Real-Time Flood Prediction Using Data-Driven and Hydrodynamic Modeling Tools

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Real-time Flood Prediction using Data-driven and Hydrodynamic Modeling Tools

Jon Goodall, Ph.D., P.E., Associate Professor
Mohamed Morsy and Jeff Sadler, Ph.D. Candidates
Civil and Environmental Engineering
University of Virginia
Overview

- Flooding warning system for VDOT using hydrodynamic watershed modeling
- Data-driven approach for flooding in Norfolk
- Rain gauge density study in Virginia Beach
- Summary
- Hampton Roads VDOT district ($11 \times 10^3$ km$^2$)
- ~500 VDOT bridges and culverts
**Regional River Severe Storm Model (R²S²)**

R²S² is a diverse, multi-function digital platform that offers various applications to VDOT’s Districts and Residencies, regional Emergency Services, and Environmental Agencies.

- **WMS 9.0**
  - GIS Data
  - Terrain (Tin)
  - Rivers & Streams
  - Watersheds

- **SMS 11.0**
  - TUFLOW
  - 2-D Hydrodynamic
  - 10 Second Time Step
  - Two Weeks Time Series
  - 495 Bridges

- **Output Data Post Processing**
  - Equivalent to 495 HEC-RAS Unsteady Models

- **HEC-HMS**
  - Sub-Watersheds
  - Rainfall Data

- **USGS Stream Gage Data**

- **NOAA Point Rainfall Data**

- **NOAA NEXRAD Data**

- **Time Series Transformation**

- **Sub-Watersheds’ Hydrographs**

- **VDOT Bridge Data**

- **USGS 10m DEM Terrain Data**

- **USGS Soil Maps**

- **USGS Land Use**

- **Interactive Bridge Flooding**

- **Predictive Flooding Atlas**

**HWR**

Water Resources
**R²S² Automation Plan**

**Objective 1**
- VDOT Bridge Data
- USGS 10m DEM Terrain Data
- USGS Soil Maps
- USGS Land Use
- NOAA Point Rainfall Data
- NOAA NEXRAD Data

**Objective 2**
- SMS 11.0 TUFLOW 2-D Hydrodynamic
  - 10 Second Time Step
  - Two Weeks Time Series
  - 495 Bridges

**Objective 3**
- Interactive Bridge Flooding
- Predictive Flooding Atlas

**HEC-HMS**
- Sub-Watersheds Rainfall Data
- Time Series Transformation

**Sub-Watersheds’ Hydrographs**

**Output Data**
- Equivalent to 495 HEC-RAS Unsteady Models

**WMS 9.0 GIS Data**
- Terrain (Tin) Rivers & Streams
- Watersheds

**NOAA**
- Point Rainfall Data
- NEXRAD Data

**USGS**
- 10m DEM Terrain Data

**Post Processing**
- USGS Stream Gage Data
- Combined Watershed, Bridges, & Rainfall Distribution

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**The High-Resolution Rapid Refresh (HRRR)**

The HRRR is a NOAA real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model initialized by 3km grids with 3km radar assimilation. Radar data is assimilated in the HRRR every 15 mins over a 1-h period adding further detail to that provided by the hourly data assimilation from the 13km radar-enhanced Rapid Refresh.
Modeling

HEC-HMS (Hydrologic Modeling System)

Modeling

TUFLOW (Two-dimensional Unsteady FLOW)

Commercial hydrodynamic computational engine, 2D GPU solver

http://www.tuflow.com
GPU (Graphical Processing Unit)

UVA resources

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<tr>
<th>ID</th>
<th>Type</th>
<th>CPU</th>
<th>RAM (GB)</th>
<th>GPU</th>
<th>GPU RAM</th>
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<td>M1</td>
<td>Desktop Dell</td>
<td>3.40 GHz, 4</td>
<td>16</td>
<td>NVIDIA Quadro K2000</td>
<td>2.00 GB, 384 SMX CUDA parallel processing cores</td>
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<tr>
<td></td>
<td>OptiPlex 990</td>
<td>Core(s)</td>
<td></td>
<td></td>
<td></td>
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<td>M2</td>
<td>Desktop Viz Lab</td>
<td>3.20 GHz, 32</td>
<td>64</td>
<td>Two units of NVIDIA GeForce</td>
<td>6.00 GB, 2688 CUDA parallel processing cores for each</td>
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<td></td>
<td>ESCHER</td>
<td>Mhz, 6 Core(s)</td>
<td></td>
<td>GTX TITAN</td>
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Amazon Web Services (AWS) instances

<table>
<thead>
<tr>
<th>EC2 Instance</th>
<th>Model</th>
<th>GPUs</th>
<th>vCPU</th>
<th>Memory (GiB)</th>
<th>GPU Memory</th>
<th>Storage (GB)</th>
<th>Hourly Fees</th>
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<td>G2</td>
<td>g2.2xlarge</td>
<td>1</td>
<td>8</td>
<td>15</td>
<td>4 (GB)</td>
<td>SSD 1 x 60</td>
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<tr>
<td></td>
<td>g2.8xlarge</td>
<td>4</td>
<td>32</td>
<td>60</td>
<td>16 (GB)</td>
<td>SSD 2 x 120</td>
<td>$2.878</td>
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<tr>
<td>P2</td>
<td>p2.xlarge</td>
<td>1</td>
<td>4</td>
<td>61</td>
<td>12 (GiB)</td>
<td>EBS</td>
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<tr>
<td></td>
<td>p2.8xlarge</td>
<td>8</td>
<td>32</td>
<td>488</td>
<td>96 (GiB)</td>
<td>EBS</td>
<td>$8.672</td>
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<tr>
<td></td>
<td>p2.16xlarge</td>
<td>16</td>
<td>64</td>
<td>732</td>
<td>192 (GiB)</td>
<td>EBS</td>
<td>$17.344</td>
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</table>

G2 Instances → NVIDIA GRID K520 GPUs
P2 Instances → NVIDIA K80 GPUs
Rainfall Forecast Data Automation and Preparation

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Data Provider</th>
<th>Relevant Data Product</th>
<th>Spatial Resolution (km)</th>
<th>Temporal Resolution (hours)</th>
<th>Forecast Hours</th>
<th>Model Cycle</th>
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<tr>
<td>HRRR</td>
<td>NCEP</td>
<td>Surface total precipitation</td>
<td>3</td>
<td>1</td>
<td>18</td>
<td>24/day</td>
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<tr>
<td>RAP</td>
<td>NCEP</td>
<td>Surface total precipitation</td>
<td>13</td>
<td>1</td>
<td>18</td>
<td>24/day</td>
</tr>
<tr>
<td>NDFD</td>
<td>NWS</td>
<td>Quantitative precipitation forecast</td>
<td>5</td>
<td>6</td>
<td>72</td>
<td>8/day</td>
</tr>
<tr>
<td>NAM</td>
<td>NCEP</td>
<td>Surface total precipitation</td>
<td>12</td>
<td>1</td>
<td>36</td>
<td>4/day</td>
</tr>
</tbody>
</table>

High-Resolution Rapid Refresh (HRRR)

- NOAA/NCEP operational weather prediction system
- We have automated HRRR data access using Python and OPeNDAP
- NDFD/QPF can be used in the future for longer-term warnings

http://ruc.noaa.gov/hrrr/displayImage.cgi?image=hrrrcrefimage&width=859&model=hrrr&title=HRRR
Objective 1: Rainfall Forecast Data Automation and Preparation

- NetCDF File/ASC Grids
- Time Series

- HEC-HMS Generated Hydrographs
- TUFLOW Model with Rainfall Data
- Subwatersheds
## Objective 2: Speeding Up the TUFLOW Model

<table>
<thead>
<tr>
<th>Model Specifications</th>
<th>Original Model</th>
<th>New Model</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>OM</td>
<td>R1</td>
</tr>
<tr>
<td>Machine</td>
<td>M1</td>
<td>M1</td>
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<tr>
<td>TUFLOW Release</td>
<td>2013-12-AC</td>
<td><strong>2016-03-AA</strong></td>
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<tr>
<td>Precision</td>
<td>Single</td>
<td>Single</td>
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<tr>
<td>Time-step (sec)</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Output Cell Size (m)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Processing Units</td>
<td>CPU</td>
<td>CPU</td>
</tr>
<tr>
<td>No. of GPUs</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Running Time (hr)</strong></td>
<td><strong>105.7</strong></td>
<td><strong>120</strong></td>
</tr>
</tbody>
</table>

120 to 2.2 hr (55x) speed up for a 15 day model simulation (for Hurricane Sandy)
Speeding Up the TUFLOW Model

Running the TUFLOW Model on AWS Instances

<table>
<thead>
<tr>
<th>EC2 Instance</th>
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<td>32</td>
<td>488</td>
<td>96 (GiB)</td>
<td>EBS</td>
<td>$8.672</td>
</tr>
</tbody>
</table>

**G2 Instances:**
- NVIDIA GRID K520 GPUs
- Each GPU includes 1536 CUDA

**P2 Instances:**
- NVIDIA K80 GPUs
- Each GPU includes 4992 CUDA
Objective 3: Post-processing and Automating Model Output

- Extract MaxWL and compute flooded depth
- Generate new shapefile for the flooded bridges
- Generate KMZ file for visualization

- GDAL/OGR Python Library
- SIMPLEKML Python Library

- Maximum water levels generated by TUFLOW model
- VDOT bridge locations and data shapefile
- Google My Maps
- Google API
- EC2
- GeoSheets
Build-up the Flood Warning Model Workflow Through AWS

Start Model Run Manually

Decision Maker

AWS EC2 g2.8/p2.8 Windows OS Model components

Request and Retrieve Rainfall Data

AWS S3 Bucket

Monitor Rainfall Data

NOAA NOMADS

Send Alerts Via Email

Access Current and Archived Flooded Locations Information

Start If Rainfall Recorded

Request Archived Outputs

AWS EC2 t2.micro Linux OS Trigger/Visualization

Send Alerts Via Email

Access Current Flooded Locations Information

Regular User
Decision Maker/Regular Users and EC2 t2.micro Instance

AWS EC2 t2.micro
Linux OS
Trigger/Visualization

Send Alerts Via Email

To

Register

User

Decision Maker

Regular User

Access Current and Archived Flooded Locations Information

Send Alerts Via Email

Access Current Flooded Locations Information

Bridgekmzs → folder includes the latest generated five KMZ files
Logs → folder includes the latest generated five log files corresponding to the KMZ files
Studyarea → folder includes KMZ files related to the study area

templates/

base.html → Navigation bar
index.html → Google maps API
log.html → Trackback
login.html → Administrator login

Server.py
Static/

Flask

Designed Using Bootstrap
(front-end framework)

Gunicorn

Nginx

Logs

Study area

Bridgekmzs

~ gunicorn ~

Index.html

Login.html

Send Alerts Via Email

Designed Using Bootstrap
(front-end framework)
You are currently viewing the model forecasted water elevation for 18 hours starting from 2017-05-16 12:00:00.

The model is up to date with the latest forecast.
Overview

• Flooding warning system for VDOT using hydrodynamic watershed modeling

• **Beginning of a data-driven approach for flooding in Norfolk**

• Rain gauge density study in Virginia Beach

• Summary
Virginia Recorded Floods (9/30/16-10/13/16)

- 1
- 2 - 4
- 5 - 8
- 9 - 12
- 13 - 19

Service Layer Credits:
Sources: Esri, DeLorme, NAVTEQ, USGS, NRCAN, METI, iPC, TomTom
- 47 events
- 1,055 flooded roadways
- 9/2010-10/2016
Named Storm Events

Nicole (9/30/2010)

Irene (8/27/2011)

Sandy (10/28/2012)

Joaquin (9/29/2015)

HERMINE (9/2/2016)

Hurricane Matthew (10/5/2016)
Rain, Tide, and Groundwater Table

**Nicole**
- Nicole (9/30/2010)
- Rain: 11.4 in
- Tide: 1.4 ft
- GW: 3.1 ft
- No. events = 101

**Matthew**
- Hurricane Matthew (10/5/2016)
- Rain: 10.2 in
- Tide: 3.4 ft
- GW: 4.1 ft
- No. events = 111

**Sandy**
- Sandy (10/28/2012)
- Rain: 4.2 in
- Tide: 2.8 ft
- GW: 2.2 ft
- No. events = 105
Rain, Tide, and Wind

Nicole
HERMINE (9/2/2016)

rain = 3.46 in
tide = 2.15 ft

Matthew
Irene (8/27/2011)

rain = 7.9 in
tide = 1.1 ft

Sandy
Joaquin (9/29/2015)

rain = 7.0 in
tide = 2.4 ft

25mph
31mph
12mph
Non-Named Storm Events

9/4/14
Thunderstorm (9/4/2014)
- rain = 2.1 in
- 1-hr peak rain = 2.1 in/hr
- tide = 0.5 ft
- 4.5mph

5/16/14
Heavy Rain (5/16/2014)
- rain = 3.8 in
- 1-hr peak rain = 2.2 in/hr
- tide = 0.6 ft
- 6.5mph

9/8/14
Rainy Monday (9/8/2014)
- rain = 5.6 in
- 1-hr peak rain = 1.9 in/hr
- tide = 1.5 ft
- 10mph
Increasing flooding?

Result of Higher GW Table?

Yearly avg. Shallow Well depths at MMPS170

Cumulative days with floods reported

Date

Year

Shallow well depth (ft above NAVD 88)

2010

2011

2012

2013

2014

2015

2016
Decision Tree

If daily rainfall > 1.5 in

If daily tide > 1.1 ft

8 flood events
0 non-flood events
Variable Importance from Random Forest Fit

Variable Name
- rain_daily_sum
- rain_hourly_max
- rain_15_min_max
- tide_daily_avg
- rain_prev_3_days
- wind_vel_daily_avg
- tide_rhrmx
- gw_daily_avg
- disttowat
- tide_r15mx
- elev
- num_imperv

Variable Importance (Mean Decrease in Gini Index)
Different Machine Learning Algorithms

K nearest neighbors
Support vector machines
Decision trees
Random forest
Logistic regression

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>True Positive Rate</th>
<th>False Positive Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>knn</td>
<td>92.50%</td>
<td>7.30%</td>
</tr>
<tr>
<td>svm</td>
<td>93.50%</td>
<td>3.70%</td>
</tr>
<tr>
<td>dt</td>
<td>97.20%</td>
<td>7.80%</td>
</tr>
<tr>
<td>rf</td>
<td>98.10%</td>
<td>3.40%</td>
</tr>
<tr>
<td>logit</td>
<td>91.60%</td>
<td>5.90%</td>
</tr>
</tbody>
</table>
Overview

- Flooding warning system for VDOT using hydrodynamic watershed modeling

- Beginning of a data-driven approach for flooding in Norfolk

- Rain gauge density study in Virginia Beach

- Summary
Rain Gauges
Problem Spots
Contributing Watersheds

Locations identified with assistance from Greg Johnson, City of Virginia Beach
Method

• Ignore nearby station(s) and try to estimate area averaged watershed precipitation with remaining rain gauges

• Compared estimated rain with vs without nearby stations
Results

1.) Typically a 30-70% difference for 1-hr and 15-min rainfall
2.) Typically a 10-30% difference for daily rainfall
Results

1.) Addition of rain gauge 3.5 km away adds little estimation confidence
2.) Arguably, rain gauges should be within 0.5 km of target location
Developing an Inexpensive Real-time Rain Gauge

Particle Photon

Piezo Element

Amplifier
Summary

• Use of **the cloud** to automate and speed up **hydrodynamic** flood warning models

• Use of **data-driven** approaches for rapid flood warning in complex coastal environments

• **Internet of Things (IoT)** for real-time rainfall monitoring

• **Longer-term goal:** Create a hybrid decision support system that takes advantage of hydrodynamic and data-driven modeling approaches and real-time monitoring
Related UVA Initiatives

• **Resilient Futures Pan-University Institute** (just announced)
  - Joins the Data Science Institute, Brain Institute, and Infectious Disease Institute as Pan-University Institutes
  - Engineering, Environmental Science, Policy, Commerce, Law, etc.
  - Key initial focus: Coastal Systems

• **Link Lab** (linklab.virginia.edu)
  - Interdisciplinary Lab in Cyber-Physical Systems
  - Computer Science, Civil Engineering, Electrical Engineering, etc.
  - Key initial focus: Smart Cities / Internet of Things
Thank you!

Questions?

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http://cee.virginia.edu/jonathangoodall

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