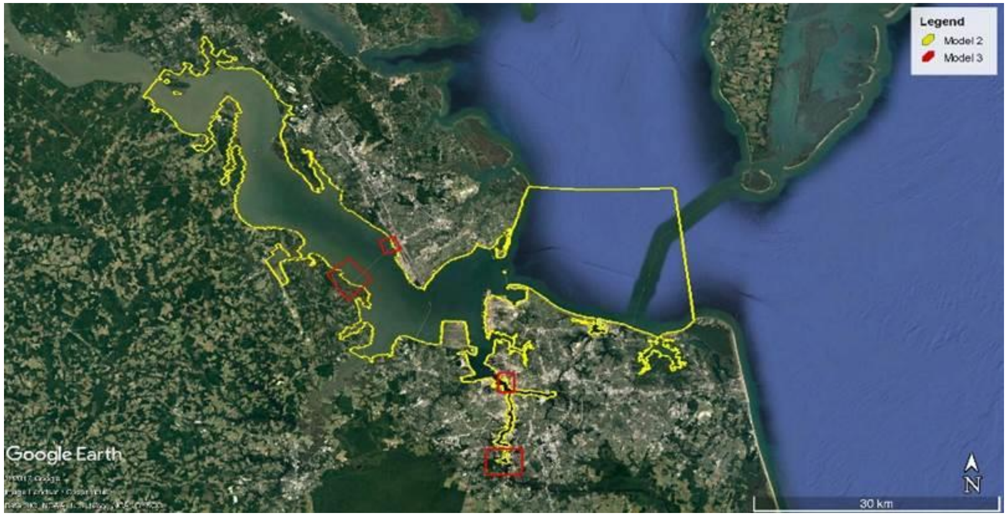
Land cover, soil Type, Manning's coefficient

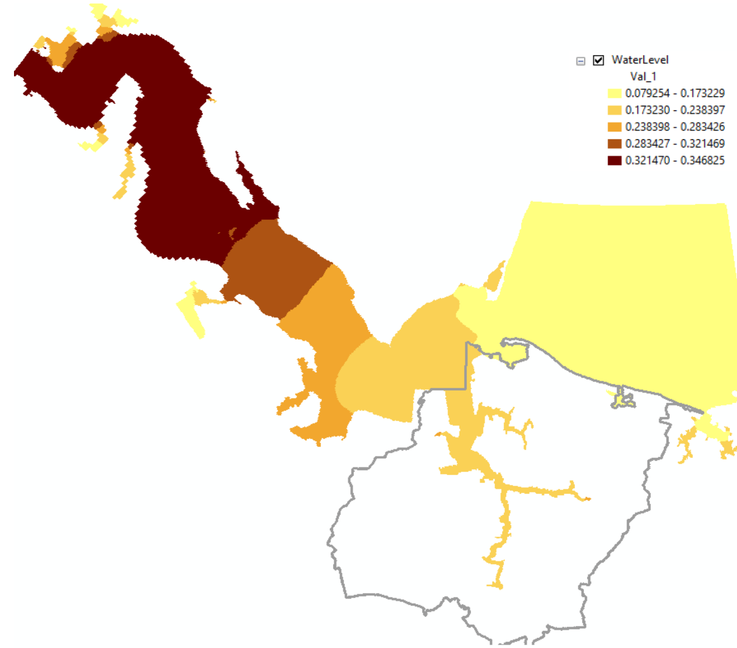


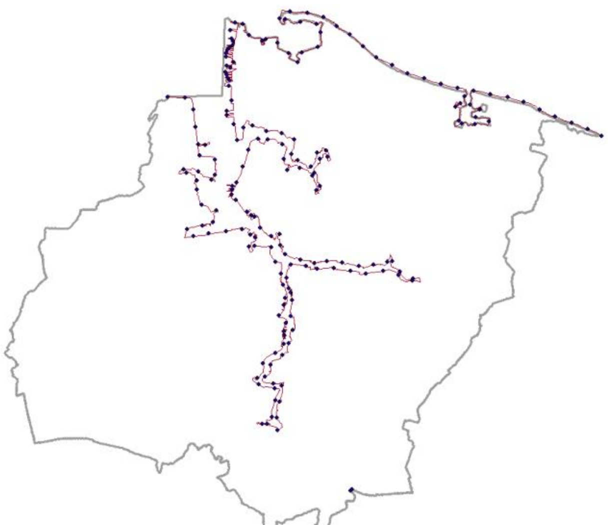
TUFLOW Model

Study Area for Combined Flood Modeling

Storm Surge Model (Delft3D)





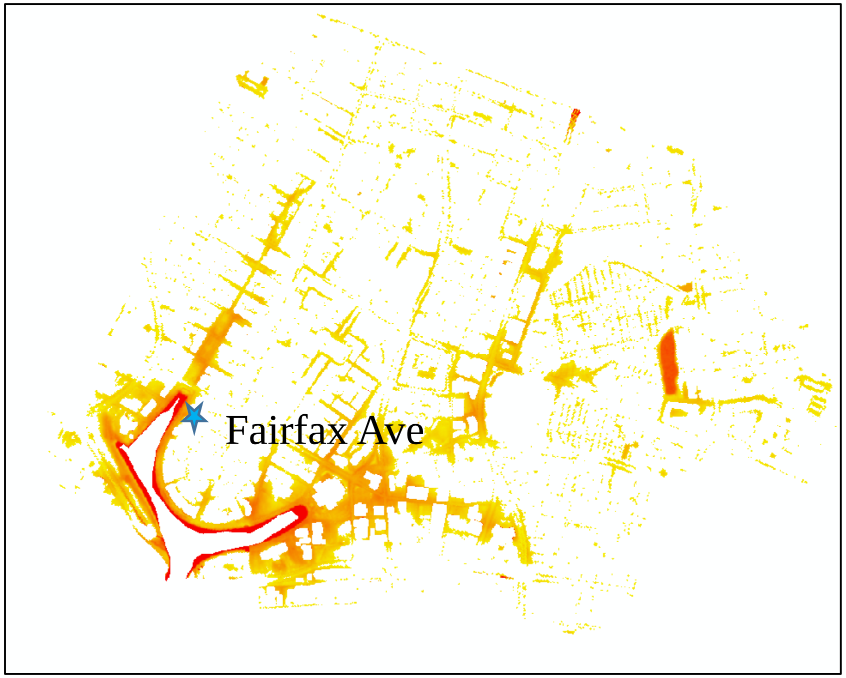


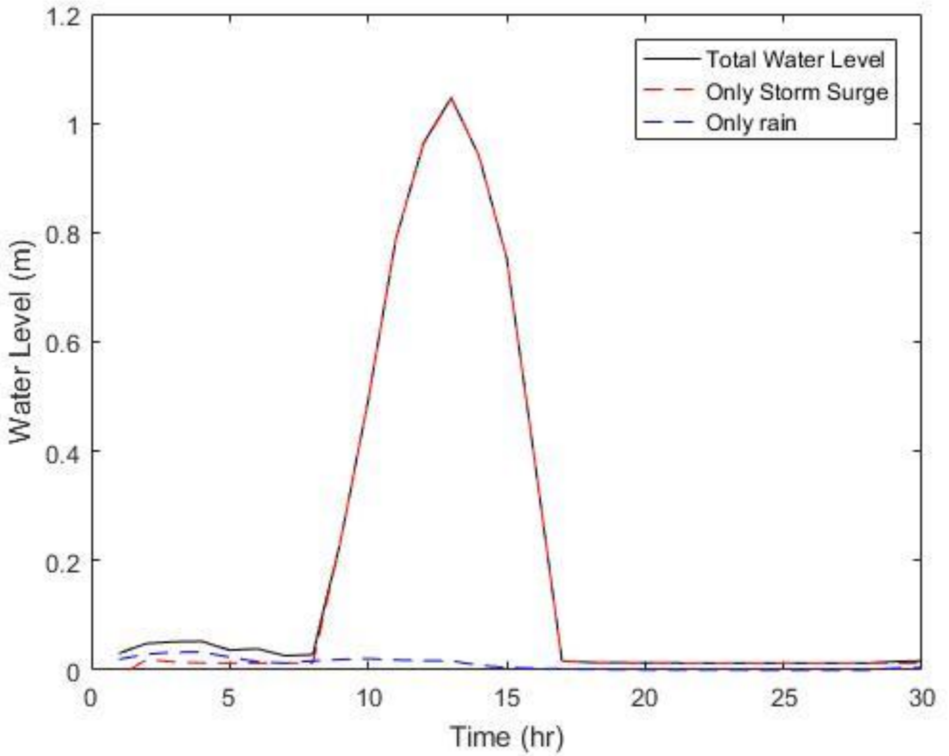
Water level boundary
condition on river banks/open coasts
(every 1000 m)

Overland Flood Model (TUFLOW)

Results

Water level at a representative point in a flood-prone neighborhood in Norfolk, VA:

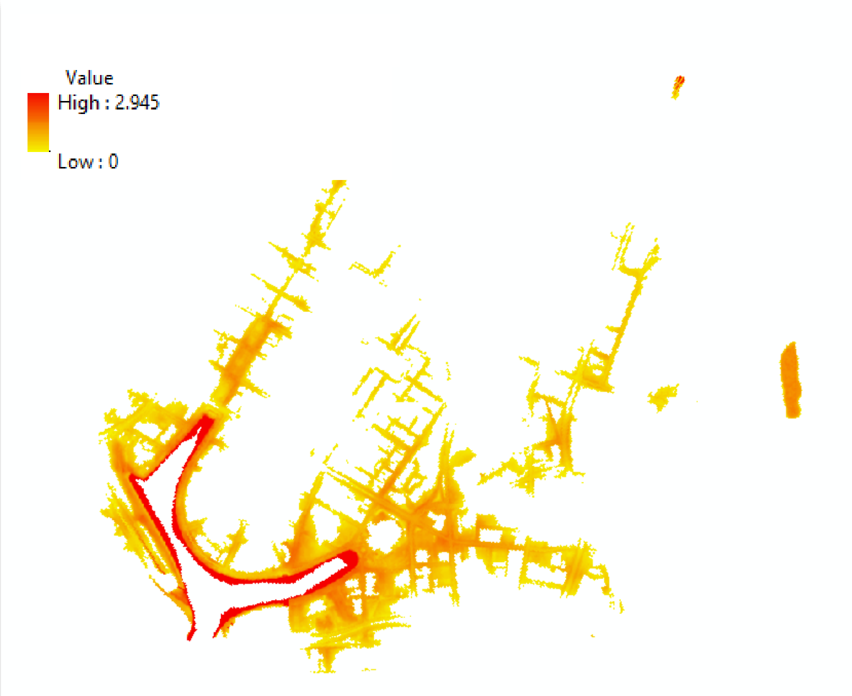




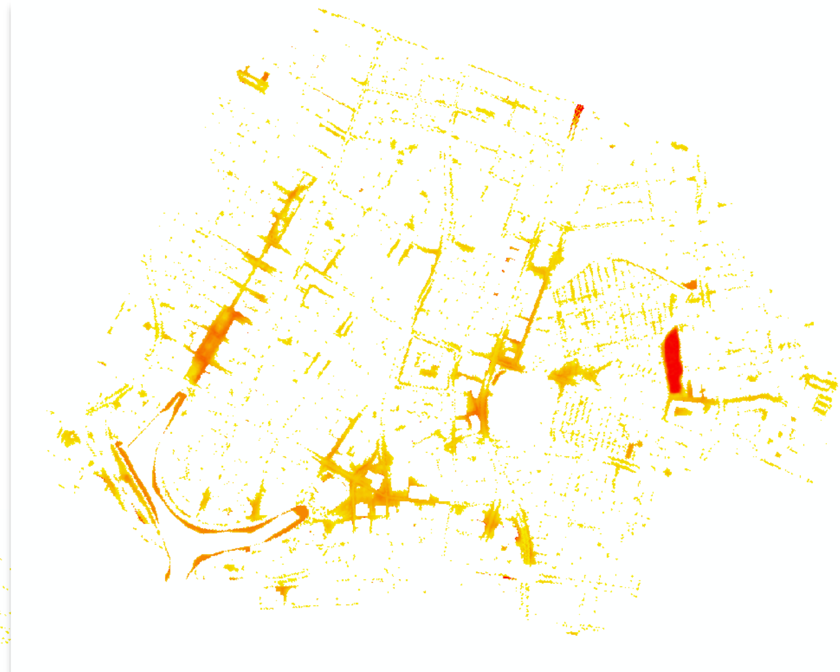
Flooding is dominated by storm surge.

Results

Scenario 1: Storm Surge Only



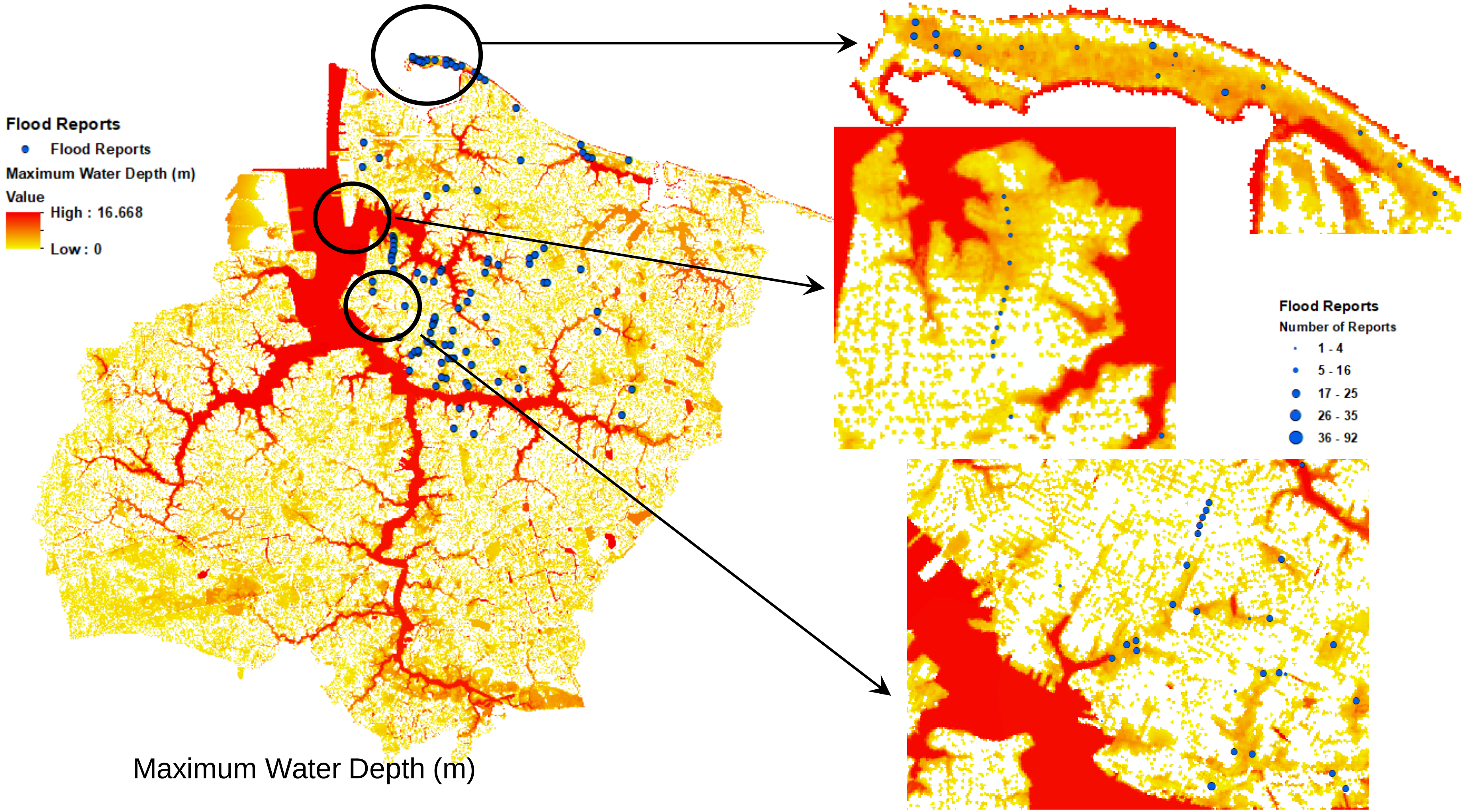
Scenario 2: Rain Only



Scenario 3: Total Water Level (Rain + Storm Surge)

Results – Qualitative Validation

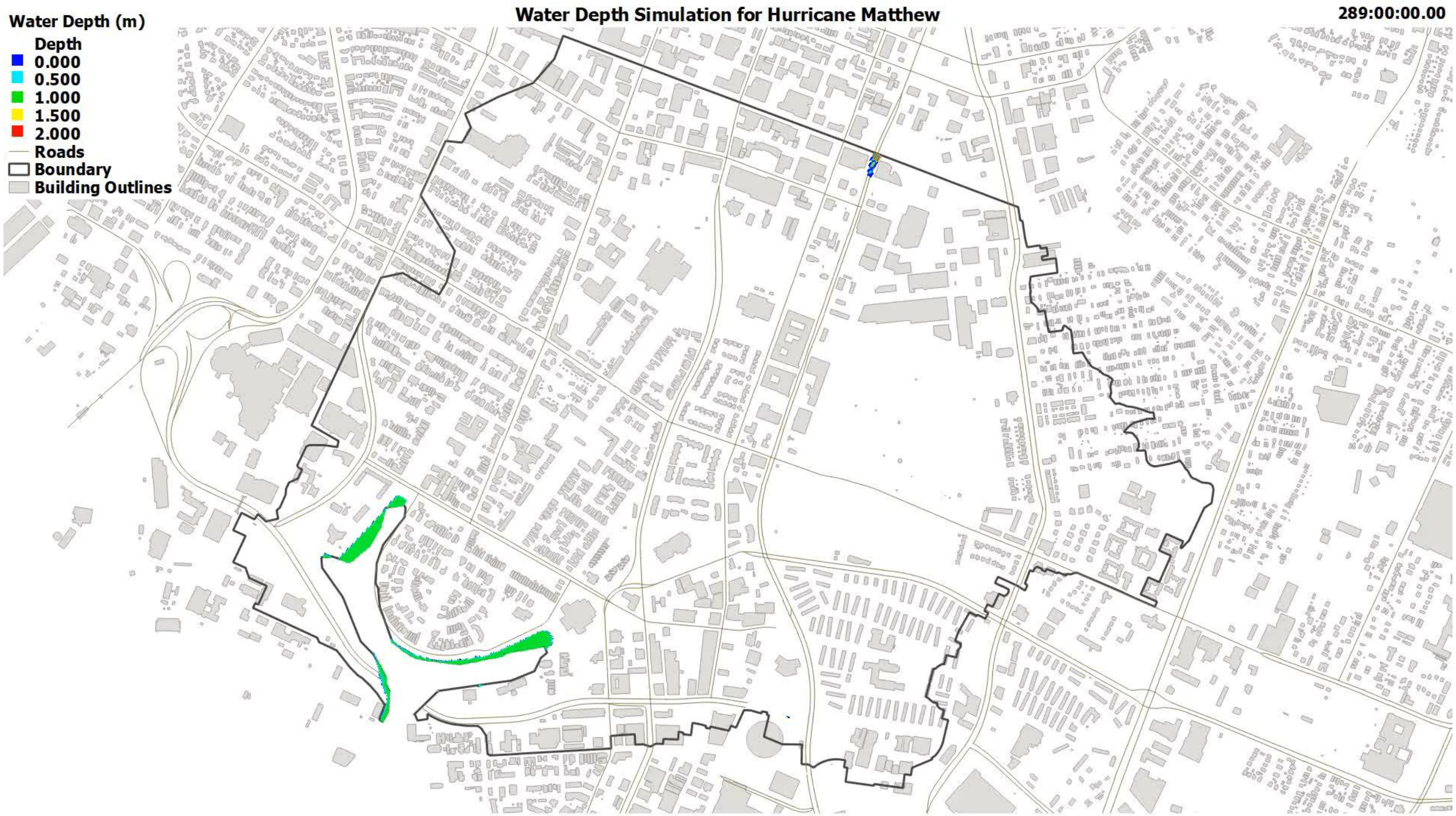
Flood reports during Hurricane Irene (2011)



Maximum Water Depth (m)

Results

Dynamic modeling of overland flooding during Hurricane Irene (2011)



Ongoing/Future Work

- Assess the performance of the combined flood modeling approach for a storm event with intense precipitation, such as Hurricane Mathew (2016)
- Taking into account flooding impact on positioning of emergency vehicles
- Extend the domain of the urban flooding model
- Assess the impacts of climate change, precipitation and relative SLR, on flooding
- Relative SLR effects on shoreline change

Acknowledgements

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Thank you!

Questions?