A Multi-Scale Ensemble-based Framework for Predicting Compound Coastal-Riverine Flooding

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Hydrosystem modeling and interactions between different components is known to be a complex process.
Introduction

Annual total precipitation changes for 1991-2012 compared to the 1901-1960 average
Cumulative changes in relative sea level from 1960 to 2015 at tide gauge stations along U.S. coasts

http://nca2014.globalchange.gov/
Growing Population and Economic Assets in Urban Watersheds
Increase in Imperviousness
Increase in Imperviousness
The American Society of Civil Engineers recently awarded dam infrastructure in the United States a grade of “D”
Historical Pics

A 5 mega-byte IBM hard drive being loaded onto an airplane in 1956. It weighed more than 2,000 pounds.

Advancements in Computational Power, Data Collection and Modeling Approaches

Before

Stevens 1,320-core supercomputer

Now
Objectives and Study Area

- The overarching objective is to forecast compound flooding (coastal-hydrologic) during extreme flood events in the Hudson River basin.
- Evaluate how meteorological uncertainties propagate through hydrologic/coastal/hydrodynamic models and translate to uncertainties in flood inundation extents in urban areas.
- Hudson River basin
- Drainage area: 36,000 km²
- Average discharge: 620 m³/s
Objectives and Study Area

• Compound storm surge and hydrologic flooding from Hurricane Irene (2011)
• Freshwater from Irene pushed the salt front beyond the mouth of the river
• One of the rare times when the Hudson River was “fresh” from end to end

Observed water levels

Hudson River at Albany NY
Water level relative to NAVD88 Datum (ft). Times in ET.

-4 -3.34 -2 -1 0 2 3 4

08/23 08/24 08/25 08/26 08/27 08/28 08/29 08/30 08/31

Major flood level: 14.24
Moderate flood level: 12.24
Minor flood level: 10.24
Near flood level: 8.24
Blowout level: 3.34
Multi Scale Ensemble-based Forecasting Framework

Global and Regional Weather Models

Hydrologic and Coastal Models

Local Scale Models

<table>
<thead>
<tr>
<th>Meteorological Forcing</th>
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<tbody>
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<td>Ensemble members</td>
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<td>(51)</td>
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- Telescoping capabilities across scales
- 1,320-core supercomputer
- 72-96 hours lead time forecasts with four cycles per day
- Guide decision making where response strategies take place

NYHOPS is Built using the Stevens Estuarine and Coastal Ocean Hydrodynamic Model (sECOM; Blumberg and Mellor, 1987)
3-Hourly gridded precipitation obtained from the North American Regional Reanalysis (NARR) was used to validate the model.
Simulated River Discharge for Hurricane Irene [2011]

Hydrologic parameters optimization using Monte Carlo simulations

Observations obtained from USGS discharge gages
Hydrologic Forecasts Forced with Ensemble Inputs

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Ensembles Streamflow Prediction
[Hudson River basin Hurricane Irene retrospective forecast using GEFS]

Color-coded threshold exceedance diagram for hurricane Sandy retrospective forecasts at 6-hr intervals using the major flood threshold

Saleh et al., 2016, A retrospective streamflow ensemble forecast for an extreme hydrologic event: a case study of Hurricane Irene and on the Hudson River basin, Journal of Hydrology and Earth System Sciences (HESS), 20, 2649-2667
Uncertainty Propagation to Hydrologic and Coastal Models [Hurricane Hermine Example]

Model Performance Example

For this event and At this station

- NOAA AHPS
- ECMWF ENS Control
- GEFS Control
- SREF NMB Control
- Median HYDRO NYHOPS
- GFS Deterministic

Rondout Creek at Rosendale, NY
Drainage area = 383 mi²
Station ID: 1367500

Minor flood level

Observed AHPS Median

0-hr 96-hr
Example of Coastal Component Ensemble Outputs

NYHOPS

Meteorological Forcing

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Deterministic members

NAMx2, GFS(+e), ECMWF.

- 2016-01-10 Flood Event was Predicted 3 days in advance.
- Ensemble usually envelopes the observations well

NYHOPS v3 124-member Ensemble Results from 20160108/03z cycle

Georgas et al., 2016
www.stevens.edu/SFAS
www.stevens.edu/SFAS

Urban Ocean Observatory at Davidson Laboratory

Stevens Flood Advisory System
Forecast Period: 2016-01-23 10:00 AM through 2016-01-26 10:00 AM ET

Non-Tidal Stations

THE PORT AUTHORITY OF NEW YORK & NEW JERSEY

Real time dual water level sensors

STEVENS INSTITUTE of TECHNOLOGY
• Combined influence of riverine and tidal components
• Tidal wetlands
• Highly urbanized watershed, more than 2 million people
• Critical facilities (e.g., Teterboro Airport, NJ Transit, Passaic Valley Sewerage Commission)
• Oradell reservoir, storage capacity of 14,000 acre-feet
• Vulnerable to inland and coastal flooding
• **Modeling Approach: integrated ocean-meteorology-hydrology-hydraulics model suite**
Hurricane Irene [August 2011]

Hydrological component D/S of Oradell Reservoir

Coastal & meteorological component [Open water]

Reservoir peak water level = 8 m

Observed water level

Observed Precipitation in Newark Airport

Acc. precipitation (mm)

Discharge (cms)
Hurricane Sandy [October, 2012]

Reservoir water level = 5.5 m

Hurricane Sandy flooding extent (USGS)
Hurricane Sandy Simulation

• 2D-Hydrodynamic model (HEC-RAS 5) forced with hydrologic and coastal boundary conditions
• High resolution surveyed bathymetry (UDEM)
• 1-3 m Lidar (NJMC & USGS, 2014)
• > 600 river surveyed cross sections
• Hydraulic structures
• Tidal wetlands
• Hydrodynamic model resolution ~10 m
Validation against USGS flood extension map, a network of high water marks and time series sensors that were deployed by USGS prior to hurricanes Irene and Sandy. 

High water marks source: http://stn.wim.usgs.gov/FEV/#Sandy
Ensemble based retrospective forecasts using GEFS meteorological forcing

72-Hours before Sandy

48-Hours before Sandy

24-Hours before Sandy

- Observations
- Uncertainty envelope
- Ensemble Members
- 5th, 50th and 95th percentile predictions
- Major flood threshold

Water level above NAVD88 (m)

Date

Water level above NAVD88 (m)

Date

Water level above NAVD88 (m)

Date

Water level above NAVD88 (m)

Date

Water level above NAVD88 (m)

Date

Water level above NAVD88 (m)

Date
Spatial validation with USGS Reanalysis Flood Extent Map

- Probability of Detection (POD) = hits / (hits + misses)
- False-Alarm Ratio (FAR) = false alarms / (hits + false alarms)
- Critical Success Index (CSI) = hits / (hits + misses + false alarms)

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<th>CSI</th>
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<tr>
<td>Sandy 5%</td>
<td>23%</td>
<td>0.20%</td>
<td>23%</td>
</tr>
<tr>
<td>Sandy 50%</td>
<td>74%</td>
<td>1%</td>
<td>74%</td>
</tr>
<tr>
<td>Sandy 95%</td>
<td>95%</td>
<td>7%</td>
<td>89%</td>
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Telescoping capabilities to the operational level of individual facilities

Sandy minus 72hrs ensemble: “Expect at least this much water over ground”
Sandy minus 72hrs ensemble: “Most likely inundation over ground”
Sandy minus 72hrs ensemble: “Potential for this much water over ground”
Telescoping capabilities to the operational level of individual facilities

- Sandy verified close to the highest percentile (95%) of the -72hr predictions in NY/NJ Harbor when NCEP GEFS reforecasts were used!

Sandy as it happened (based on Observed Levels)
Summary & Future Work

- A multi-scale ensemble based hydrologic-coastal-hydrodynamic framework to predict flooding

- This operational flood forecasting framework provides increased fidelity, yielding insights on short-term flood forecasts, mitigation strategies and best management practices

- Uncertainties cascading from one modeling component to another may impact predictive performance and lead to false flood alerts and missed flooding events

- The practice of using ensembles was advantageous in providing envelopes of uncertainty in simulated inundation extents but it may have limitations when predicting peak timing and magnitude

- Uncertainty in hydrologic modeling approach (e.g. fully distributed model vs. semi-distributed) and modeling parameters vs. uncertainty in meteorological inputs

- Improve reservoirs and groundwater components representation

- Feedbacks from different components (Two way coupling)
Thank You!

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