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

Firas Saleh, Venkatsundar Ramaswamy, Nickitas Georgas, Alan Blumberg and Julie Pullen

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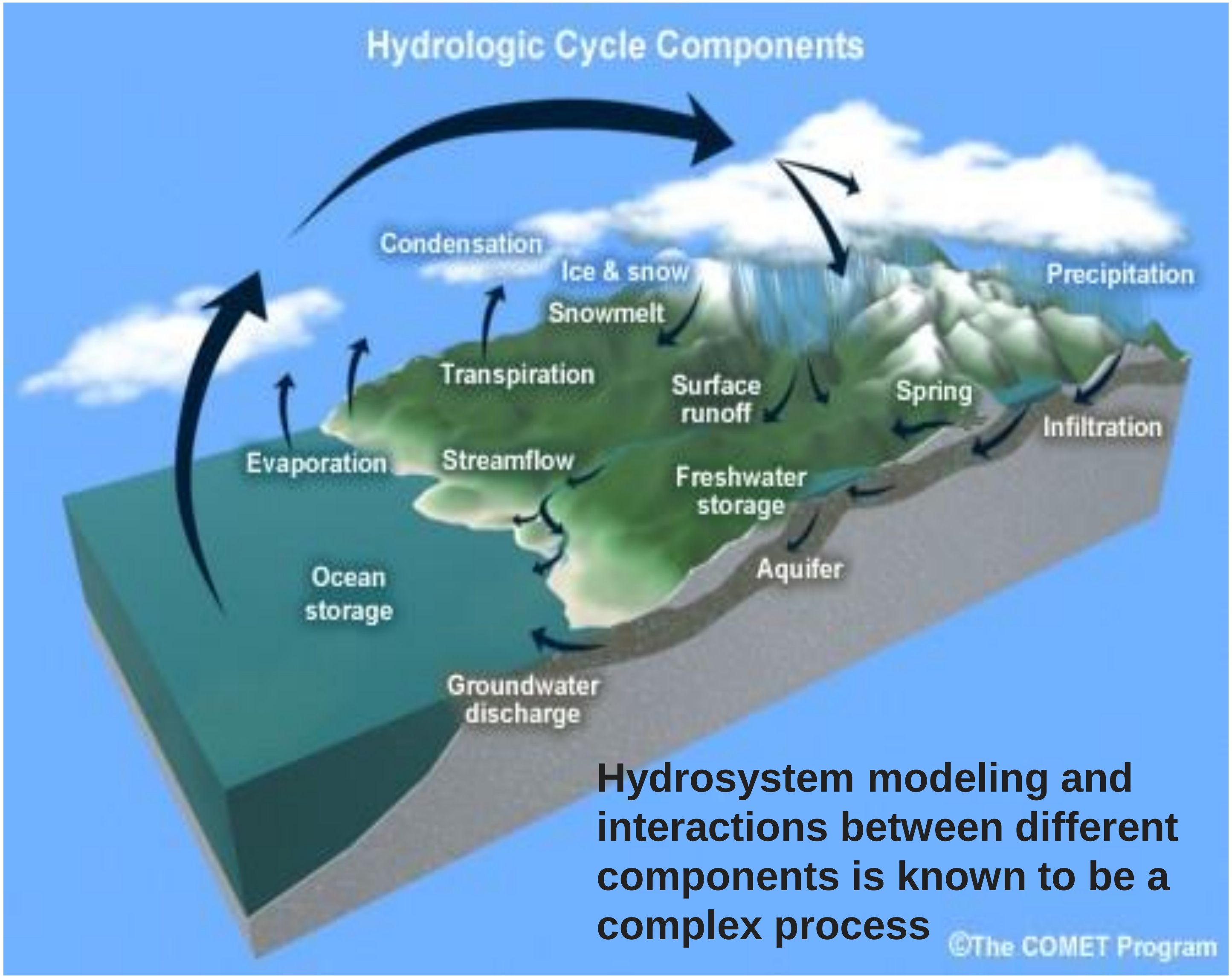
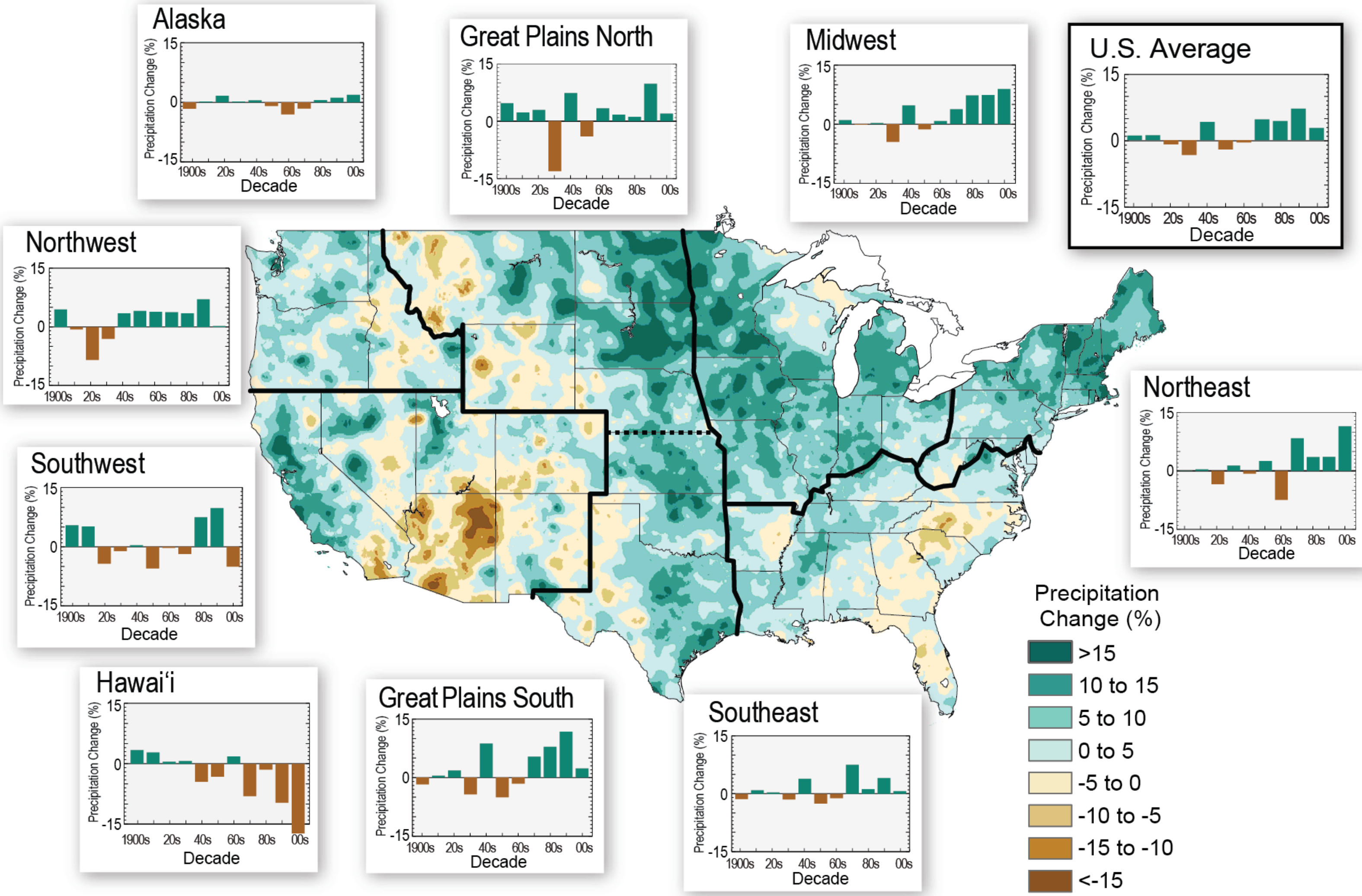
Introduction



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

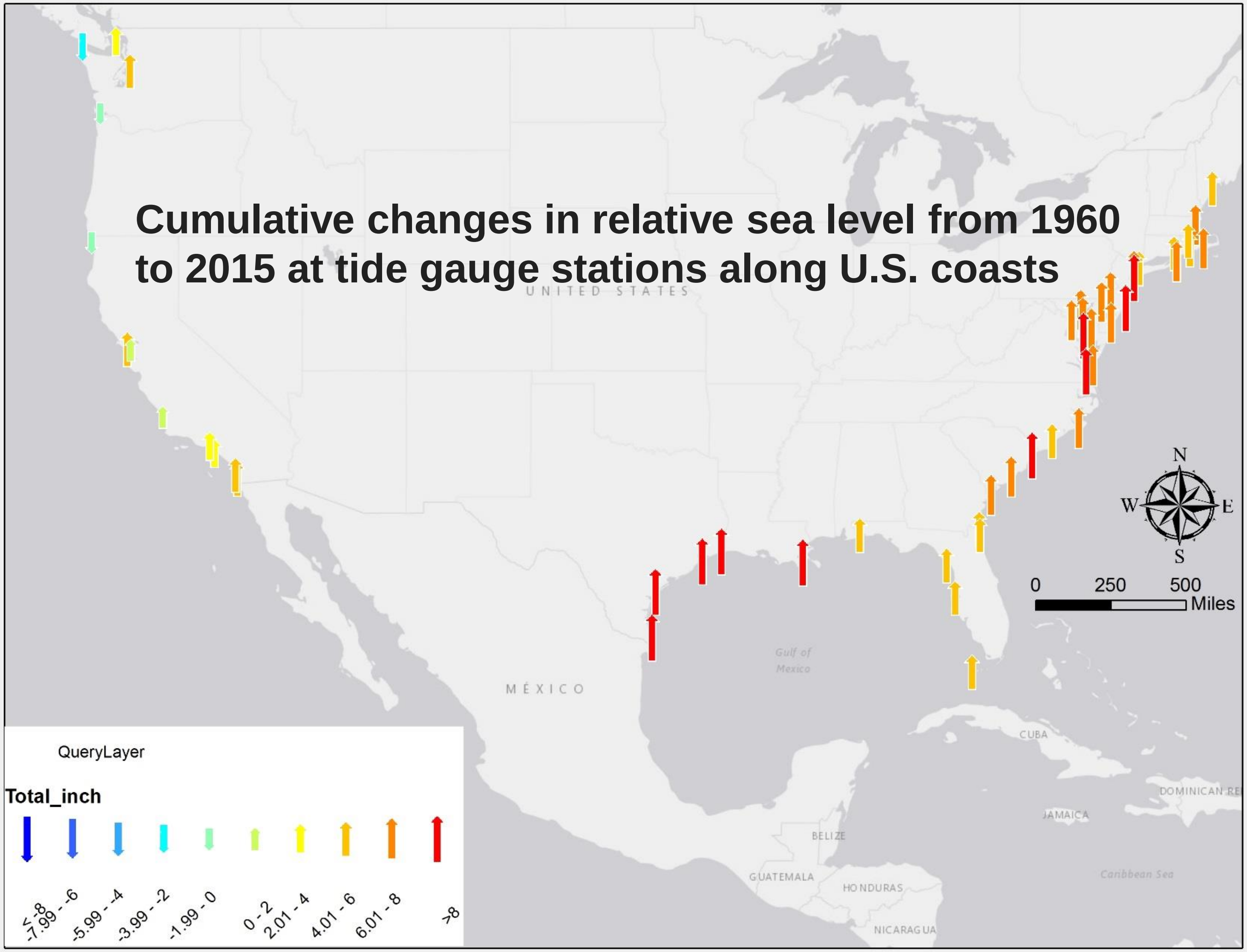
Introduction

Annual total precipitation changes for 1991-2012 compared to the 1901-1960 average



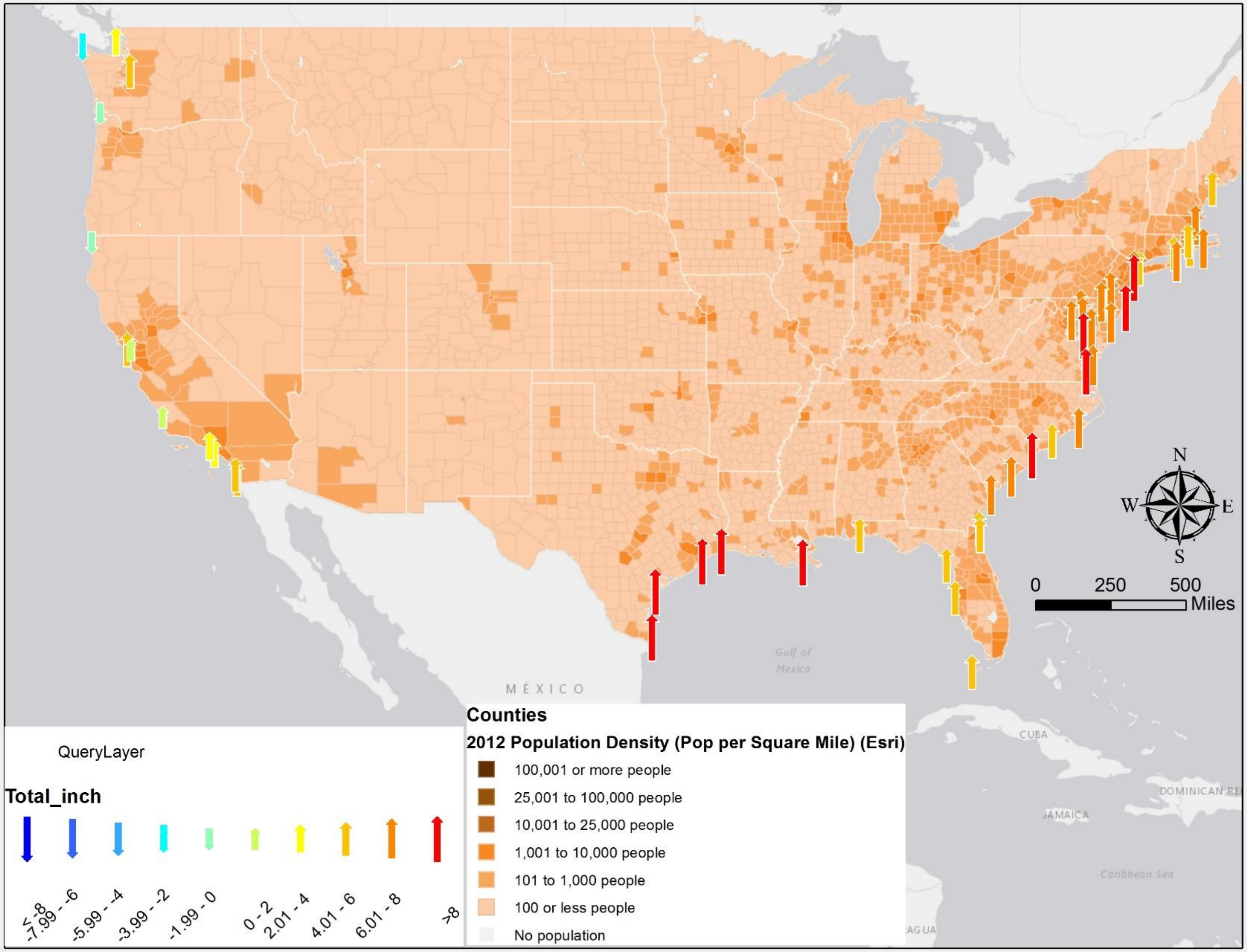
http://nca2014.globalchange.gov/

Introduction

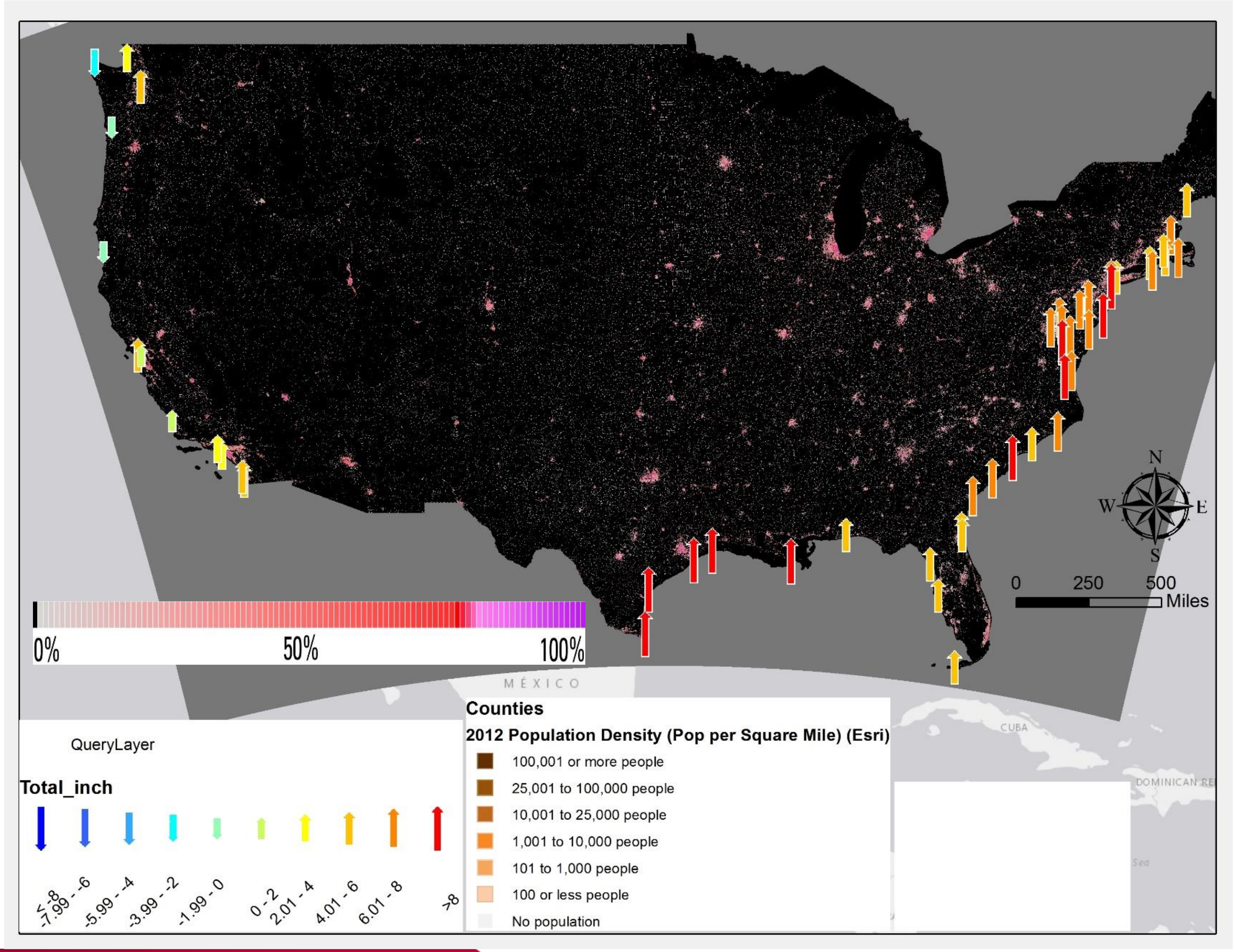


http://nca2014.globalchange.gov/

Growing Population and Economic Assets in Urban Watersheds



Increase in Imperviousness



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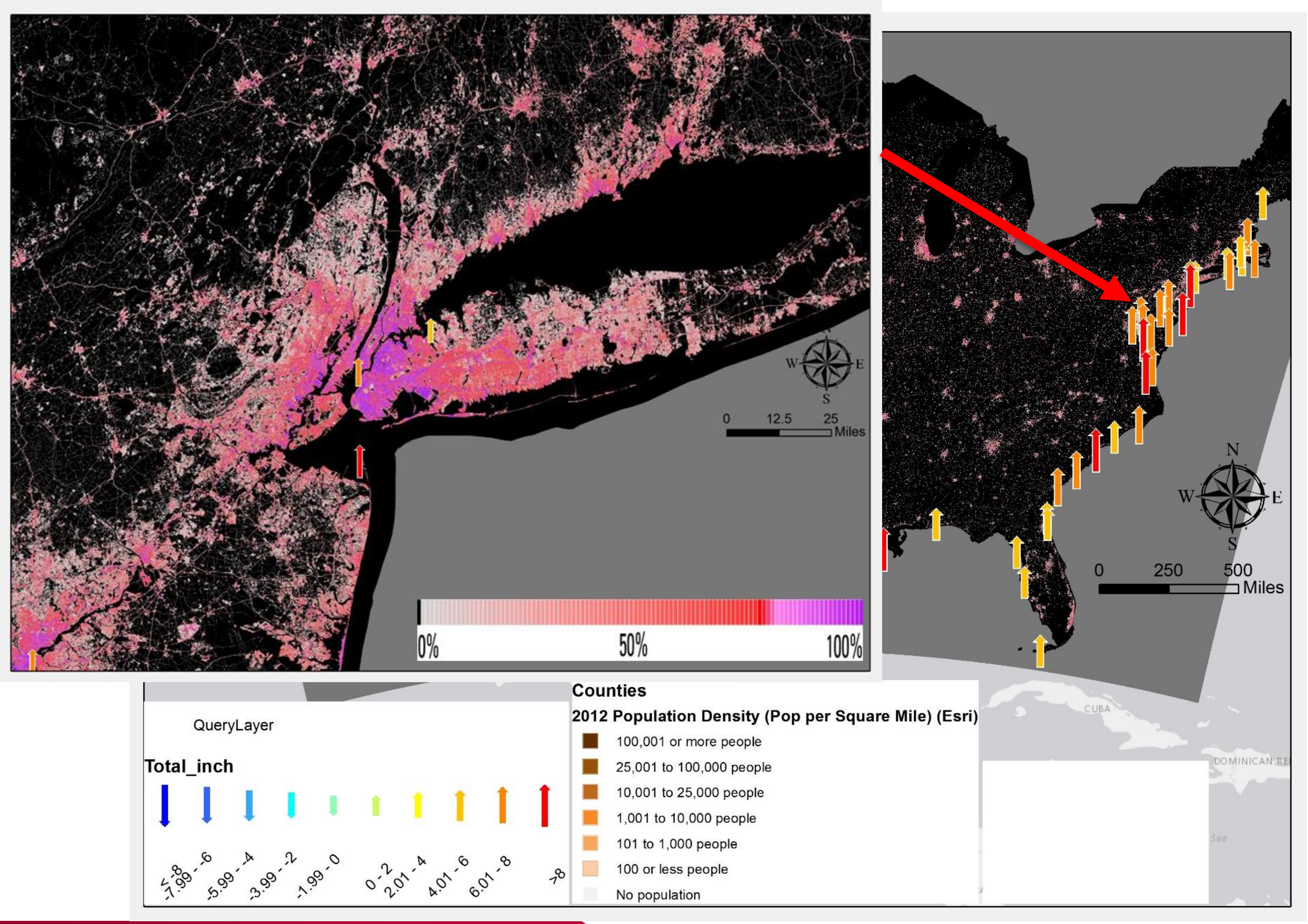
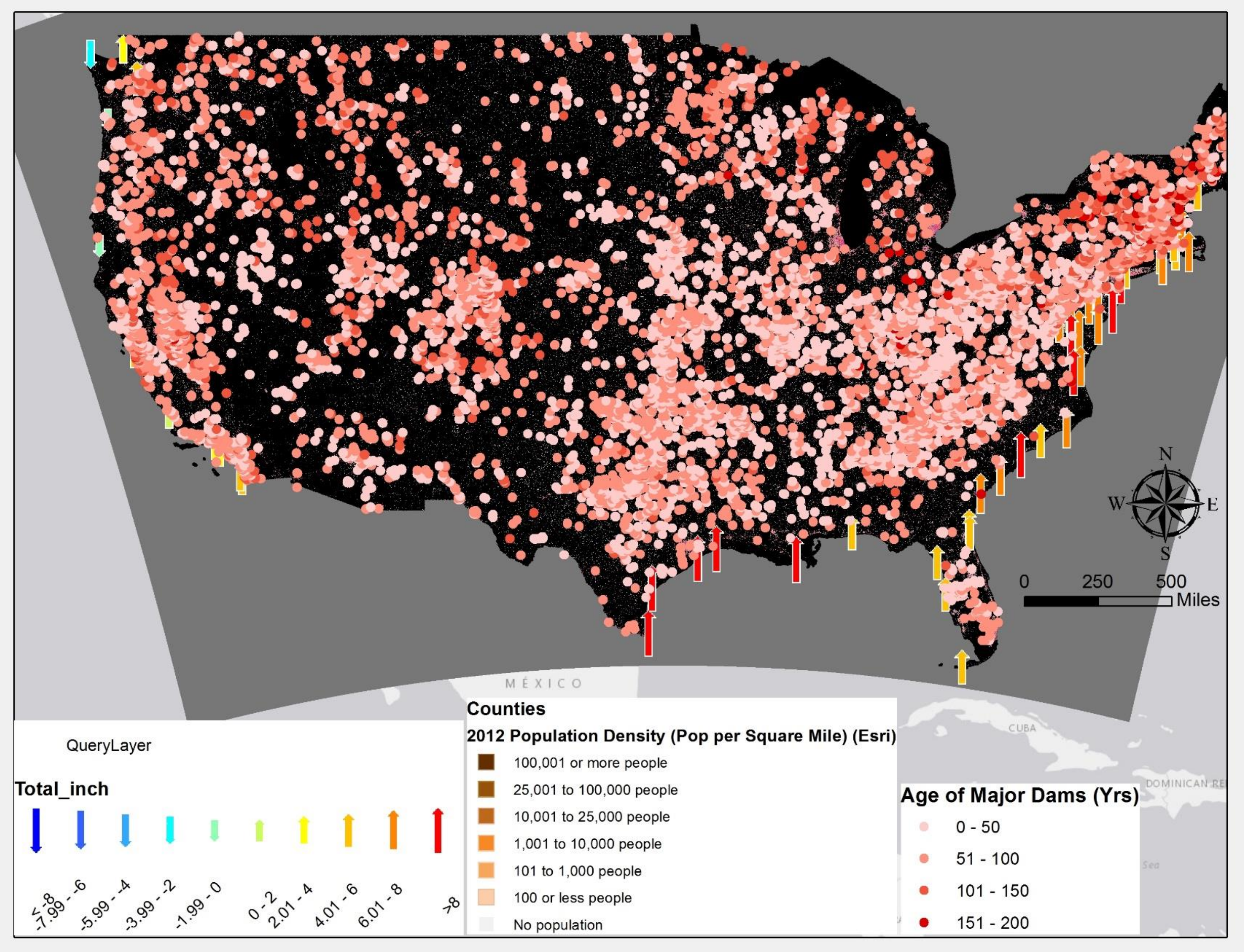


Aging Infrastructure Designed Assuming Climate Stationarity



The American Society of Civil Engineers recently awarded dam infrastructure in the United States a grade of "D"

Advancements in Computational Power, Data Collection and Modeling Approaches

Before

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

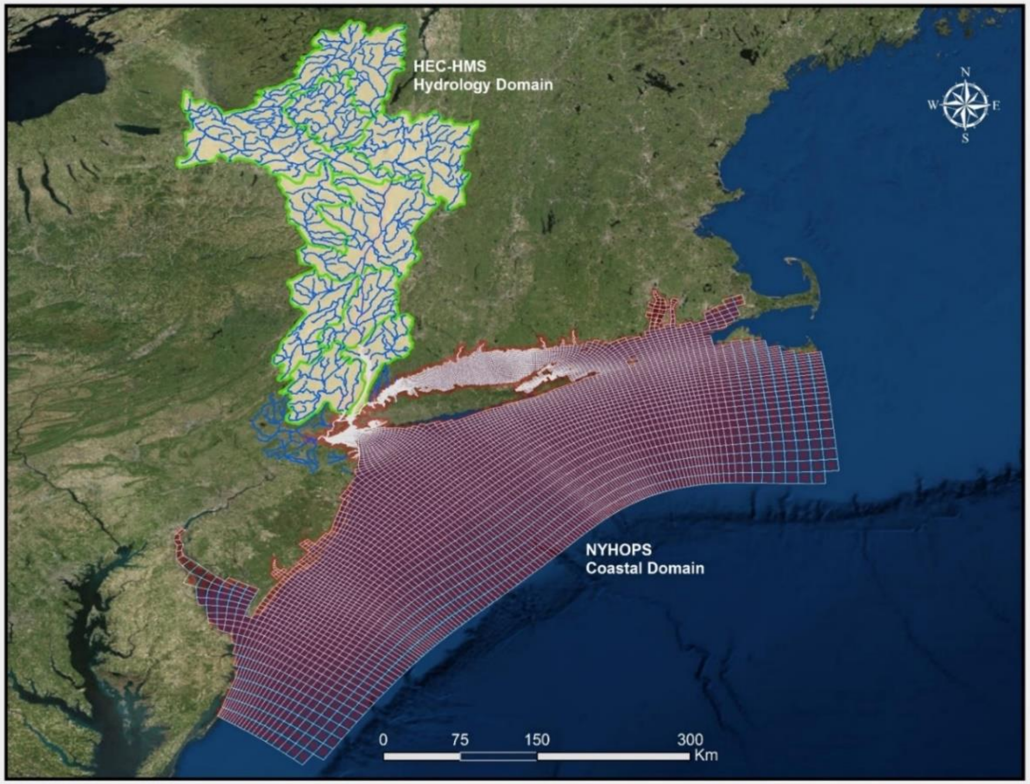
@HistoricalPics

Now

Stevens 1,320-core supercomputer

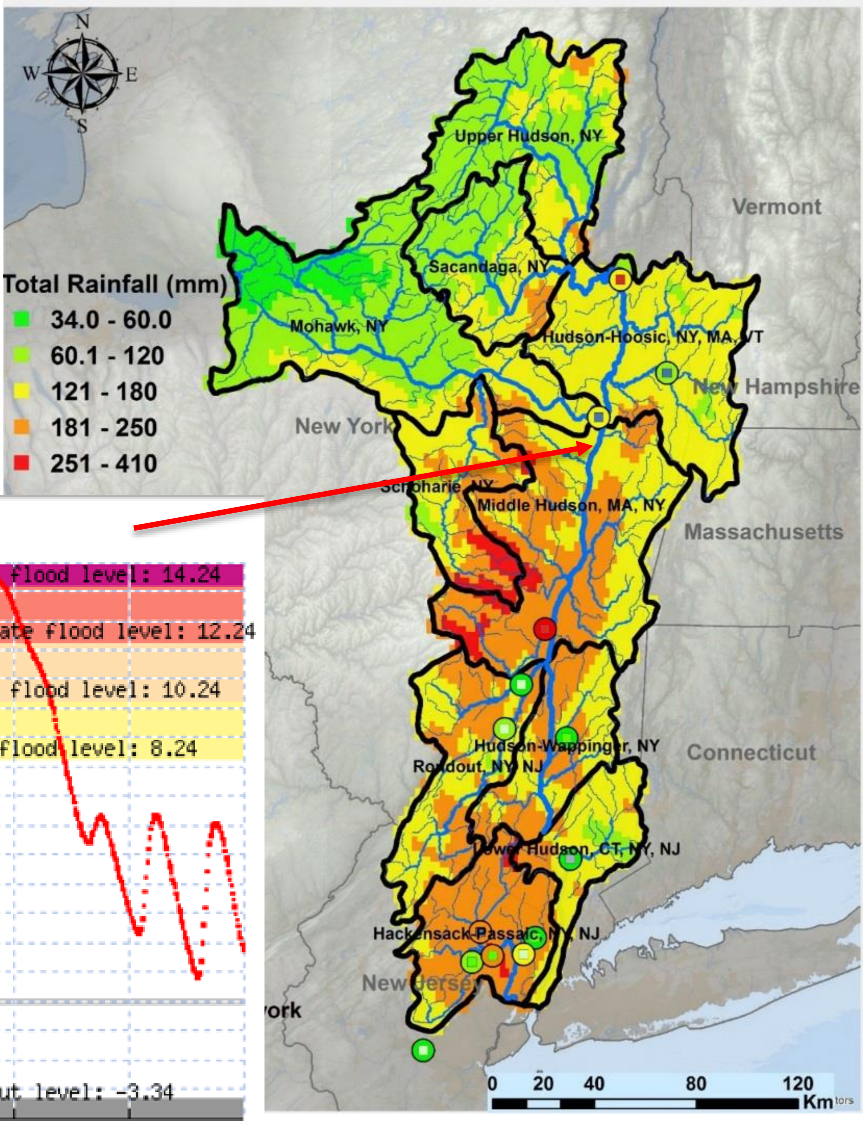
Objectives and Study Area

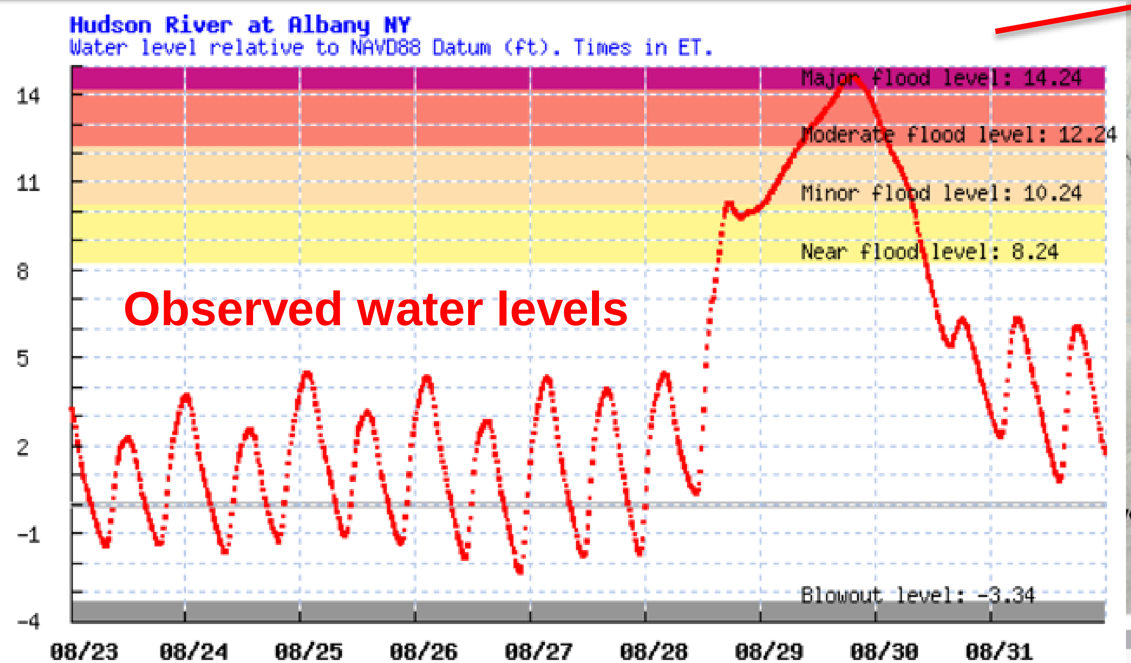
- The overarching objective is to forecast compound flooding (coastal-hydrologic) during extreme flood events in the Hudson River basin
- Evaluate how meteorological uncertainties propagate through hydrologic/coastal/hydrodynamic models and translate to uncertainties in flood inundation extents in urban areas
- Hudson River basin
- Drainage area: 36,000 km^2
- Average discharge: 620 m^3/s



Objectives and Study Area

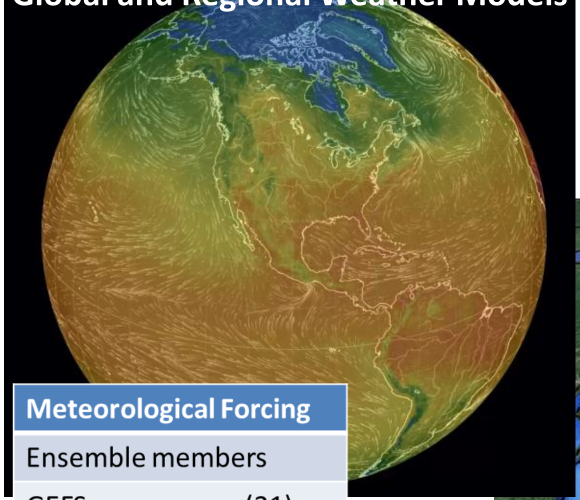
- Compound storm surge and hydrologic flooding from Hurricane Irene (2011)
- Freshwater from Irene pushed the salt front beyond the mouth of the river
- One of the rare times when the Hudson River was “fresh” from end to end





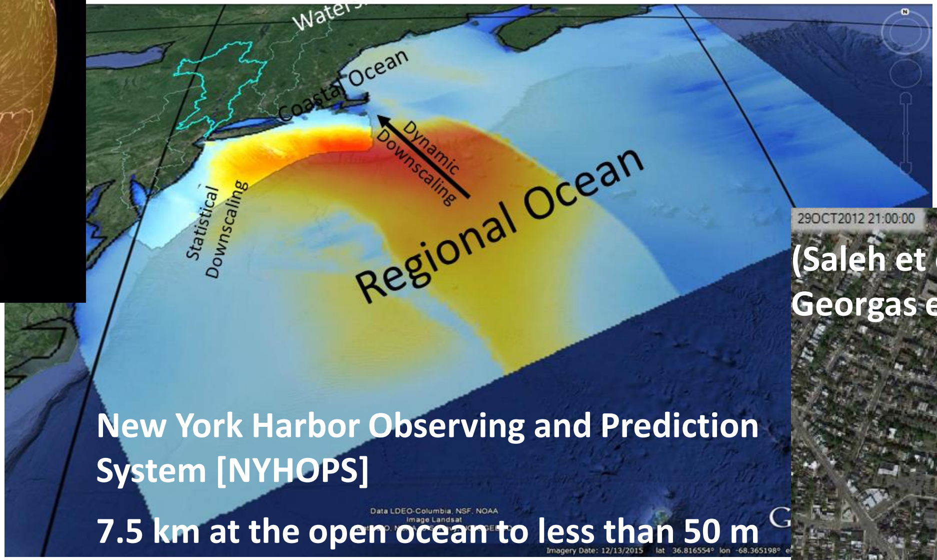
Multi Scale Ensemble-based Forecasting Framework

Global and Regional Weather Models



Meteorological Forcing	
Ensemble members	
GEFS	(21)
ECMWF	(51)
CMC	(21)
SREF	(26)
Deterministic members	
NAMx2,GFS(+e),ECMWF.	

Hydrologic and Coastal Models



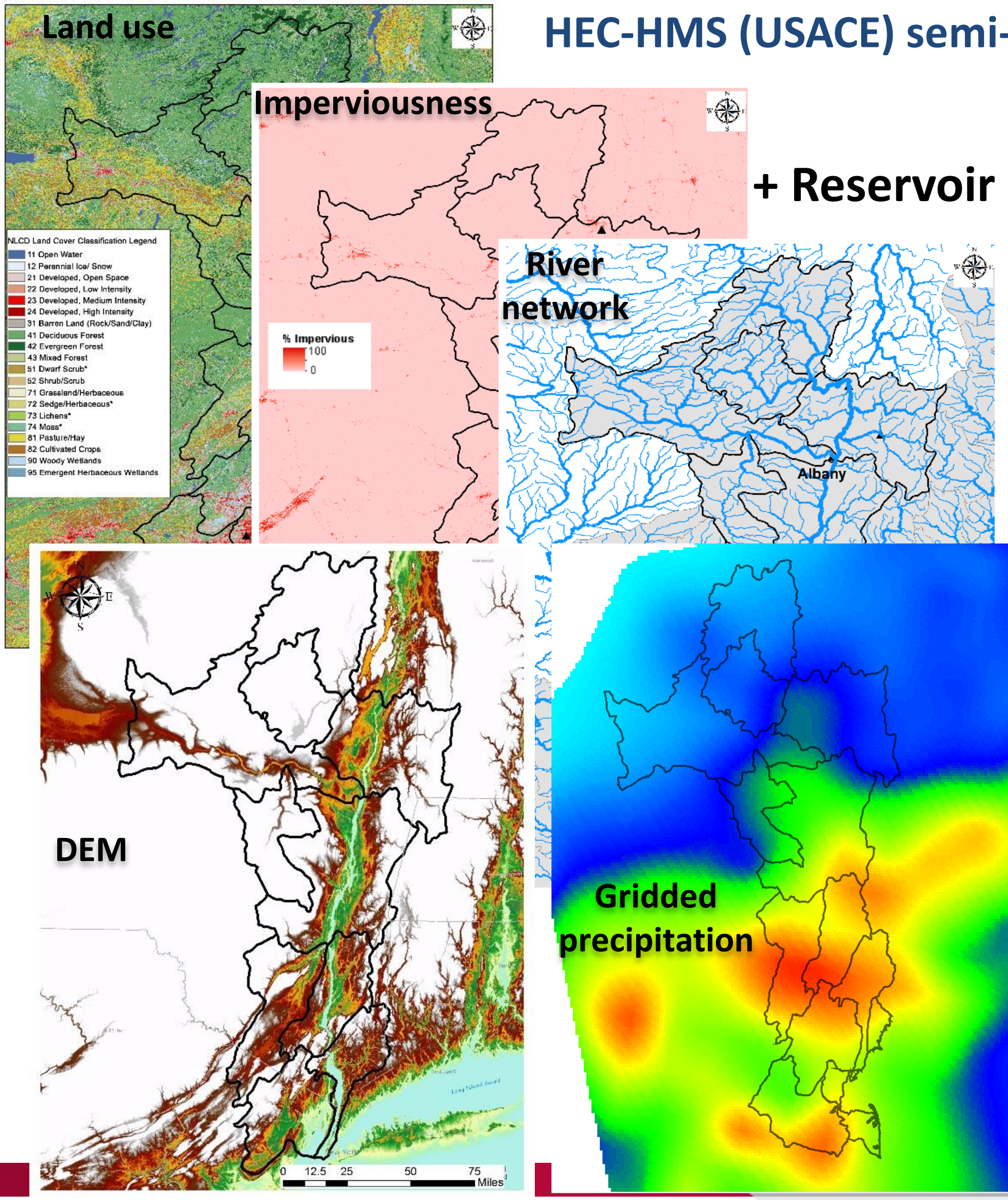
Local Scale Models

- 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

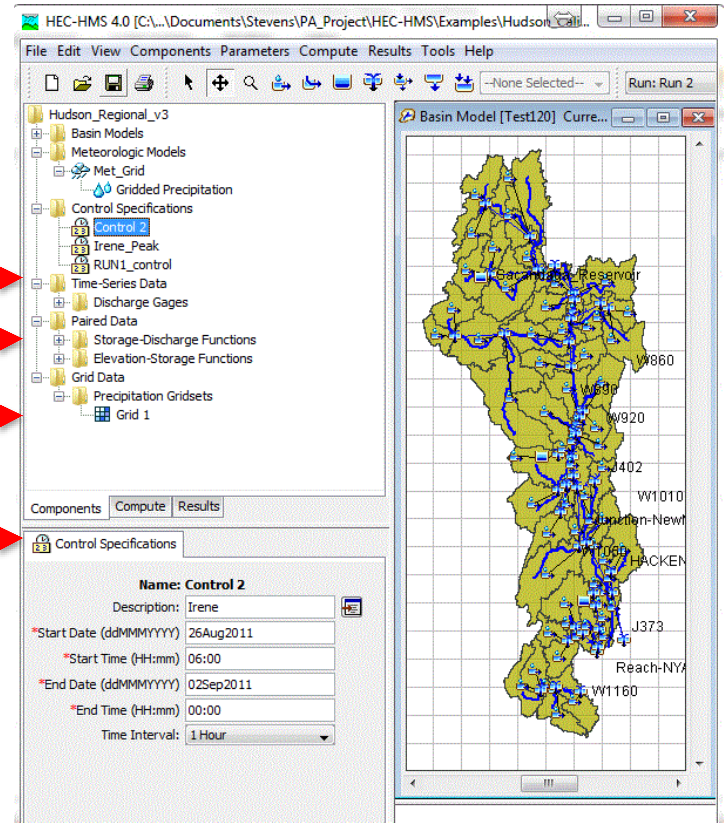
NYHOPS is Built using the Stevens Estuarine and Coastal Ocean Hydrodynamic Model (sECOM; Blumberg and Mellor, 1987]

Hudson Hydrologic Model Setup

HEC-HMS (USACE) semi-distributed hydrological model

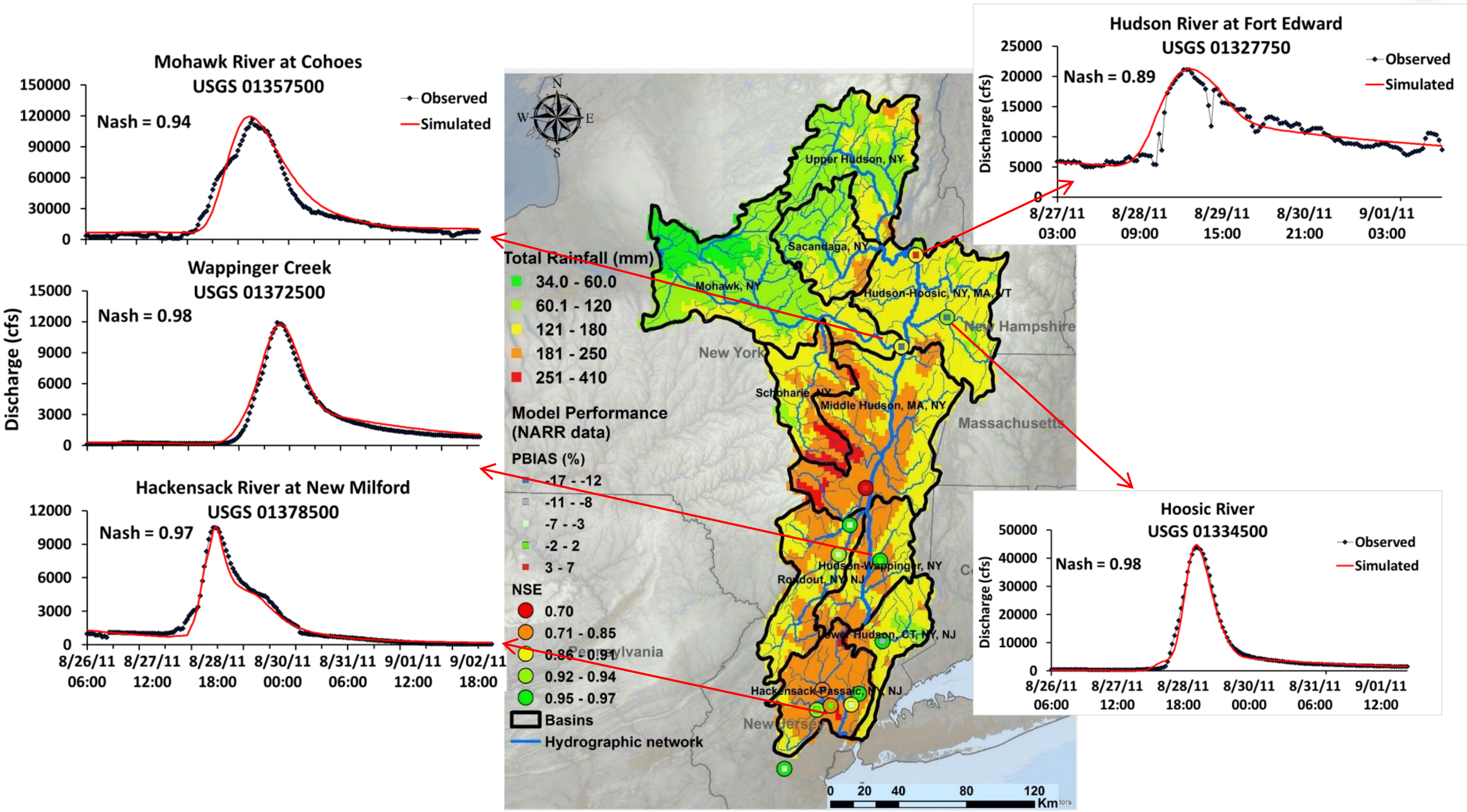


+ Reservoir data



3-Hourly gridded precipitation obtained from the North American Regional Reanalysis (NARR) was used to validate the model

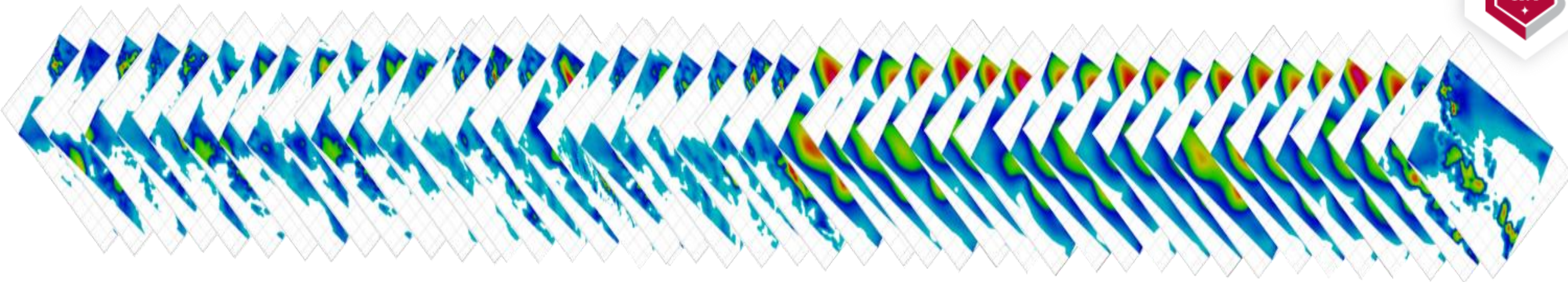
Simulated River Discharge for Hurricane Irene [2011]



Hydrologic parameters optimization using Monte Carlo simulations

Observations obtained from USGS discharge gages

Hydrologic Forecasts Forced with Ensemble Inputs



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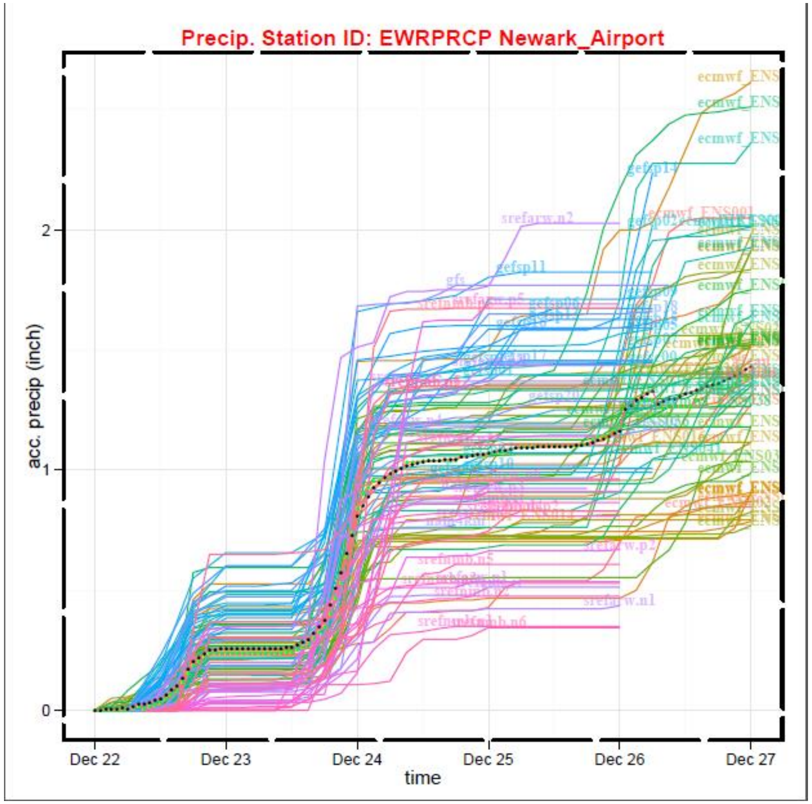
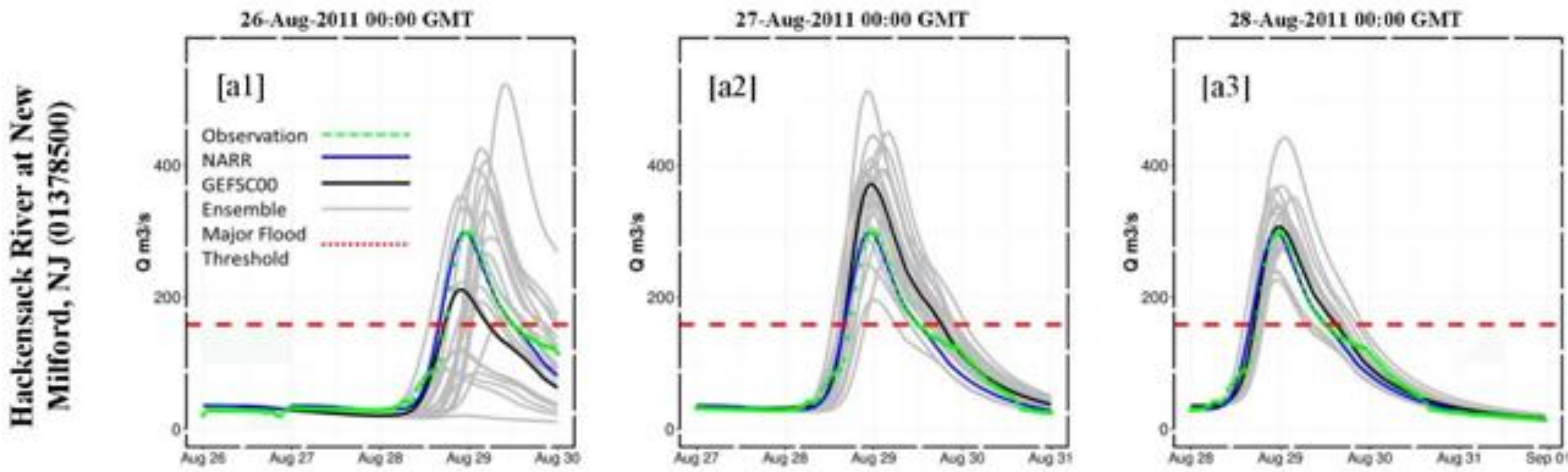


Ensembles Streamflow Prediction

[Hudson River basin Hurricane Irene retrospective forecast using GEFS]

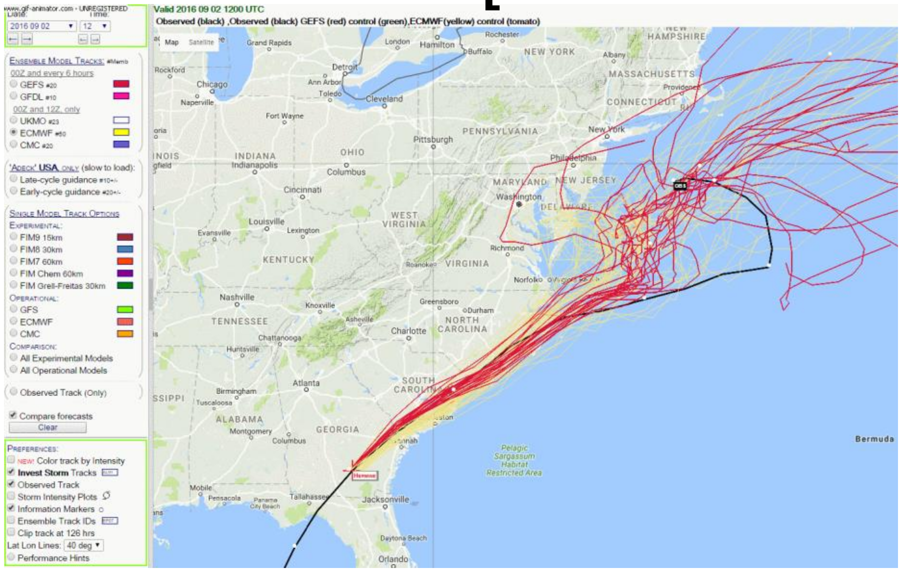


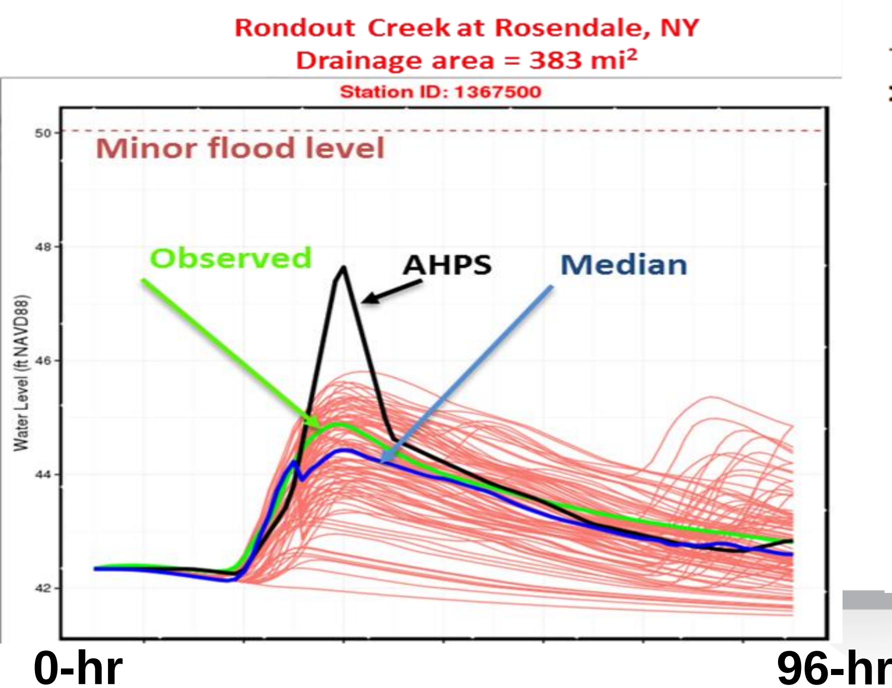
Station & major flood threshold	Time / Forecast hr	8/26/2011 0:00	8/26/2011 6:00	8/26/2011 12:00	8/26/2011 18:00	8/27/2011 0:00	8/27/2011 6:00	8/27/2011 12:00	8/27/2011 18:00	8/28/2011 0:00	8/28/2011 6:00	8/28/2011 12:00	8/28/2011 18:00	8/29/2011 0:00	8/29/2011 6:00	8/29/2011 12:00	8/29/2011 18:00	8/30/2011 0:00	8/30/2011 6:00	8/30/2011 12:00	8/30/2011 18:00	8/31/2011 0:00	8/31/2011 6:00	8/31/2011 12:00	8/31/2011 18:00
Hackensack River at New Milford, NJ (01378500) 158 m3/s	08/26/2011 t00	0	0	0	0	0	0	0	0	0	0	14	52	67	62	48	33								
	08/27/2011 t00					0	0	0	0	0	0	62	100	100	95	86	48	5	0	0	0				
	08/28/2011 t00									0	0	43	100	100	100	81	14	0	0	0	0	0	0	0	0
	Observed																								
Passaic River at Little Falls, NJ (01389500) 283 m3/s	08/26/2011 t00	0	0	0	0	0	0	0	0	0	0	5	24	67	67	67	67								
	08/27/2011 t00					0	0	0	0	0	0	19	90	100	100	100	100	100	100	100	100				
	08/28/2011 t00									0	0	5	86	100	100	100	100	100	100	100	100	100	100	100	100
	Observed																								

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

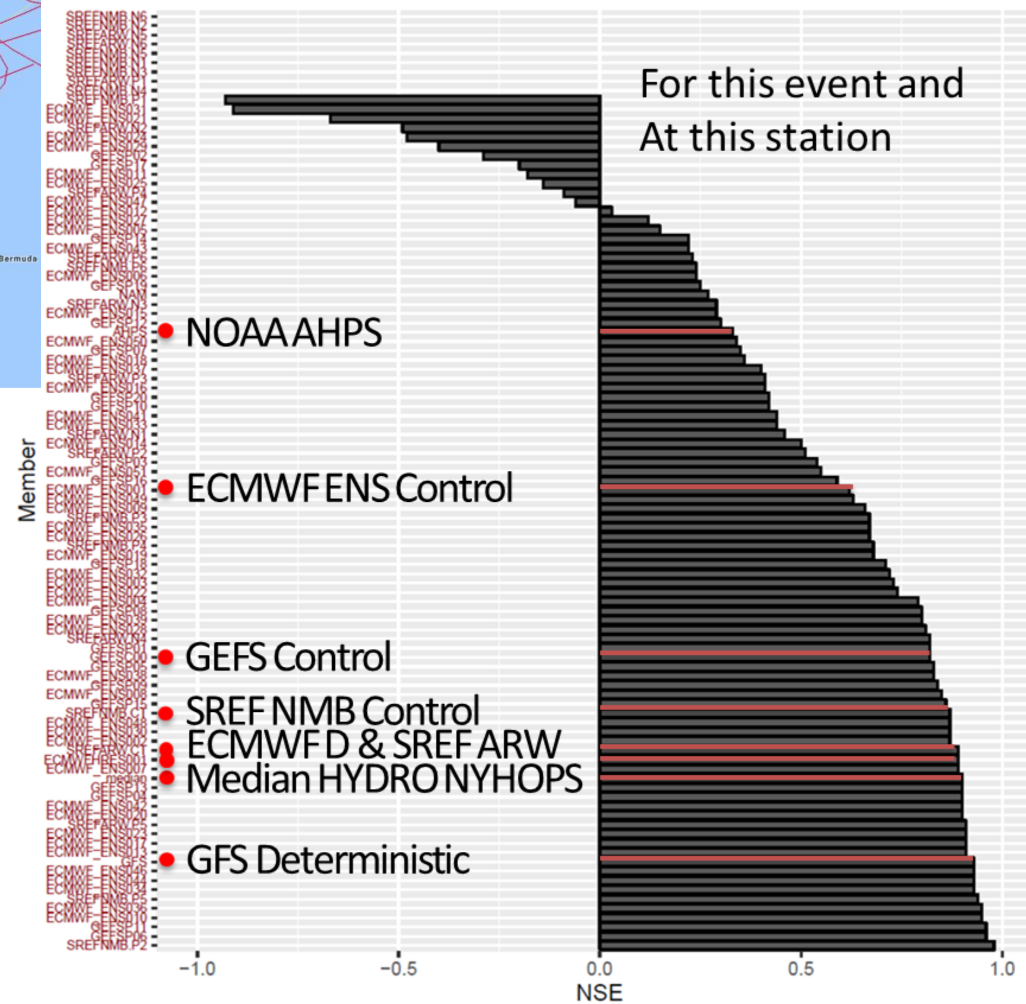
Saleh et al., 2016, A retrospective streamflow ensemble forecast for an extreme hydrologic event: a case study of Hurricane Irene and on the Hudson River basin, ***Journal of Hydrology and Earth System Sciences (HESS)***, 20, 2649-2667

Uncertainty Propagation to Hydrologic and Coastal Models [Hurricane Hermine Example]





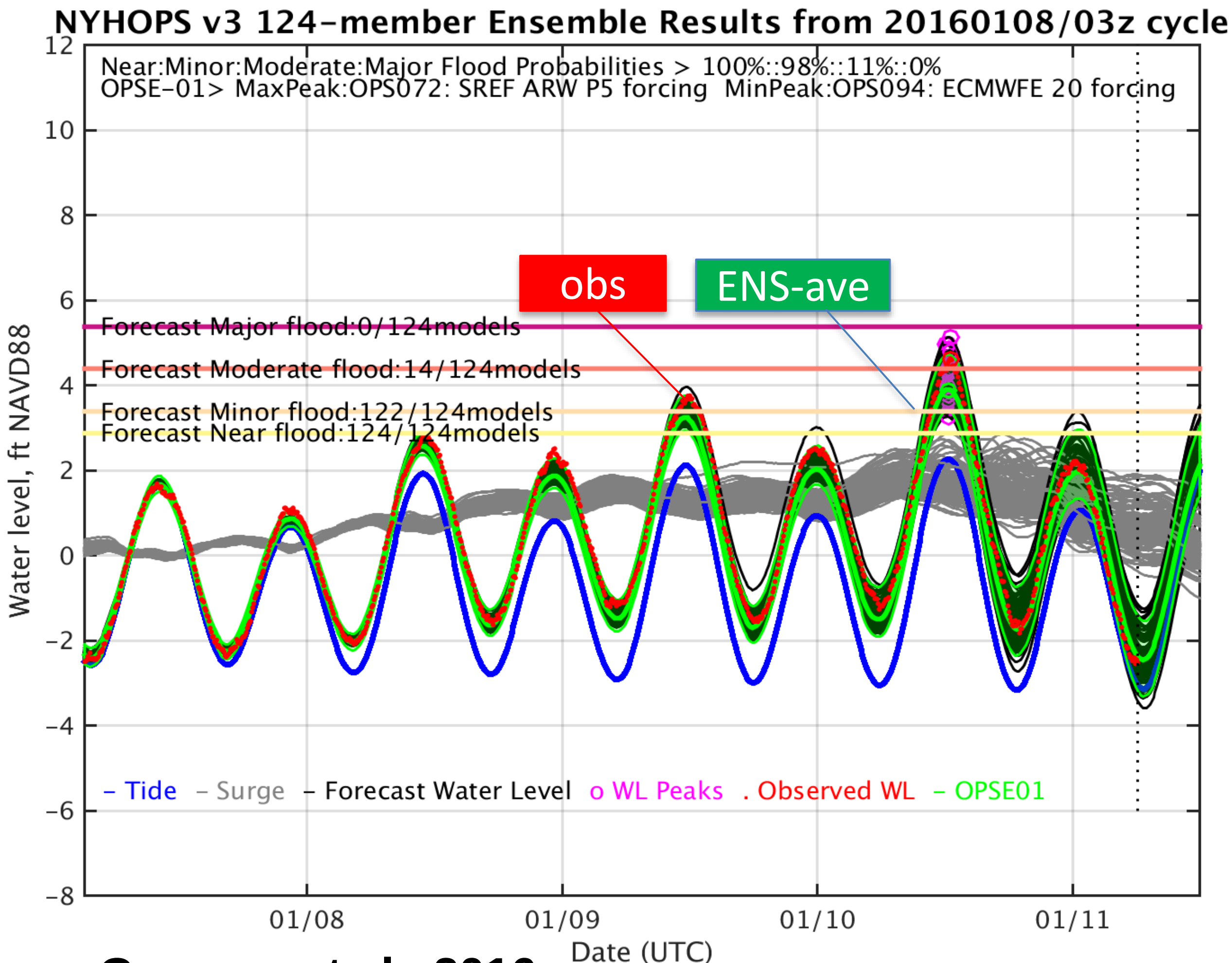
Model Performance Example



Example of Coastal Component Ensemble Outputs NYHOPS

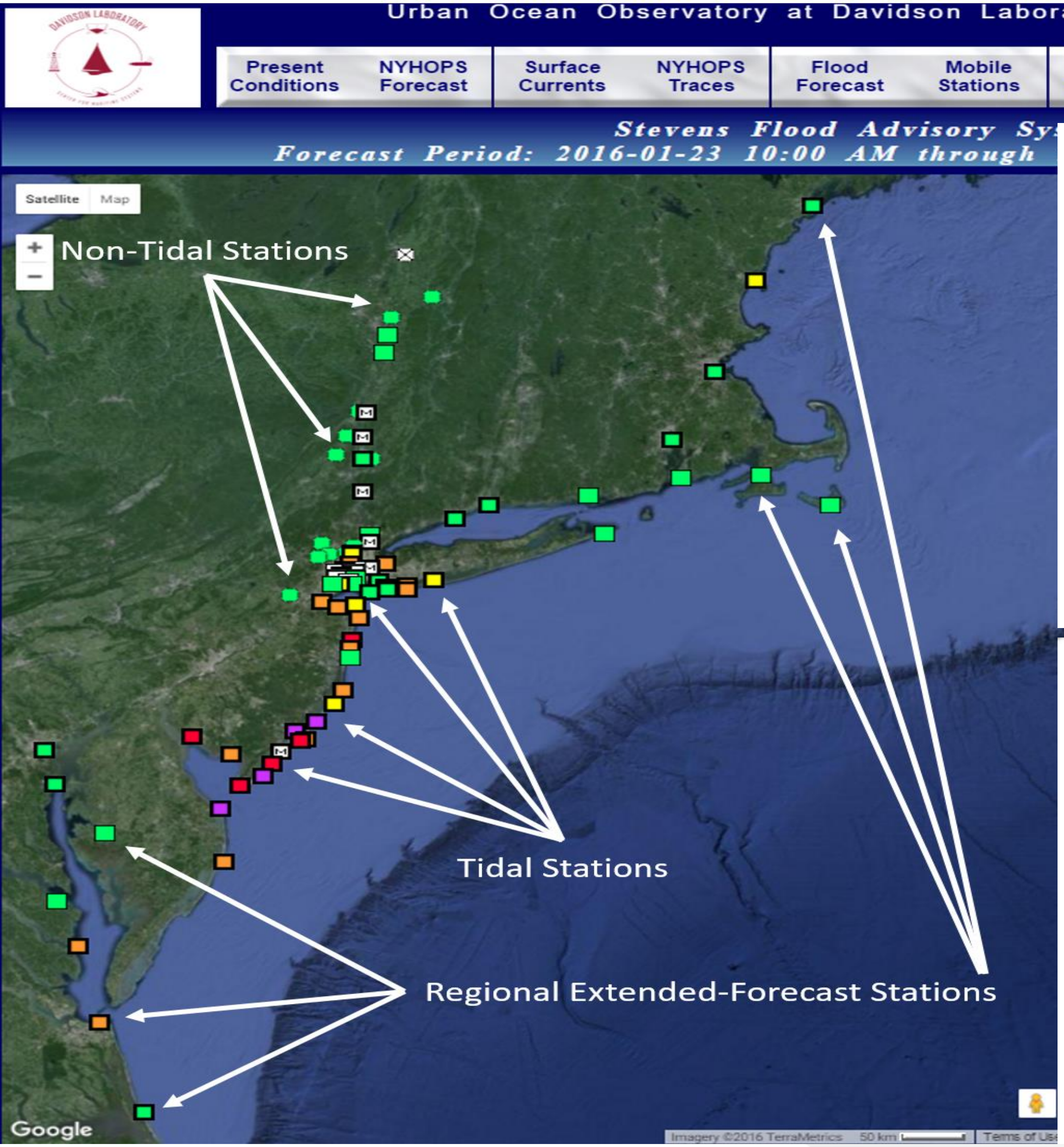
Meteorological Forcing	
Ensemble members	
GEFS	(21)
ECMWF	(51)
CMC	(21)
SREF	(26)
Deterministic members	
NAMx2,GFS(+e),ECMWF.	

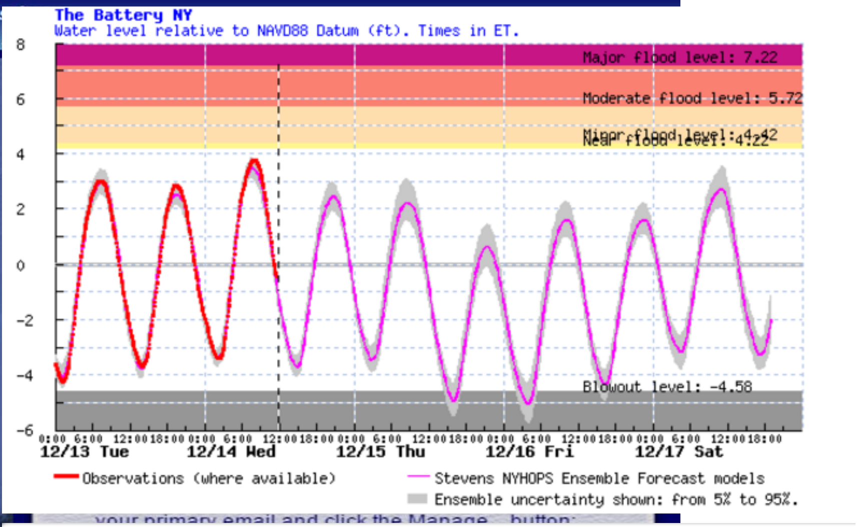
- 2016-01-10 Flood Event was Predicted 3 days in advance.
- Ensemble usually envelopes the observations well

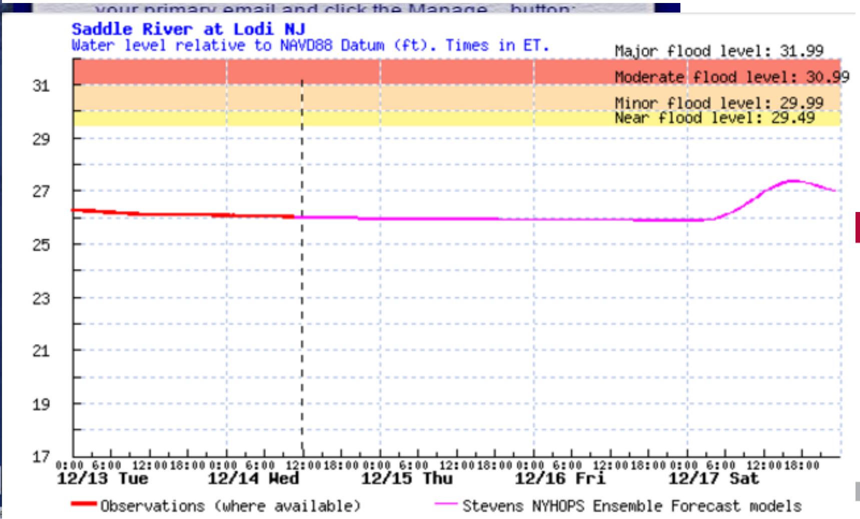


Georgas et al., 2016

www.stevens.edu/SFAS







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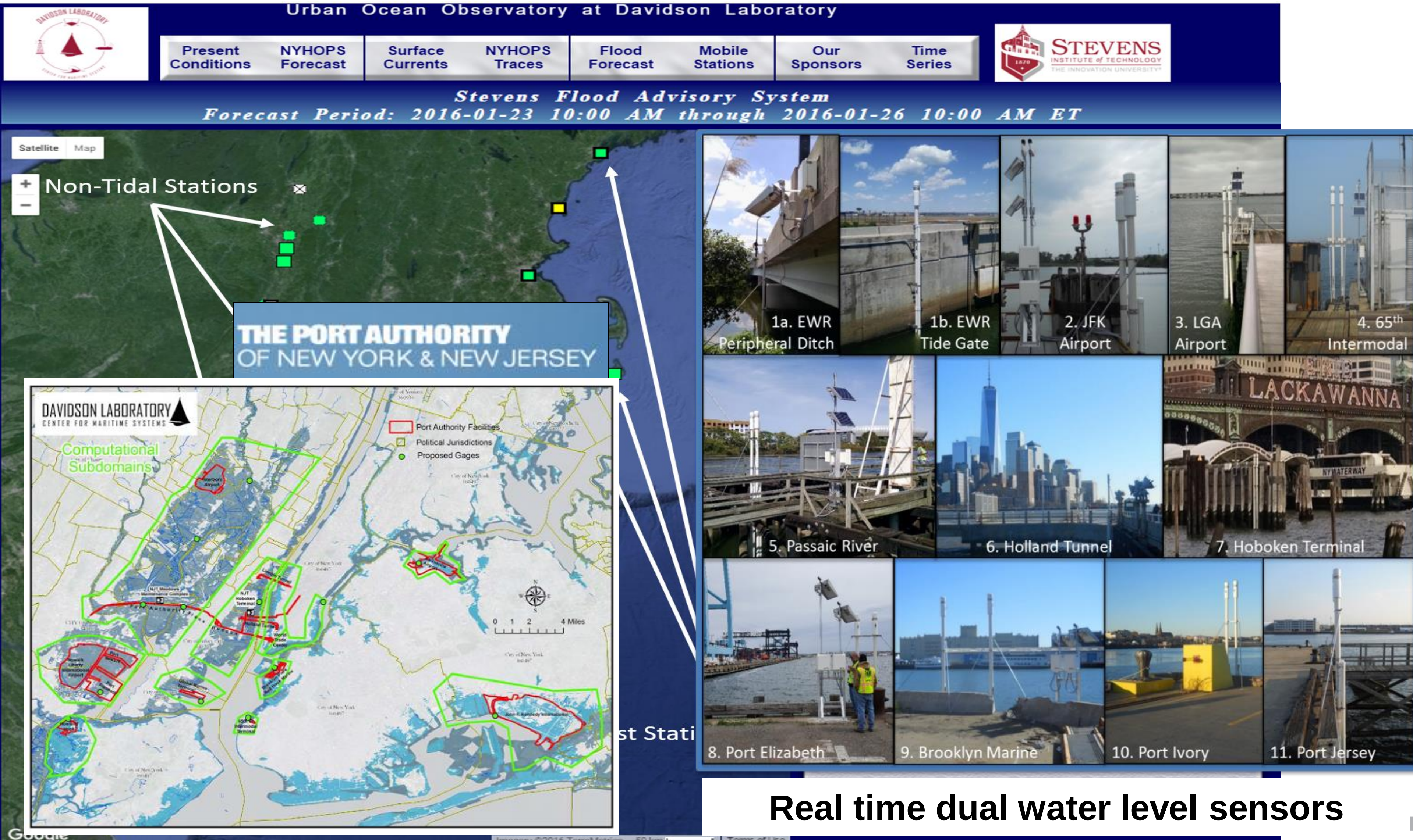
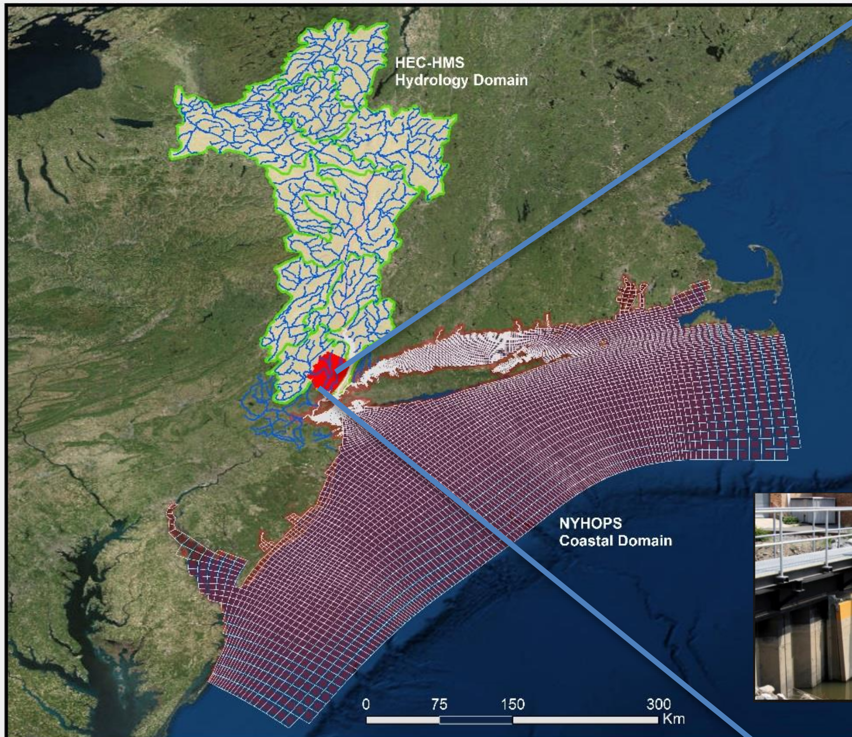
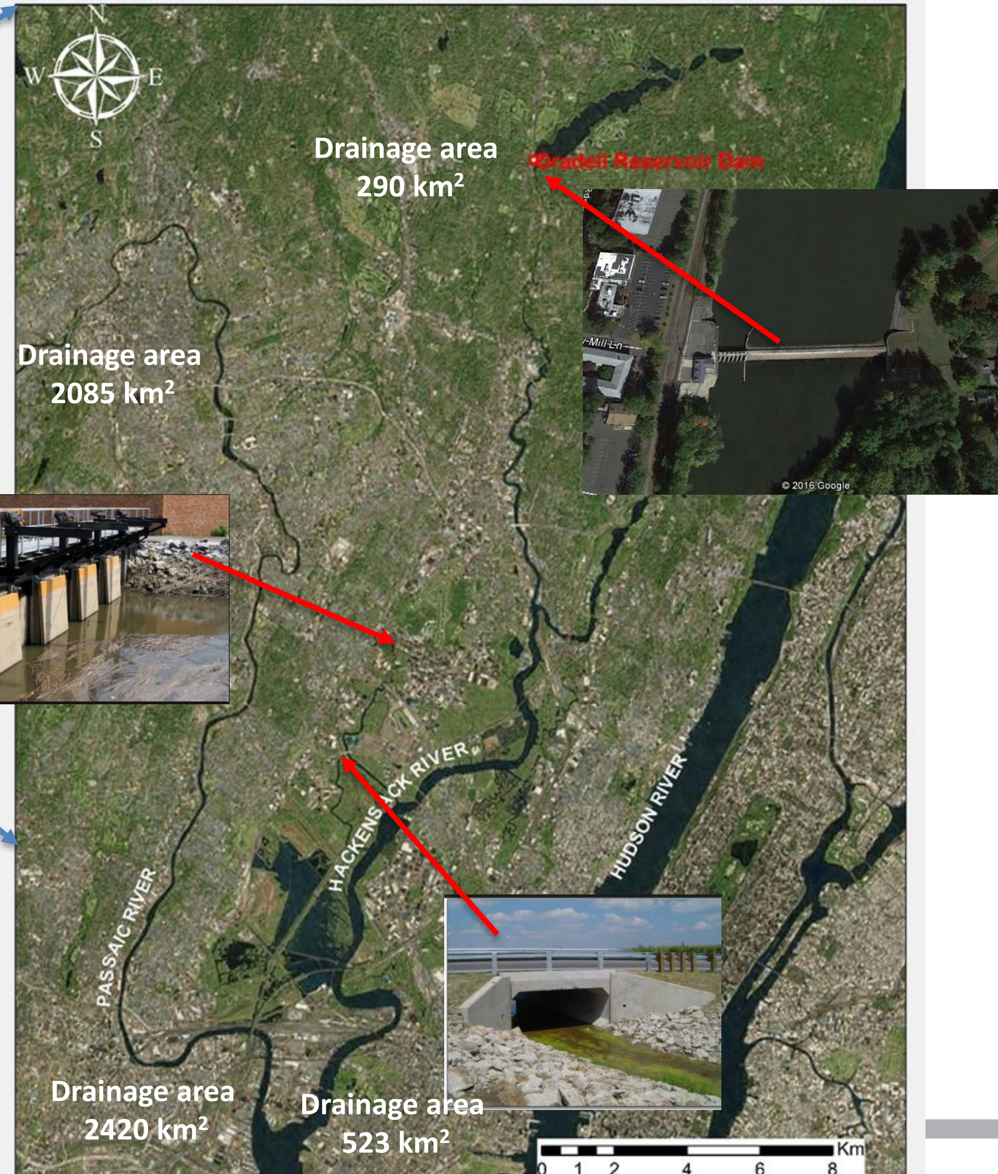


Real time dual water level sensors

Framework Hyper Resolution Applications

Hackensack ($523\ km^2$) & Passaic ($2420\ km^2$) Rivers



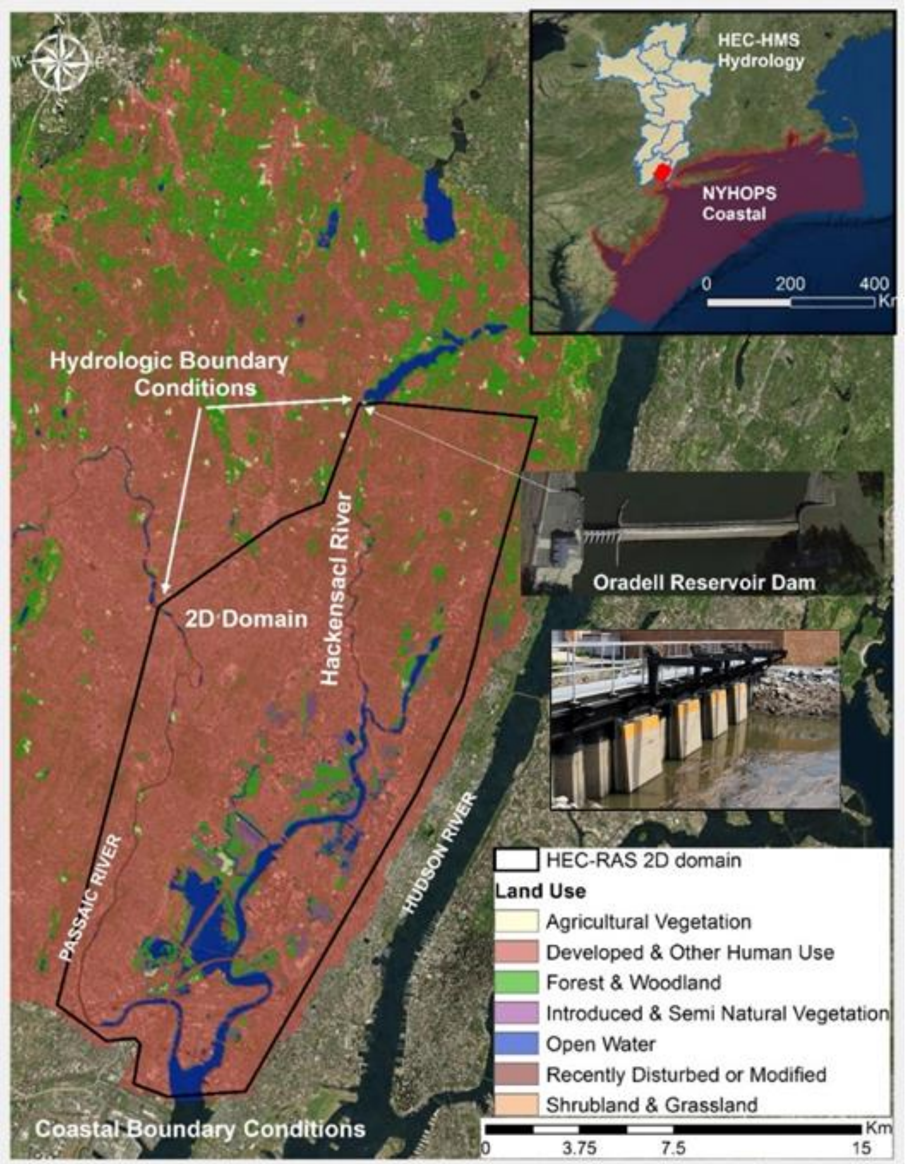


http://www.bergenfield-weather.com/irene_11.php

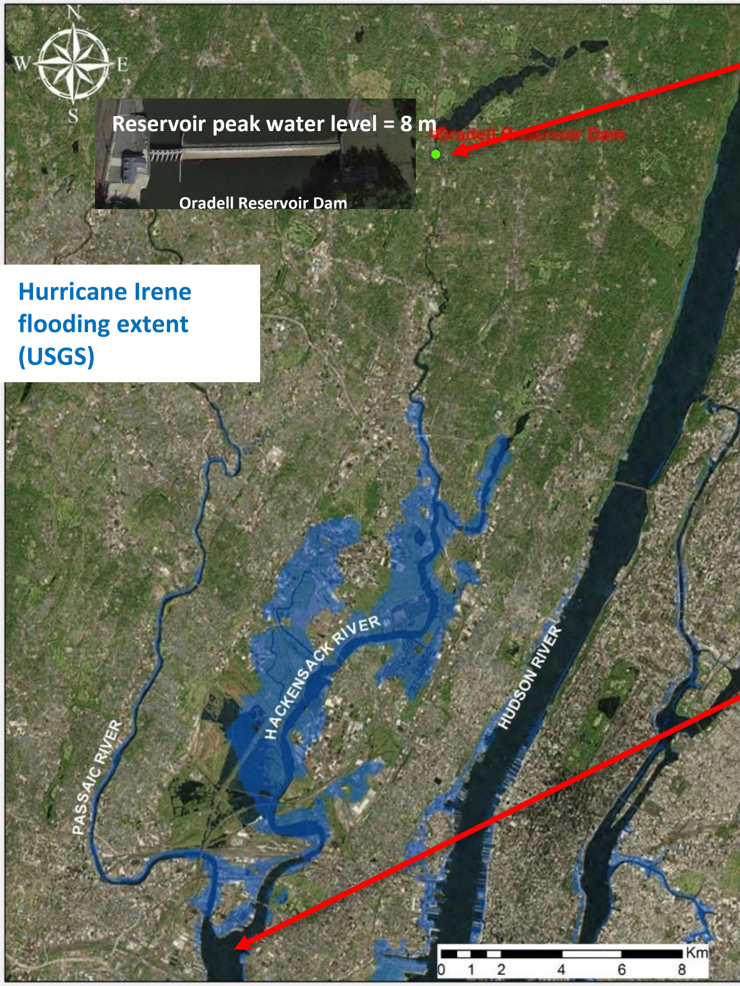
Newark Bay

Framework Hyper Resolution Applications

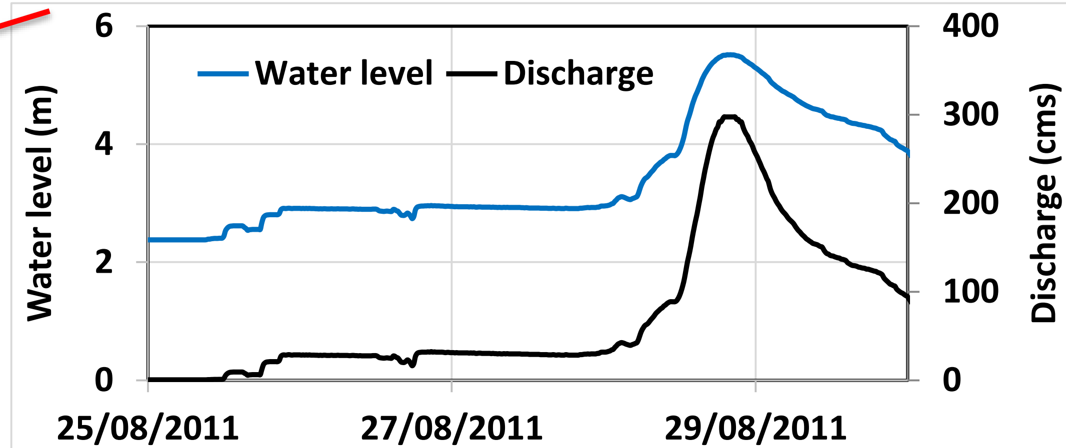
- Combined influence of riverine and tidal components
- Tidal wetlands
- Highly urbanized watershed, more than 2 million people
- Critical facilities (e.g., Teterbero Airport, NJ Transit, Passaic Valley Sewerage Commission)
- Oradell reservoir, storage capacity of 14,000 acre-feet
- Vulnerable to inland and coastal flooding
- <u>Modeling Approach</u>: integrated ocean-meteorology-hydrology-hydraulics model suite



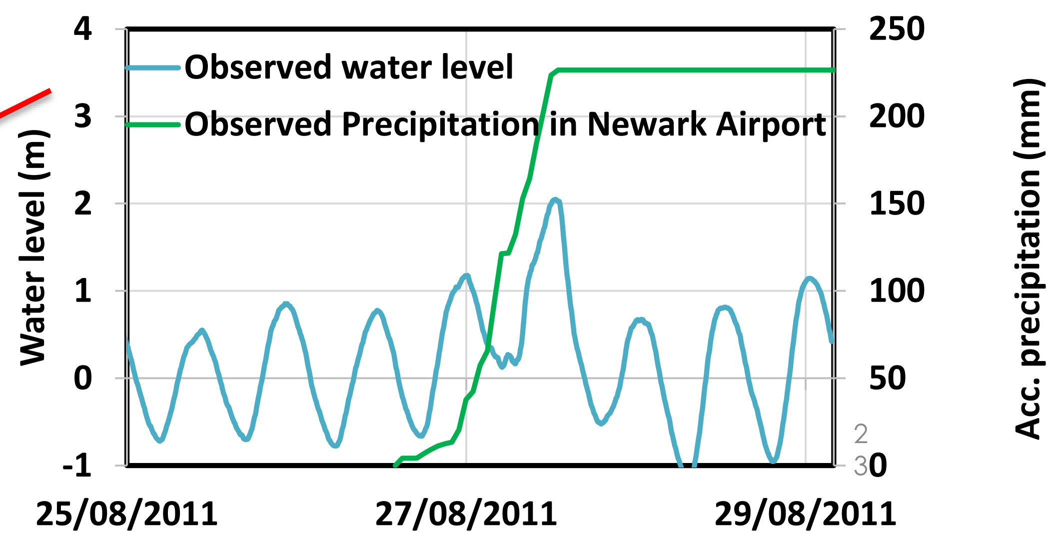
Hurricane Irene [August 2011]



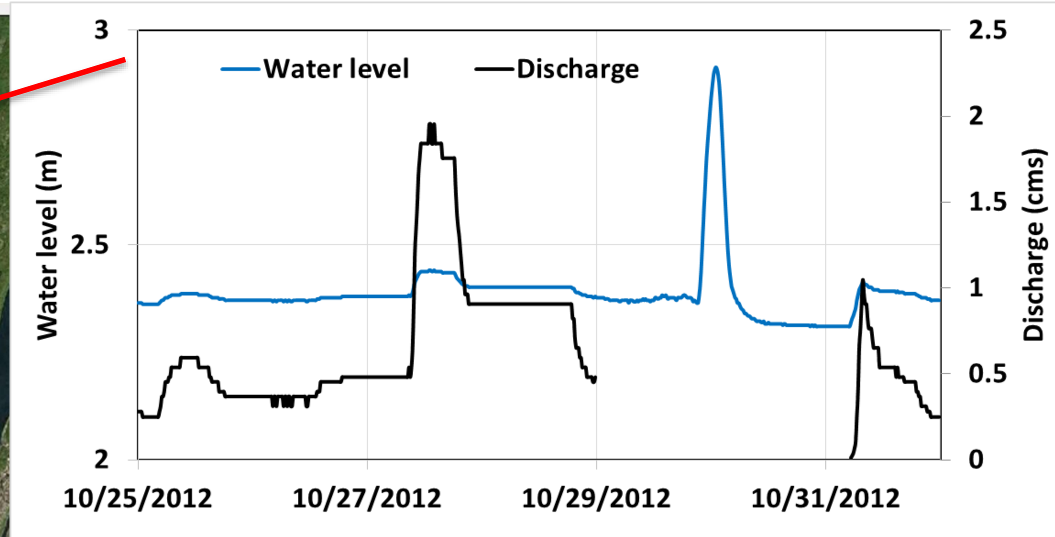
Hydrological component D/S of Oradell Reservoir

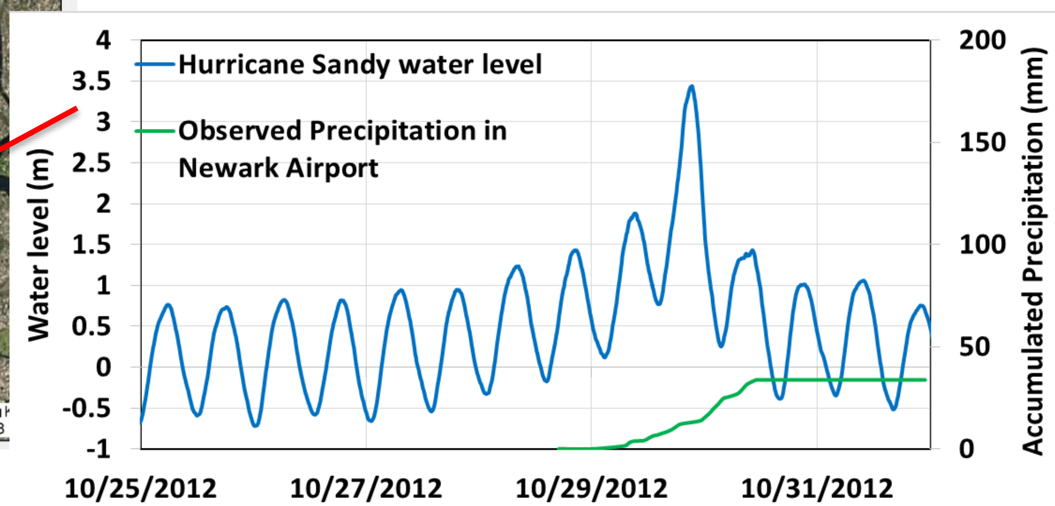


Coastal & meteorological component [Open water]



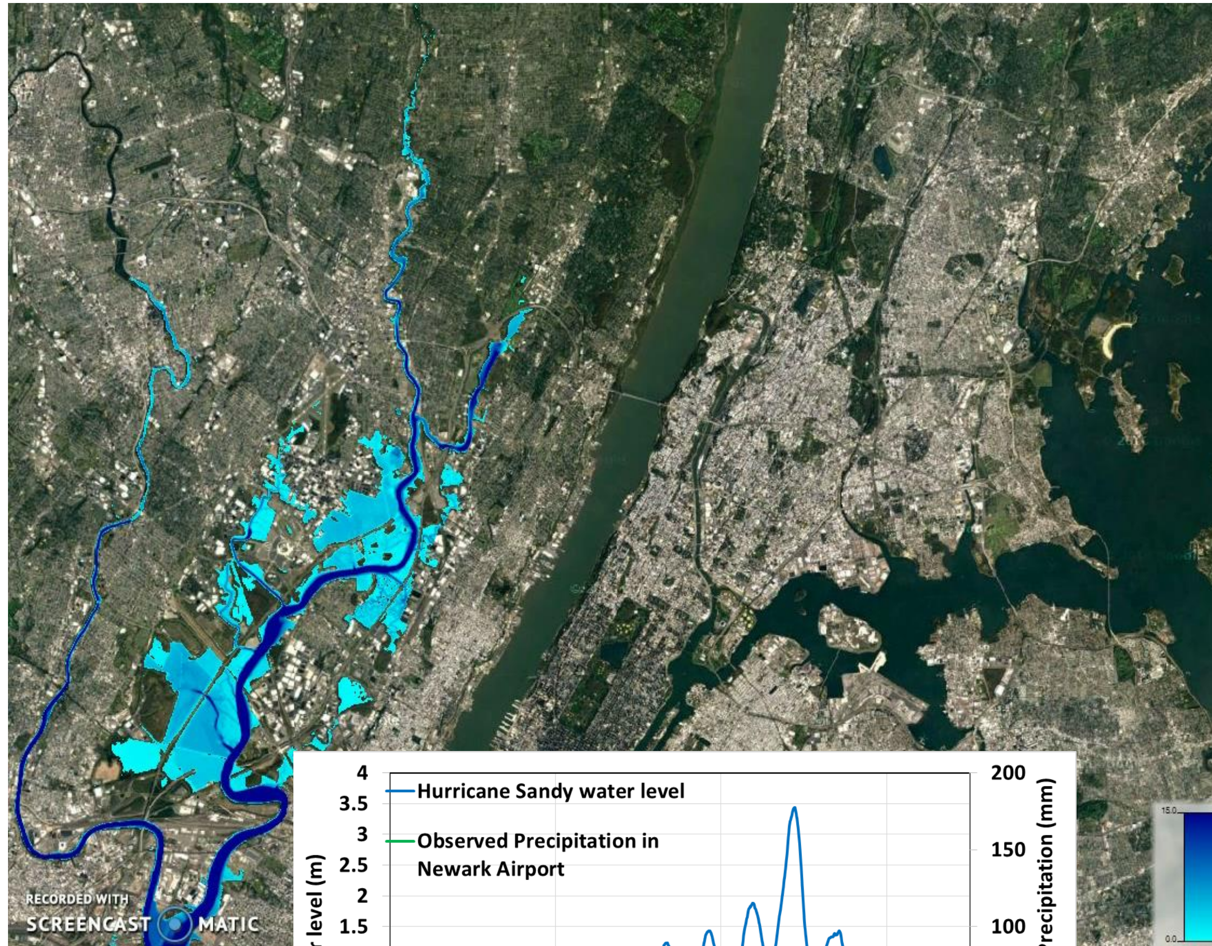
Hurricane Sandy [October, 2012]

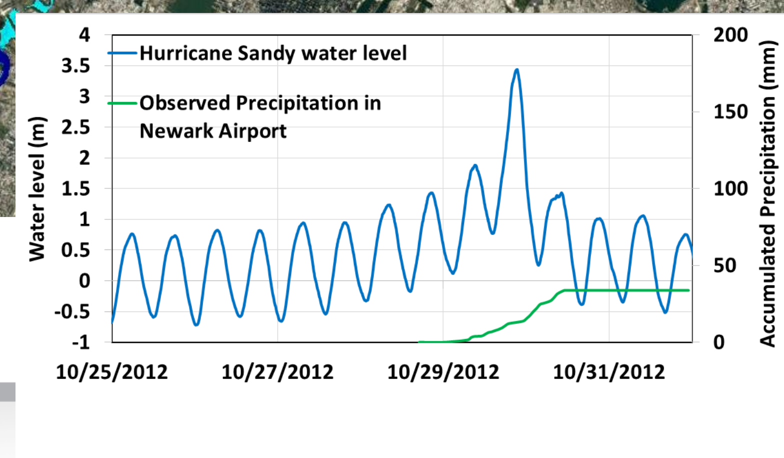




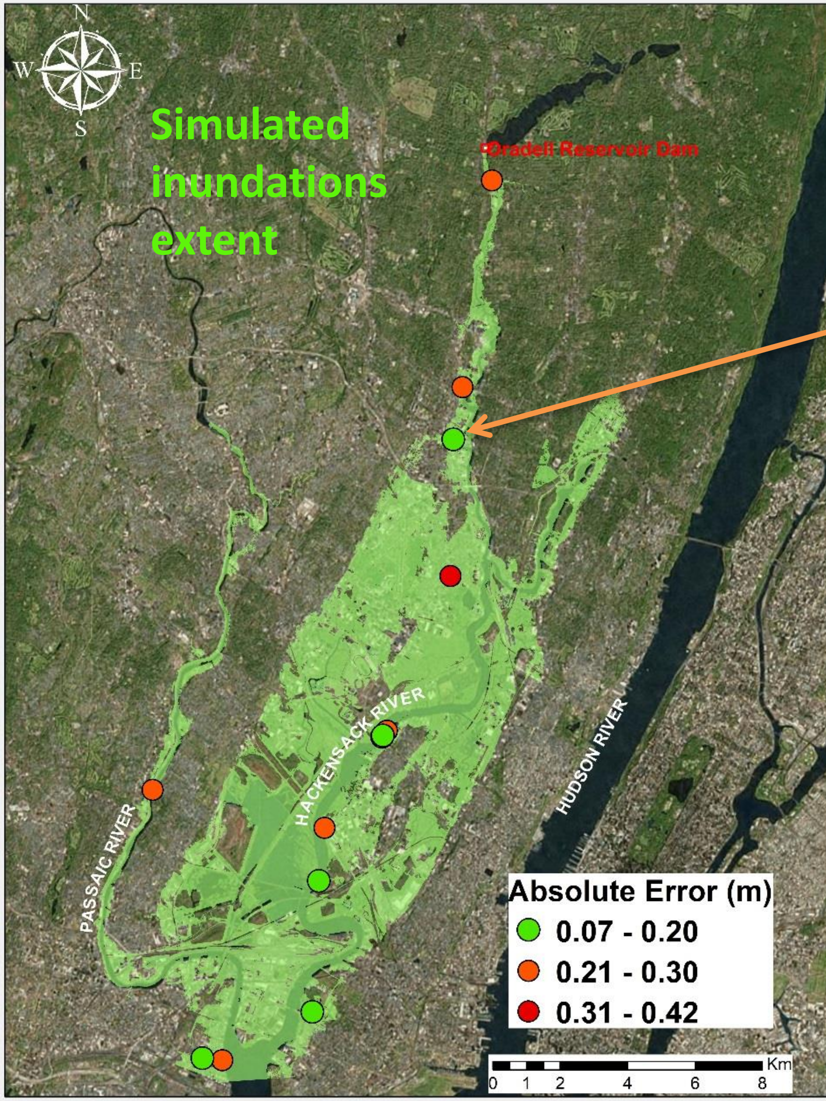
Hurricane Sandy Simulation

- **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**

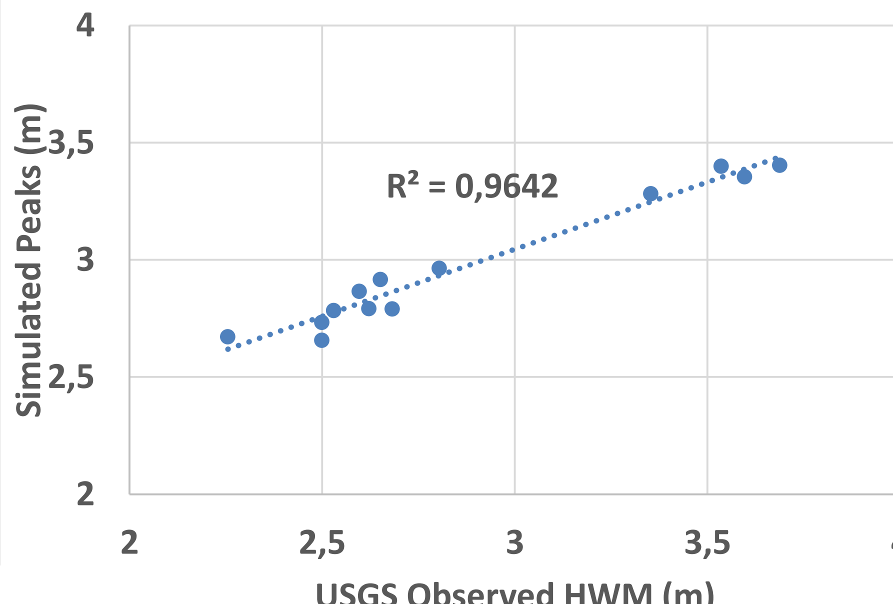




Framework Validation [Hurricane Sandy]



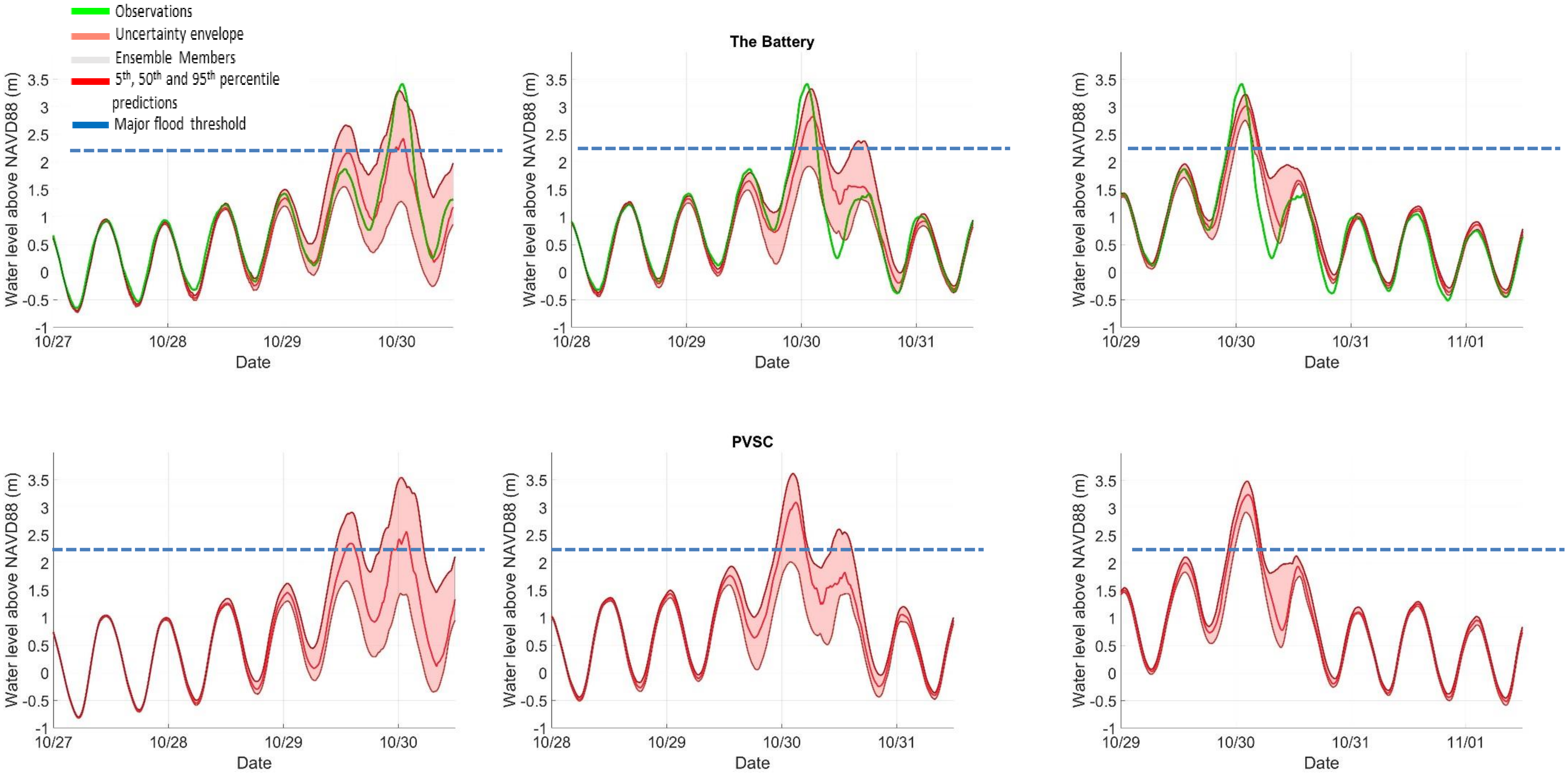
Validation against USGS flood extension map, a network of high water marks and time series sensors that were deployed by USGS prior to hurricanes Irene and Sandy.



High water marks source: http://stn.wim.usgs.gov/FEV/#Sandy

Ensemble based retrospective forecasts using GEFS meteorological forcing

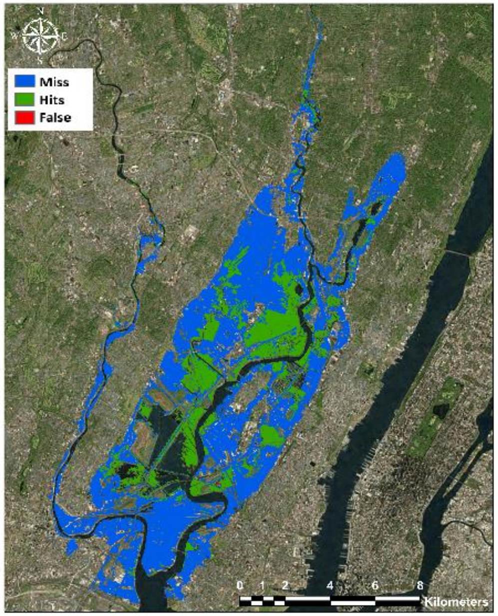
72-Hours before Sandy | **48-Hours before Sandy** | **24-Hours before Sandy**



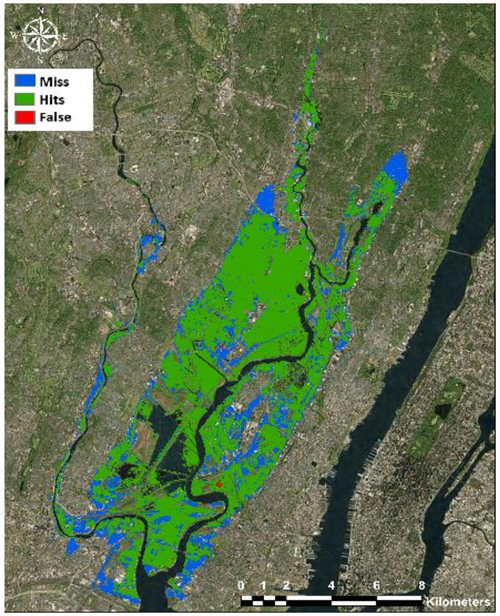
Retrospective Forecast of Hurricane Sandy

Framework forced with GEFS retrospective meteorological forcing / 72-hours

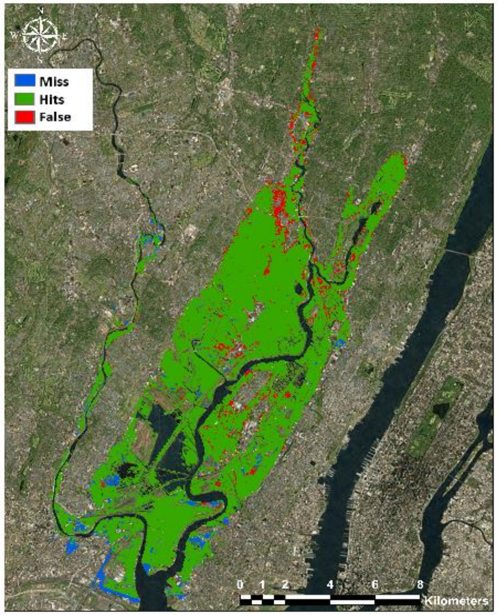
Ensembles 5th percentile



Ensembles Median



Ensembles 95th percentile



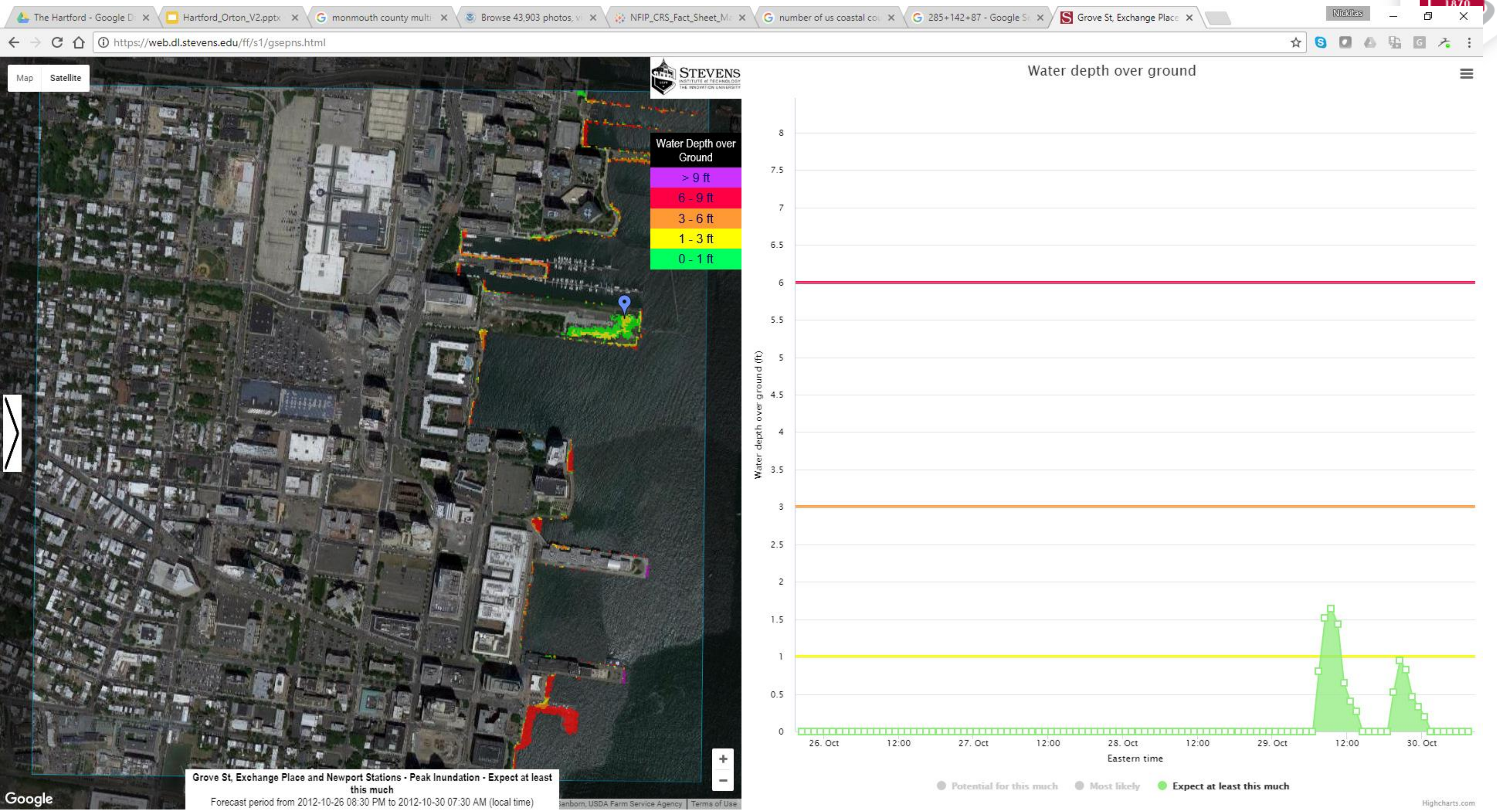
Spatial validation with USGS Reanalysis Flood Extent Map

- **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)

	POD	FAR	CSI
Sandy 5%	23%	0.20%	23%
Sandy 50%	74%	1%	74%
Sandy 95%	95%	7%	89%

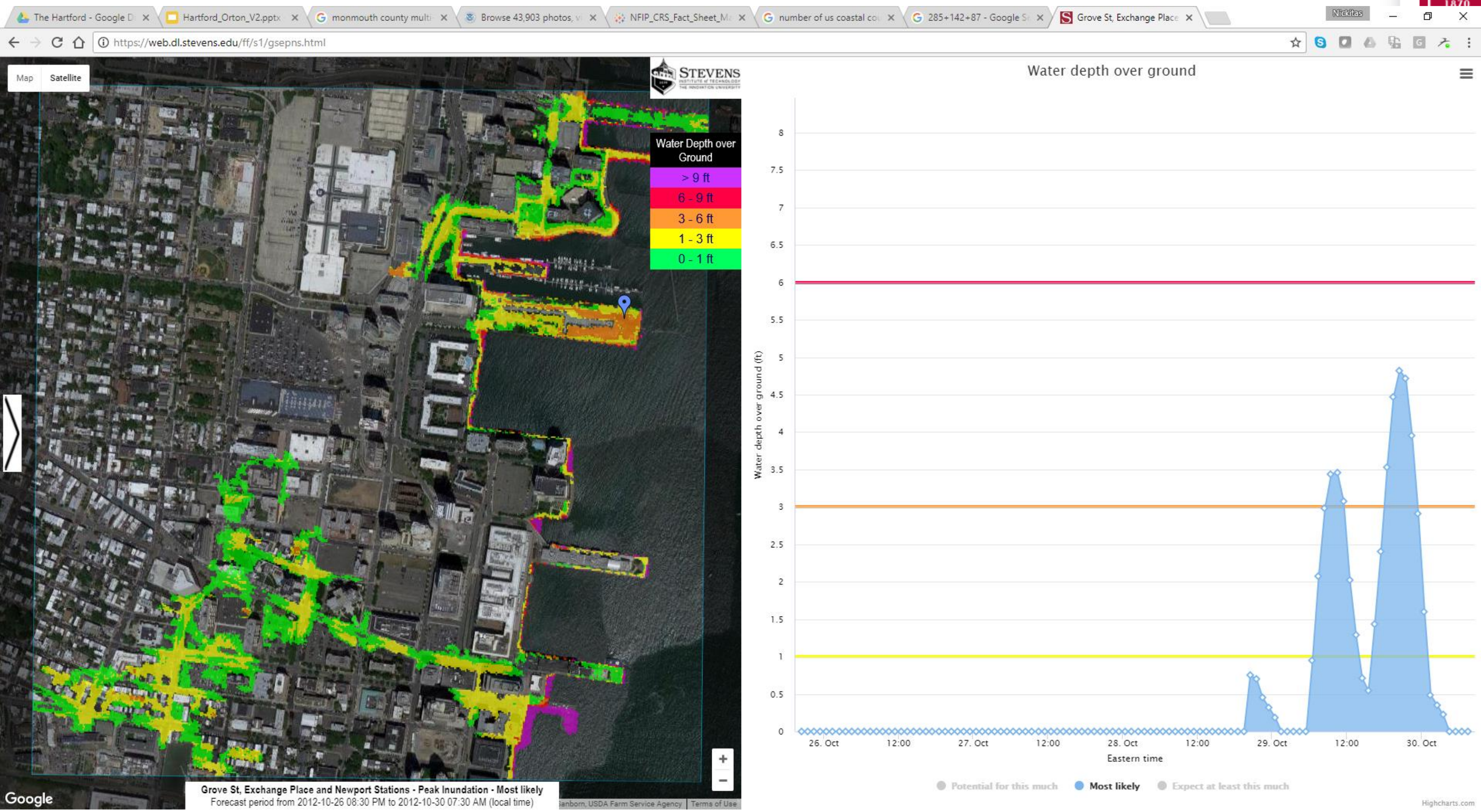
Saleh, F., Ramaswamy, V., Wang, Y., Georgas, N., Blumberg, A. F., and Pullen, J.: A Multi-Scale Ensemble-based Framework for Forecasting Compound Coastal-Riverine Flooding: The Hackensack-Passaic Watershed and Newark Bay, ***Advances in Water Resources*** (in review, Manuscript ID ADWR_2017_243)

Telescoping capabilities to the operational level of individual facilities



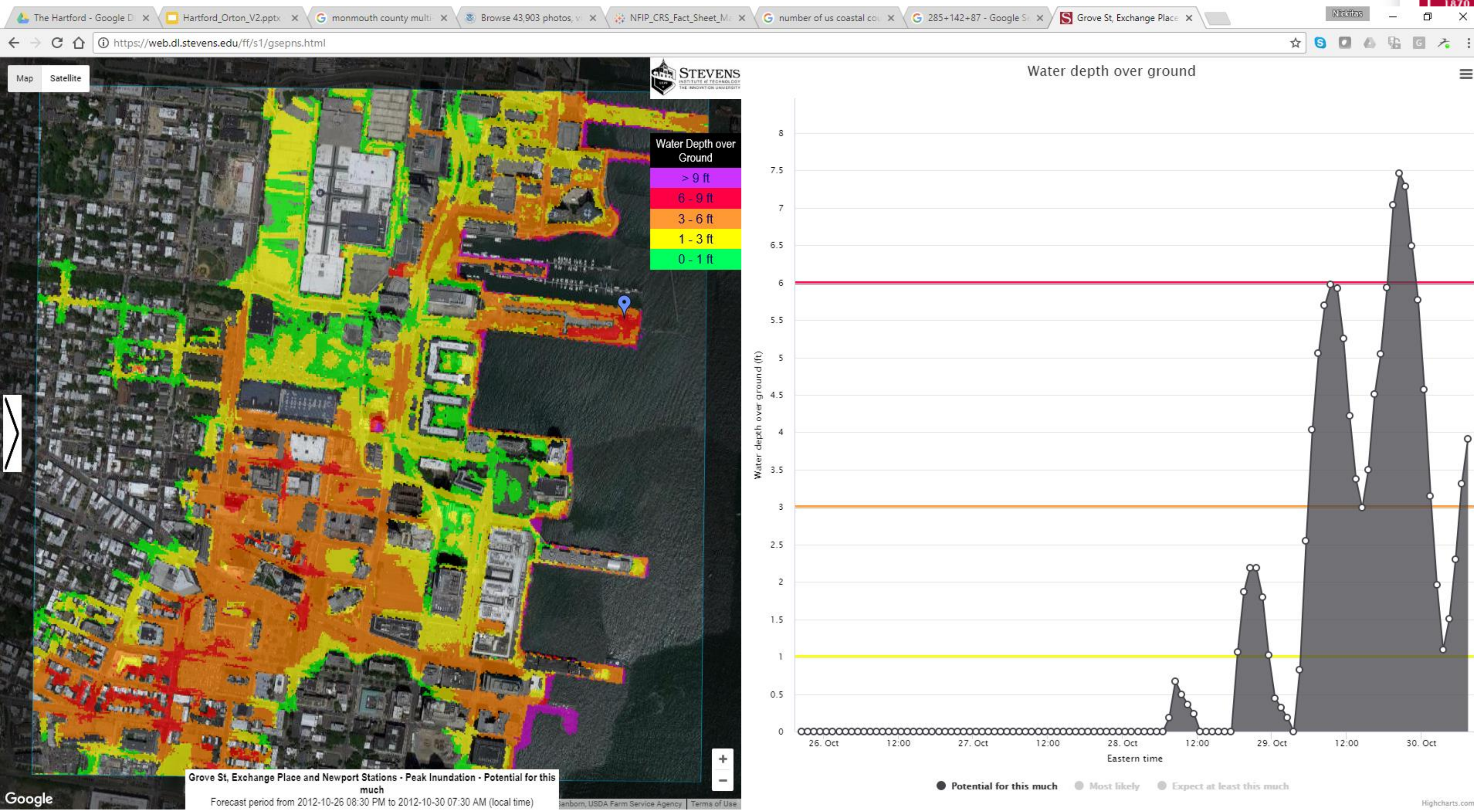
Sandy minus 72hrs ensemble: “Expect at least this much water over ground”

Telescoping capabilities to the operational level of individual facilities



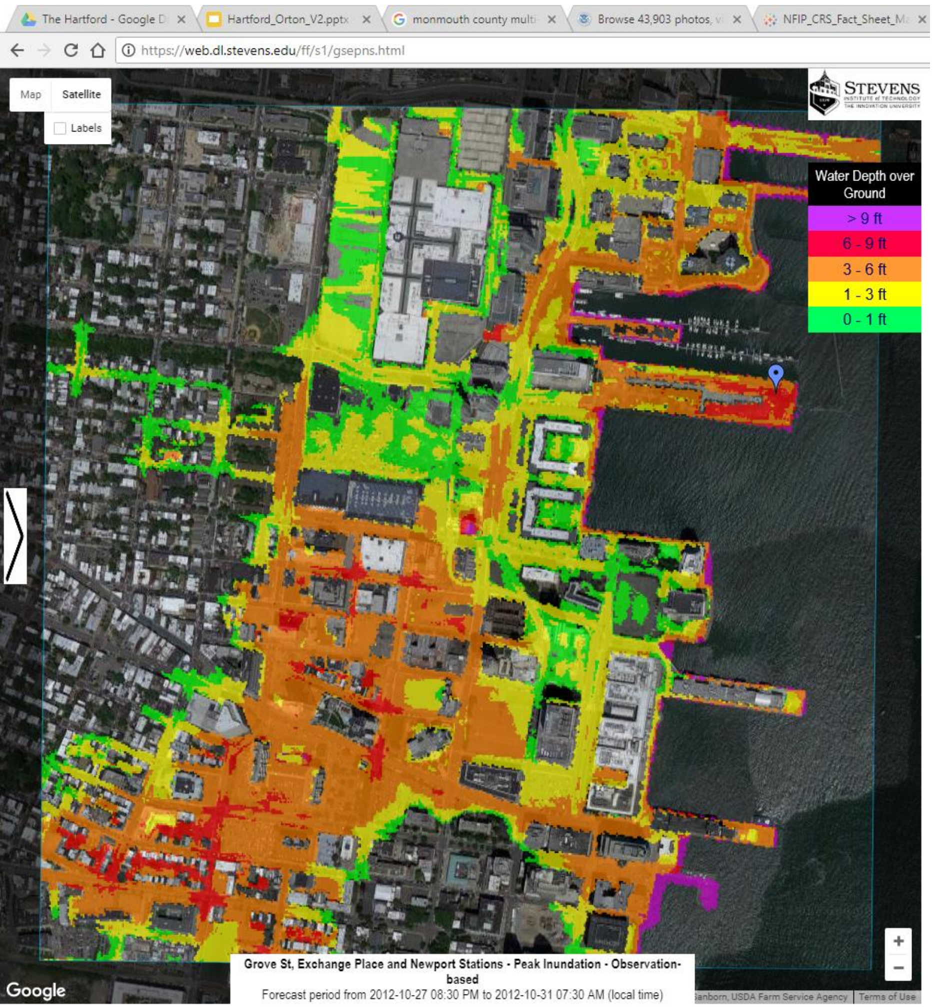
Sandy minus 72hrs ensemble: “Most likely inundation over ground”

Telescoping capabilities to the operational level of individual facilities



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)

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Thank You!

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