5-19-2017

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

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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 ($11 \times 10^3 \text{ km}^2$)
• ~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.

- VDOT Bridge Data
- USGS 10m DEM Terrain Data
- USGS Soil Maps
- USGS Land Use
- NOAA Point Rainfall Data
- NOAA NEXRAD Data
- Time Series Transformation
- WMS 9.0 GIS Data
  - Terrain (Tin)
  - Rivers & Streams
  - Watersheds
- Combined Watershed, Bridges, & Rainfall Distribution
- USGS Stream Gage Data
- SMS 11.0 TUFLOW
  - 2-D Hydrodynamic
  - 10 Second Time Step
  - Two Weeks Time Series
  - 495 Bridges
- HEC-HMS
  - Sub-Watersheds
  - Rainfall Data
- Sub-Watersheds’ Hydrographs
- USGS
  - 10m DEM Terrain Data
  - Land Use
  - Soil Maps
- NOAA
  - Point Rainfall Data
  - NEXRAD Data

Output Data
- Post Processing
- Equivalent to 495 HEC-RAS Unsteady Models
- Interactive Bridge Flooding
- Predictive Flooding Atlas

VDOT Bridge Data

HWR
Water Resources
R²S² Automation Plan

Objective 1

- USGS 10m DEM Terrain Data
- USGS Soil Maps
- NOAA Point Rainfall Data
- NOAA NEXRAD Data
- USGS Sub-Watersheds and Terrain Data

Time Series Transformation

Objective 2

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

Sub-Watersheds’ Hydrographs

SMS 11.0 Output Data

Post Processing

Equivalent to 495 HEC-RAS Unsteady Models

Objective 3

Interactive Bridge Flooding

Predictive Flooding Atlas

VDOT Bridge Data

USGS

NOAA

WMS 9.0 GIS Data

Terrain (Tin) Rivers & Streams

Watersheds

NOAA Point Rainfall Data

NOAA NEXRAD Data

HEC-HMS Sub-Watersheds Rainfall Data

Sub-Watersheds

Rainfall Data
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

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>CPU</th>
<th>RAM (GB)</th>
<th>GPU</th>
<th>GPU RAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Desktop Dell OptiPlex 990</td>
<td>3.40 GHz, 4 Core(s)</td>
<td>16</td>
<td>NVIDIA Quadro K2000</td>
<td>2.00 GB, 384 SMX CUDA parallel processing cores</td>
</tr>
<tr>
<td>M2</td>
<td>Desktop Viz Lab 3.20GHz, 3201 MHz, 6 Core(s)</td>
<td>64</td>
<td>Two units of NVIDIA GeForce GTX TITAN</td>
<td>6.00 GB, 2688 CUDA parallel processing cores for each</td>
<td></td>
</tr>
</tbody>
</table>

### 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>
</tr>
</thead>
<tbody>
<tr>
<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>
<td>$0.767</td>
</tr>
<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>
</tr>
<tr>
<td>P2</td>
<td>p2.xlarge</td>
<td>1</td>
<td>4</td>
<td>61</td>
<td>12 (GiB)</td>
<td>EBS</td>
<td>$1.084</td>
</tr>
<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>
</tr>
<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>
</tr>
</tbody>
</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>
</tr>
</thead>
<tbody>
<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>
</tr>
<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=hrrcrefimage&width=859&model=hrrr&title=HRRR
Objective 1: Rainfall Forecast Data Automation and Preparation

- Rainfall automation workflow
- NetCDF File/ASC Grids
- Time Series
- HEC-HMS Generated Hydrographs
- TUFlow Model with Rainfall Data
- Subwatersheds
## Objective 2: Speeding Up the TUFLOW Model

| Model Specifications | Original Model | New Model | | | |
|----------------------|---------------|-----------|---|---|
|                      | OM            | R1        | R2|
| Machine              | M1            | M1        | M2|
| TUFLOW Release       | 2013-12-AC    | 2016-03-AA | 2016-03-AA|
| Precision            | Single        | Single    | Single|
| Time-step (sec)      | 10            | 10        | 10|
| Output Cell Size (m) | 25            | 25        | 25|
| Processing Units     | CPU           | CPU       | GPU|
| No. of GPUs          | -             | -         | 2|
| **Running Time (hr)**| **105.7**     | **120**   | **2.2**|

120 to 2.2 hr (55x) speed up for a 15 day model simulation (for Hurricane Sandy)
Running the TUFLOW Model on AWS Instances

<table>
<thead>
<tr>
<th>EC2 Instance</th>
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<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

---

![Graph](image-url)
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 Maps
EC2
Google API
Geosheets
Build-up the Flood Warning Model Workflow Through AWS

1. **Start Model Run Manually**
   - **AWS EC2 g2.8/p2.8**
     - **Windows OS**
     - **Model components**

2. **Request and Retrieve Rainfall Data**
   - **NOAA NOMADS**

3. **Model Outputs**
   - **AWS S3 Bucket**

4. **Monitor Rainfall Data**
   - **Request Archived Outputs**

5. **Start If Rainfall Recorded**
   - **AWS EC2 t2.micro**
     - **Linux OS**
     - **Trigger/Visualization**

6. **Send Alerts Via Email**
   - **Access Current and Archived Flooded Locations Information**
   - **Send Alerts Via Email**
   - **Access Current Flooded Locations Information**

7. **Regular User**
   - **Decision Maker**
## Decision Maker/Regular Users and EC2 t2.micro Instance

### AWS EC2 t2.micro
- Linux OS
- Trigger/Visualization

### Regular User
- Access Current Flooded Locations Information

### Decision Maker
- Send Alerts Via Email
- Access Current and Archived Flooded Locations Information

### Nginx
- Index.html → Google maps API
- Log.html → Trackback
- Login.html → Administrator login

### Flask
- Server.py
  - Static/
    - 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

### Design
- 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
Legend
- Tide Gauge
- Rain Gauge
- Shallow Wells
- Flood locations

Data from City of Norfolk and HRSD
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
- Wde = 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
- Wde = 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
- Wde = 10mph
Increasing flooding?

Result of Higher GW Table?
Legend

Flood Occurrences
- 0
- 1 - 19

Elevation Value
- High: 47.4813
- Low: -15.1491
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)

- 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
Different Machine Learning Algorithms

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

True Positive Rate:
- knn: 92.50%
- svm: 93.50%
- dt: 97.20%
- rf: 98.10%
- logit: 91.60%

False Positive Rate:
- knn: 7.30%
- svm: 3.70%
- dt: 7.80%
- rf: 3.40%
- logit: 5.90%
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

Amplifier

Piezo Element
Summary

• Use of **the cloud** to automate and speedup **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

This work was supported by research grants and contracts provided by the Virginia Department of Transportation through the Virginia Transportation Research Council and the US Department of Transportation through the Mid-Atlantic Transportation Sustainability Center.