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# Modeling and Simulation of Rainfall-Runoff Flooding using Probabilistic Precipitation Forecasts

David R. Judi, Byron Tasseff

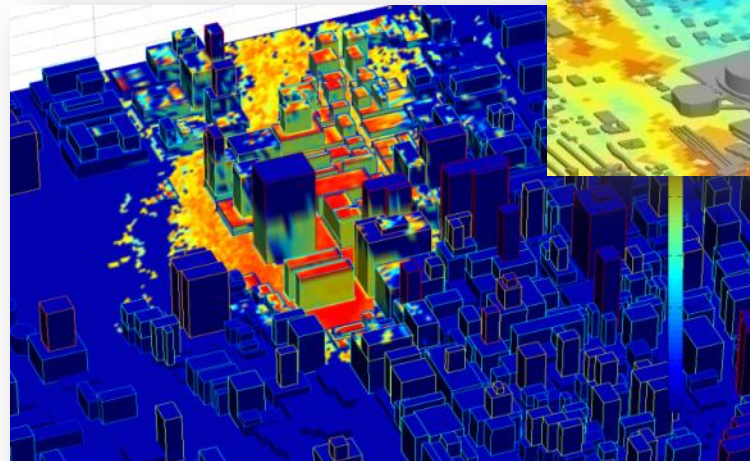
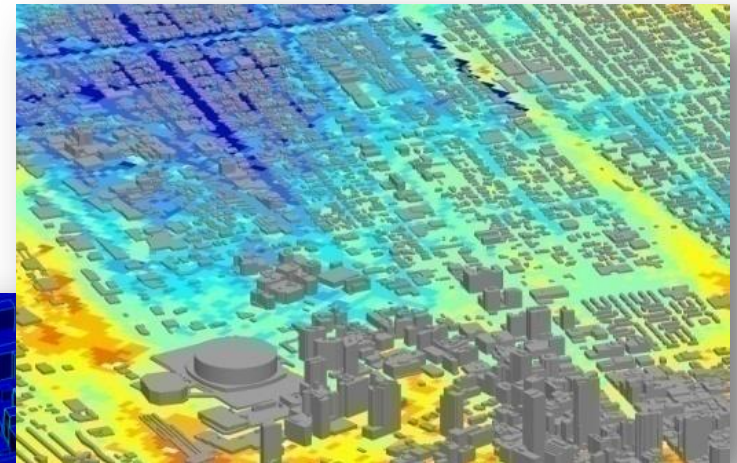
June 18, 2014

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# Overview

- Why a National Laboratory
- Flood Hazard Modeling Methodology
- Adaptation to Hydrology
  - Verification\Validation
- Data Requirements
- Case Study

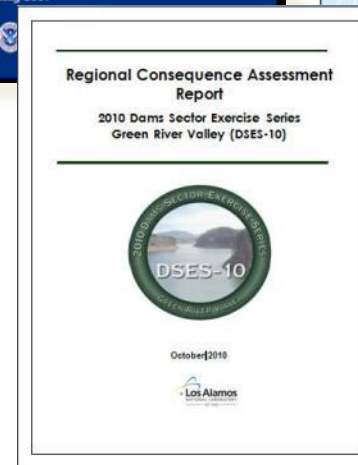
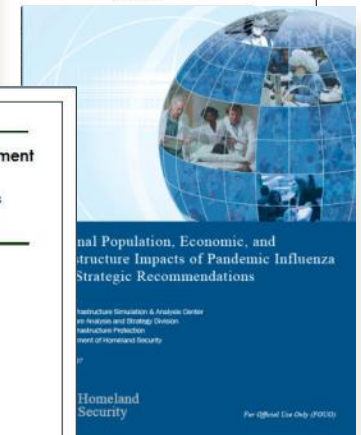


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# Energy and Infrastructure Analysis at Los Alamos

## LANL

- Goal
  - Provide scientifically robust solutions to infrastructure system resilience challenges affecting National Security at local, regional, national, and global scales
- Mission Execution Objectives
  - Research, develop, and transition advanced technologies to operational use in federal missions
  - Trusted source of expertise on modeling, simulation and analysis of infrastructure



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# What is NISAC?

The National Infrastructure Simulation and Analysis Center (NISAC) is a combination of people, data, and models

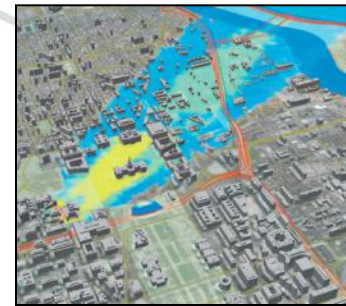
- Improve the understanding, preparation, and mitigation of the consequences of infrastructure disruptions
- Provide an operations-tested DHS capability to respond quickly to urgent infrastructure protection issues.
- Provide scientifically robust solutions to infrastructure resiliency problems at multiple resolutions under local, regional, national and global scales.



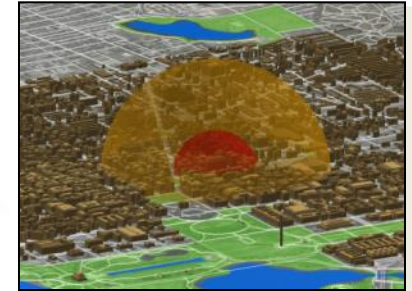
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# Hazards of Concern

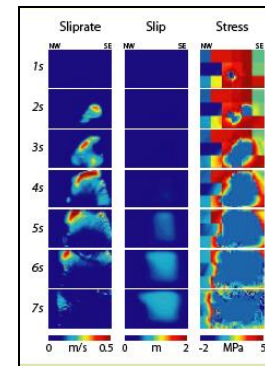
- Natural
  - Accident
  - Drought
  - Earthquake
  - **Flood**
  - Heat Wave
  - **Hurricane**
  - Ice Storm
  - Landslide
  - Pandemic
  - Space Weather
  - **Tsunami**
  - Volcano
  - Wildfire
- Terrorist
  - Biological
  - Chemical
  - Cyber
  - Explosive
    - IED
    - VBIED
    - aircraft
  - Insider
  - Nuclear
  - Physical Assault
  - Radiological



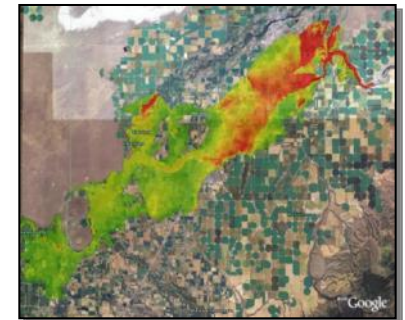
CBR Dispersion Modeling



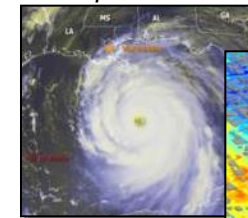
Blast



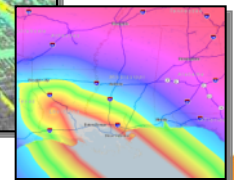
Earthquake



Dam Break

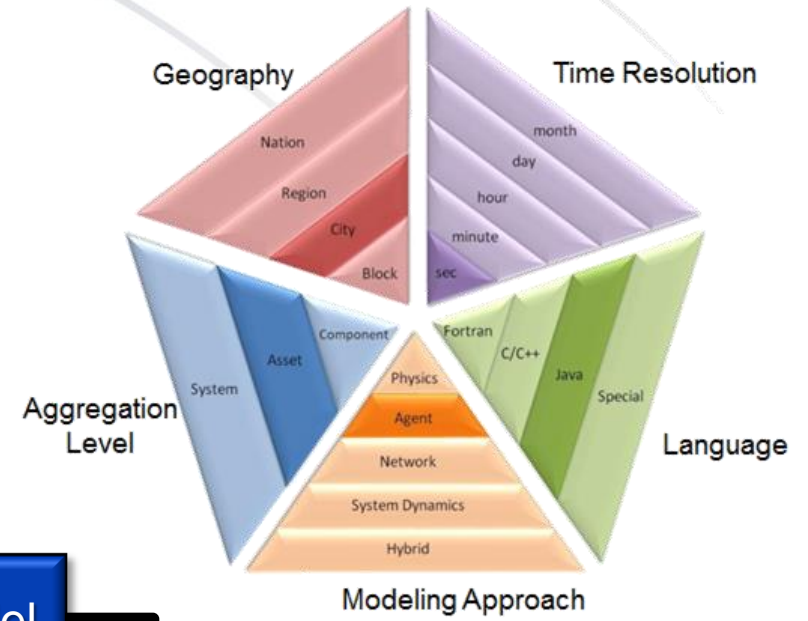
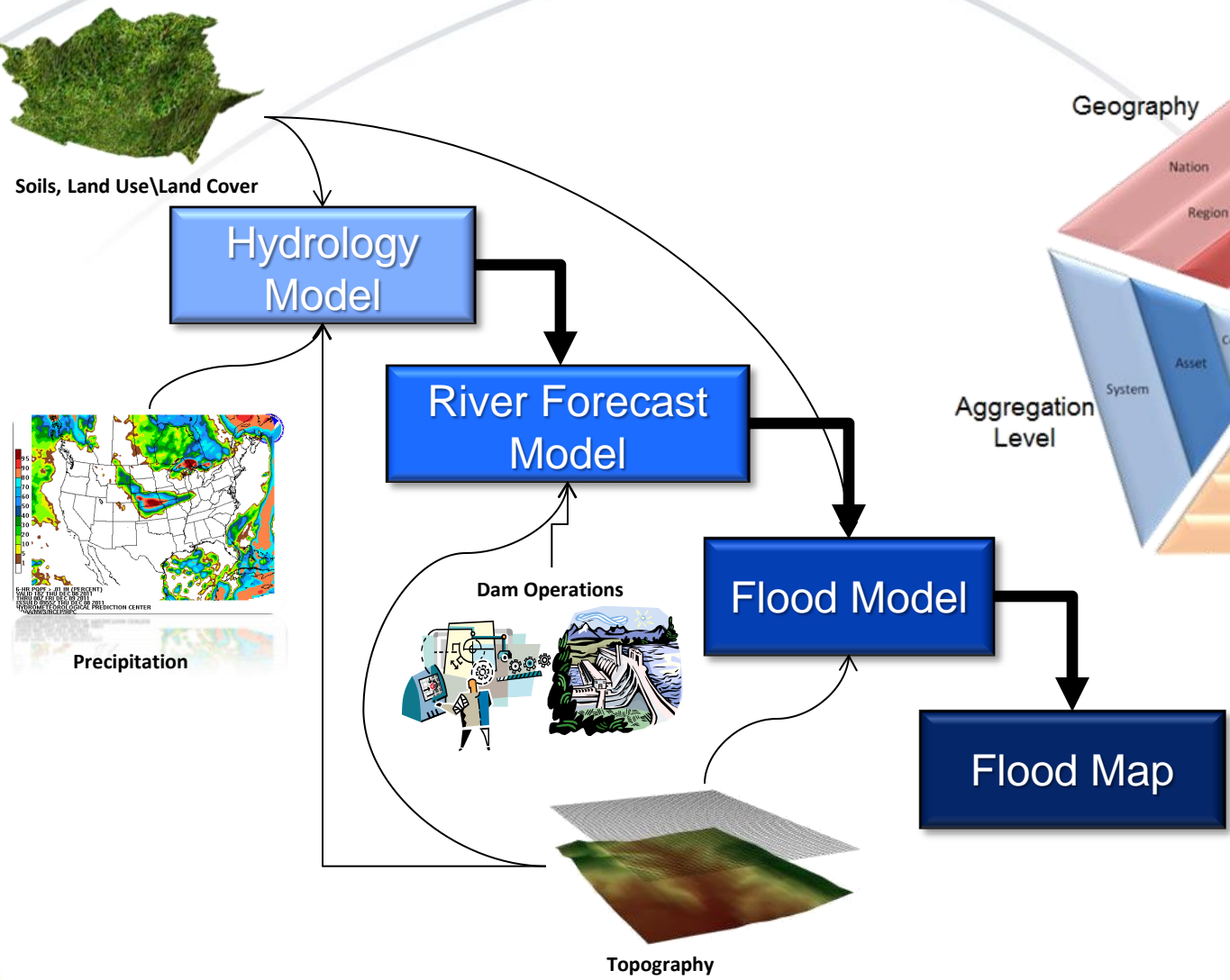


Hurricane (flooding, winds)



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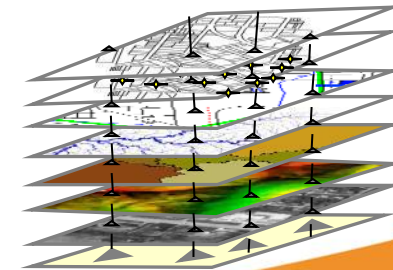
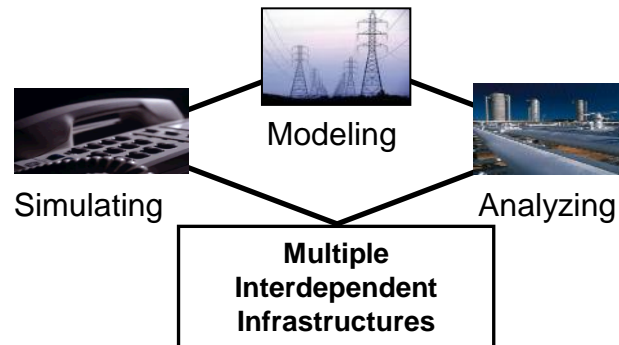
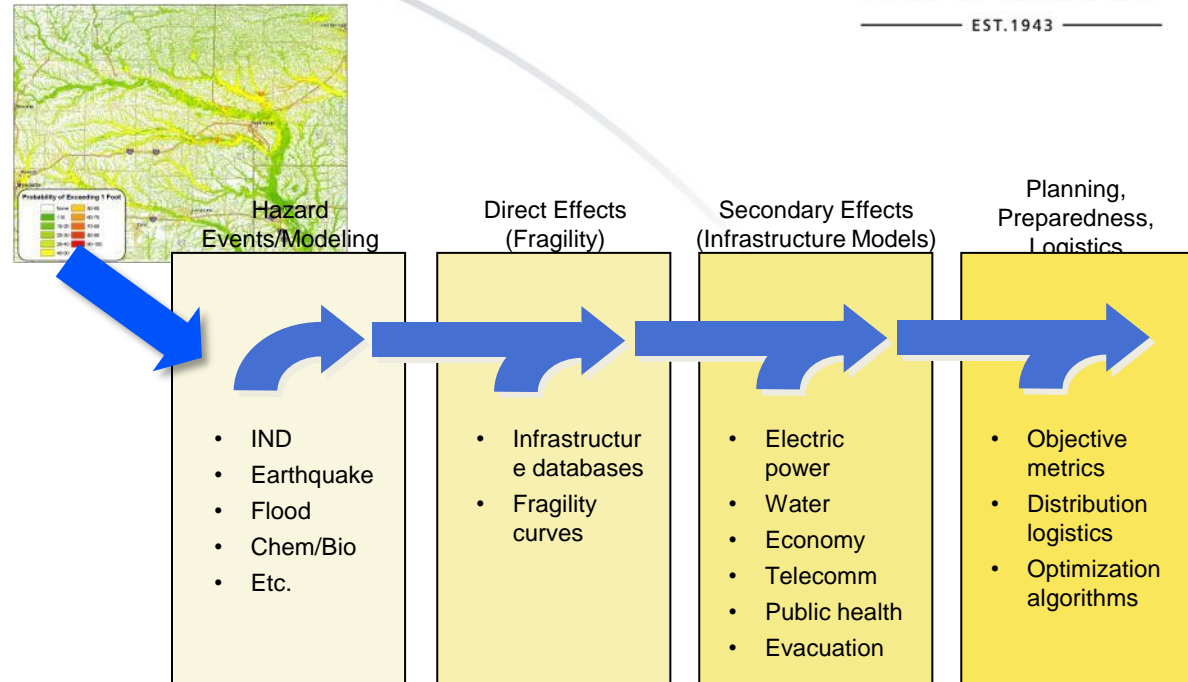
# Predictive Flood Model Workflow



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# Flood Impact Assessment

- Probabilistic Flood Risk Map
- Infrastructure Assessment
  - Fragility Models
  - Infrastructure System Impact Models
- Cascading Impacts
  - Infrastructure interdependencies
  - Workforce and economic impacts



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# Flood Modeling and Simulation

## ■ Flood Modeling

- Completely physics-based using state-of-the-art numerical techniques and computing resources
- Adaptable to wide-range of surface water applications
- Supported more than 100 fast-response and preplanned studies for DHS

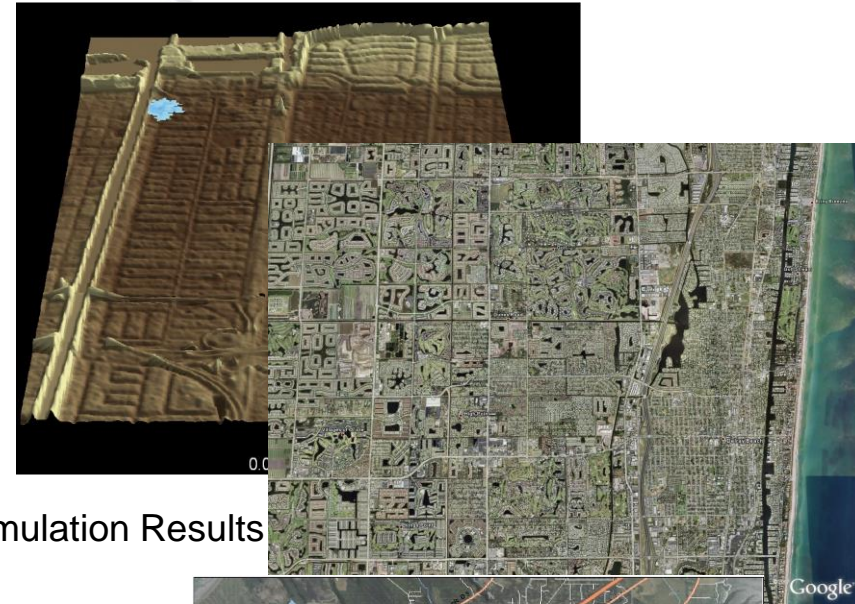
## Navier-Stokes Equations

assuming hydrostatic pressure

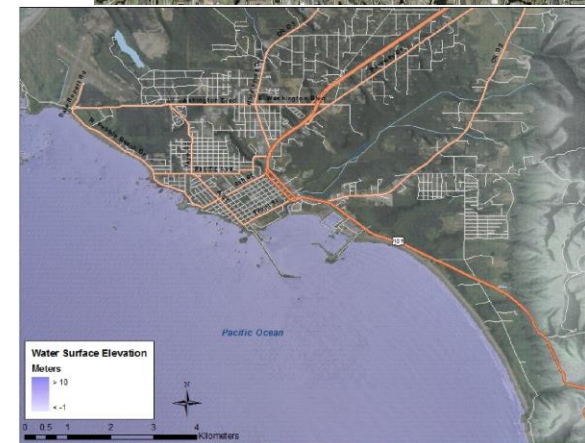
$$\text{mass conservation} \quad \frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = 0$$

$$\text{momentum conservation} \quad \frac{\partial}{\partial t}(uh) + \frac{\partial}{\partial x}(u^2h + g \frac{h^2}{2}) + \frac{\partial}{\partial y}(uvh) = gh(S_{ox} - S_{fx})$$

$$\frac{\partial}{\partial t}(vh) + \frac{\partial}{\partial x}(uvh) + \frac{\partial}{\partial y}(v^2h + g \frac{h^2}{2}) = gh(S_{oy} - S_{fy})$$



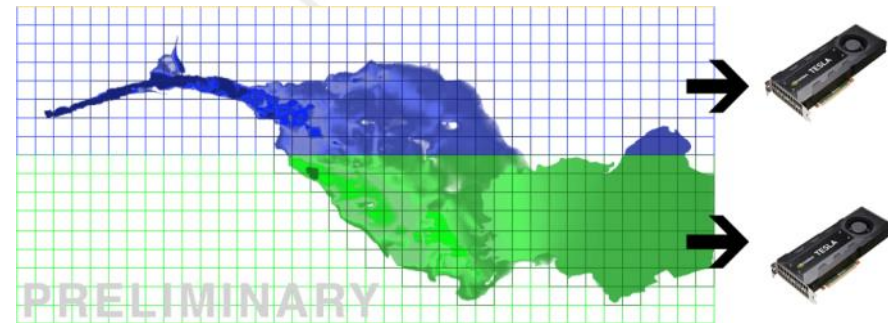
Simulation Results



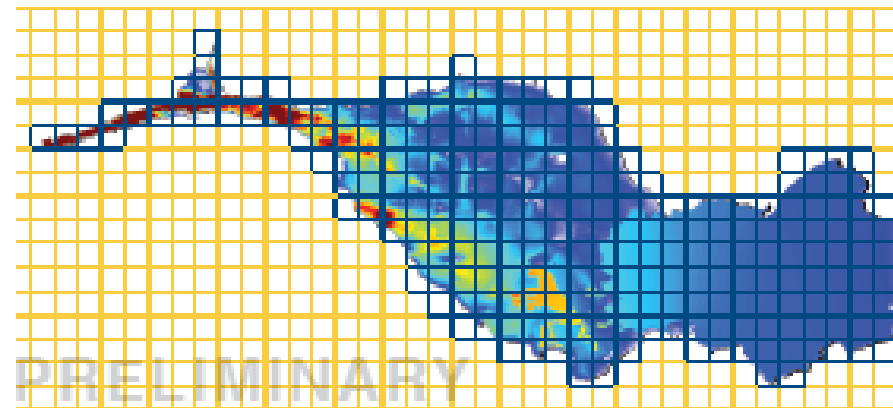
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# Computational Enhancements

- Multi-GPU (Graphics Cards)
  - Memory limitations with single
    - Consequence is reduced resolution
  - Requires domain decomposition for equal loading
  - Boundary cell communication between cards
- Domain Tracking
  - Limit the number of computations required to reach a solution



Domain Decomposition

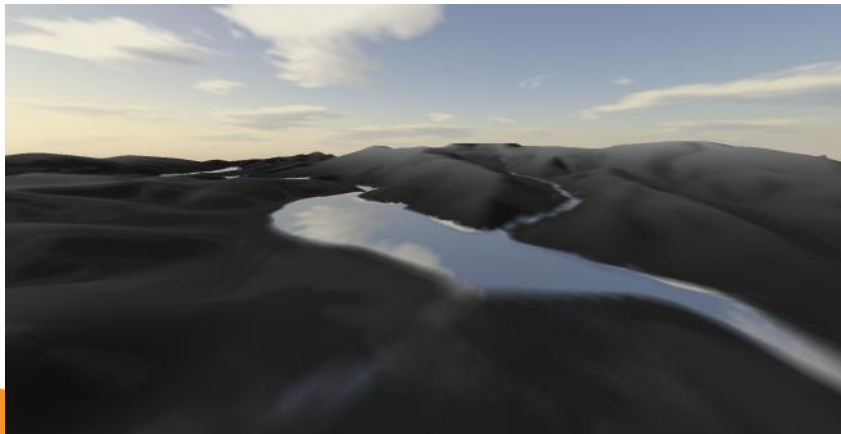
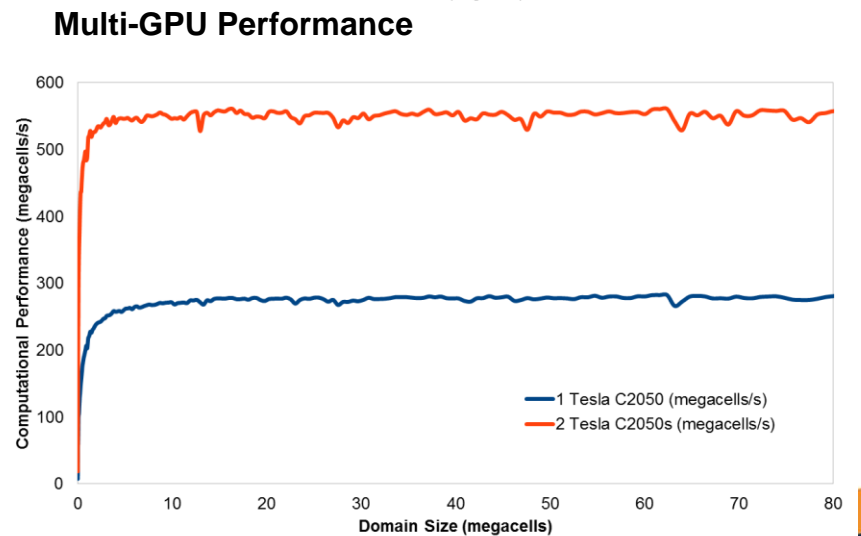
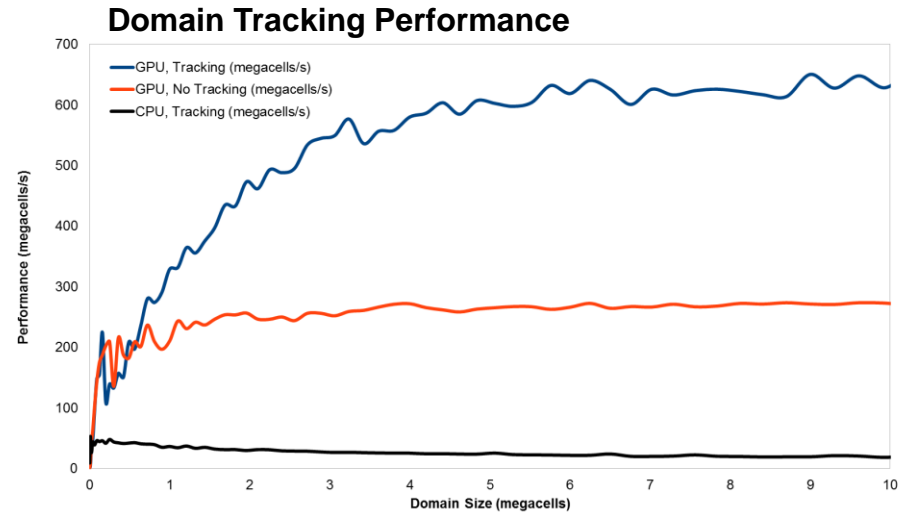


Domain Tracking

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# GPU: Performance and Visualization

- Computational Benchmark
  - Speed ups realized
  - Room for improvement with multi-GPU
- Visualization
  - Directly linked with GPU simulation (data sharing)
  - Working towards faster than real-time interaction
    - Topography manipulation



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# Adaptation for Hydrologic Applications

The Green-Ampt Model is a conceptual representation of the infiltration process, developed in 1911 by Green and Ampt. Infiltration is evaluated using saturated hydraulic conductivity, capillary suction, and soil moisture deficit

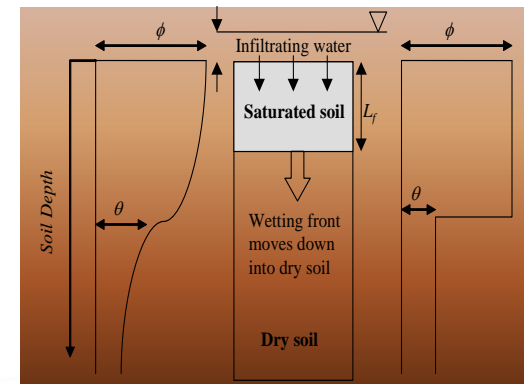
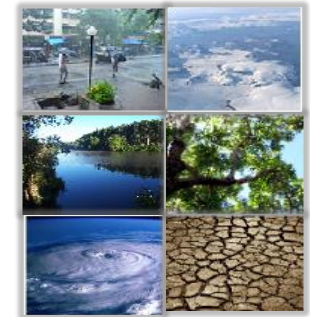
## Green-Ampt Infiltration Rate

$$f(t) = K_s \left( 1 + \frac{\Psi_{mf} \cdot \Delta\theta}{F} \right)$$

mass cons

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = R(t) - f(t)$$

$f$  = infiltration depth  
 $K_s$  = Saturated hydraulic conductivity  
 $t$  = time coordinate  
 $\Delta\theta$  = soil moisture deficit  
 $\Psi_{mf}$  = capillary suction head  
 $R$  = rainfall depth



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# Hydrology V&V

- Assessment of numerical performance with shallow depths

- Peer-reviewed benchscale comparison<sup>1</sup>

- ~ 70 configurations (geometry, rainfall) Los Alamos Canyon Watershed

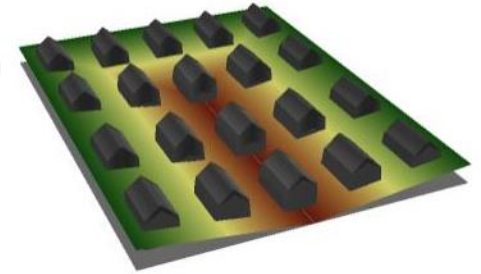
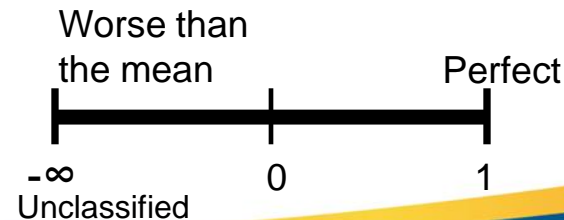
- Watershed rainfall/runoff observations

- Green's Bayou Watershed, Houston, TX

- Metrics

- Nash-Sutcliffe

$$NS = 1 - \frac{\sum_{t=1}^T (Q_o^t - Q_m^t)^2}{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2}$$



# Benchscale V&V

		Model Geometry					
		Y20	Y12	X20	X12	S20	S12
Rainfall Hyetographs	Q7T20	0.84	0.38	-1.34	0.27	-0.18	0.23
	Q7T40	0.97	0.96	0.78	0.94	0.86	0.84
	Q7T60	0.98	0.89	0.82	0.95	0.84	0.94
	Q15T20	0.96	0.96	0.91	0.96	0.89	0.88
	Q15T40	0.99	0.98	0.95	0.97	0.97	0.97
	Q15T60	0.99	0.98	0.95	0.98	0.97	0.98
	Q25T20	0.98	0.97	0.95	0.88	0.95	0.89
	Q25T40	0.99	0.99	0.98	0.99	0.96	0.99
	Q25T60	0.99	0.98	0.97	0.99	0.96	0.99

## 54 Simulations

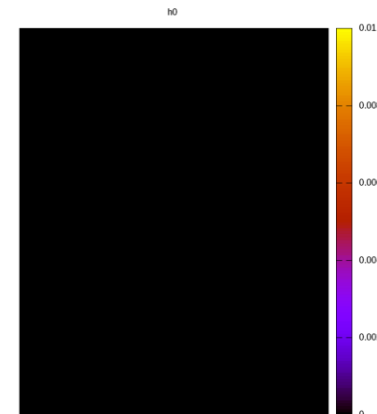
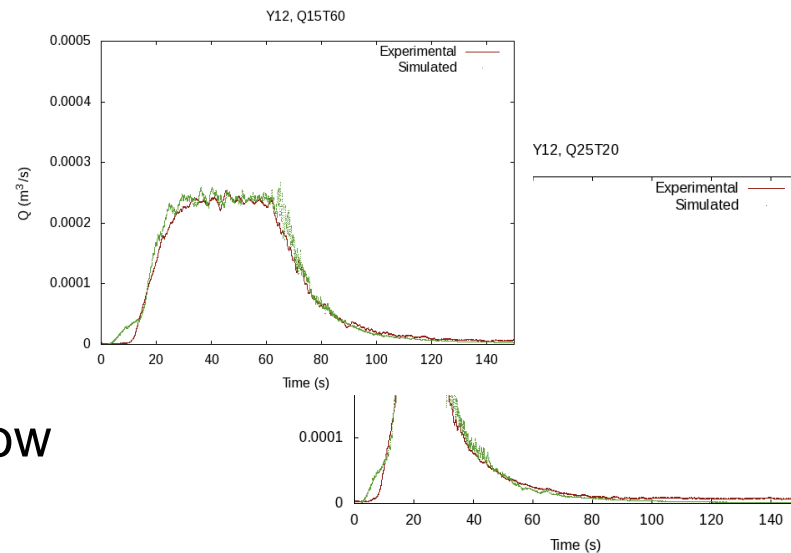
- Building orientations normal to the domain
- 9 rainfall patterns

## Results

- NS Average: 0.84
- NS Low: -1.34
- NS High: 0.99

## Conclusion

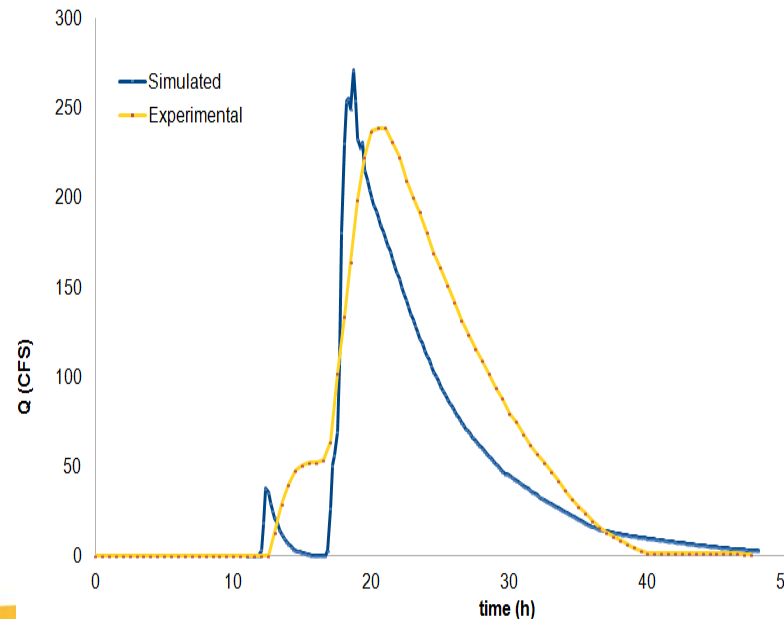
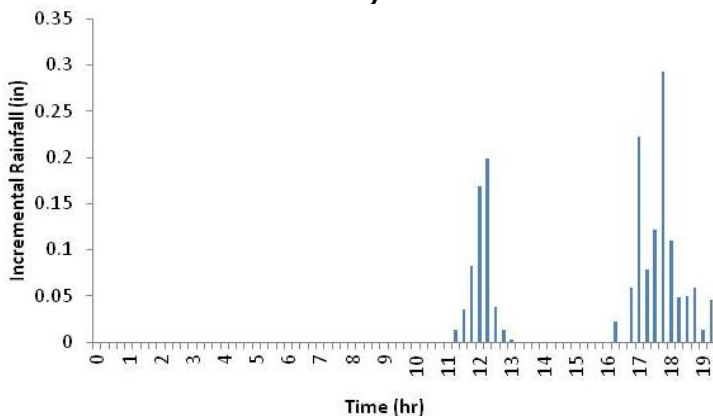
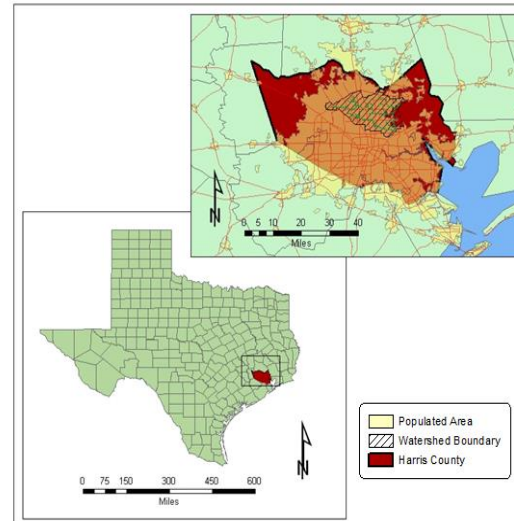
- Numerical formulation adequate to capture dynamics of very shallow water depths
- Missing validation for infiltration



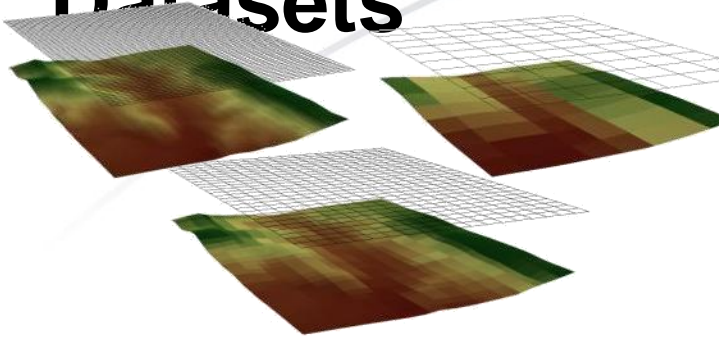
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# Watershed Validation

- Green's Bayou
  - Harris County, TX
  - Watershed area: 196 mi<sup>2</sup>
  - Urban, and open space
- Calibrated soil parameters
  - Conductivity: 1.8-3.2mm/hr
- Event
  - 20 hour rainfall May 23, 1993
- Results
  - NS efficiency 0.74

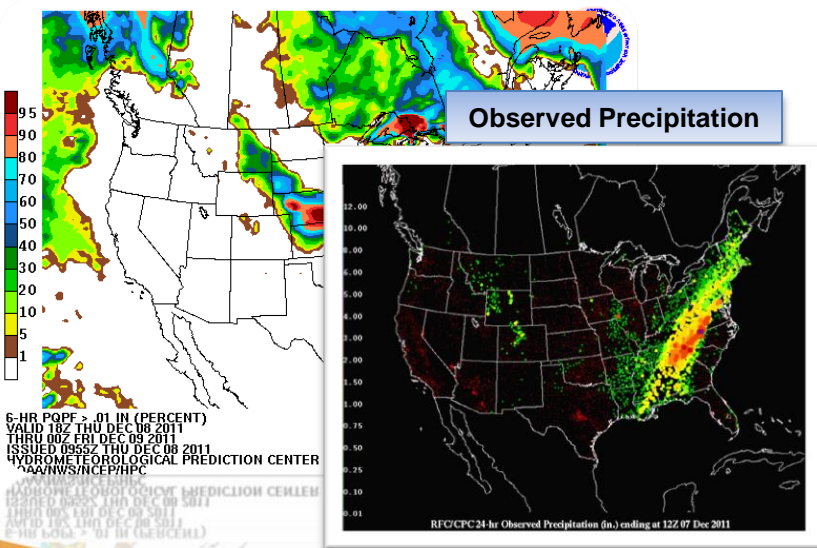


# Data Requirements met by National Los Alamos Datasets



Topographic Resolution

Probabilistic Precipitation



Flood Modeling Data		
Data	Sources	Type
Rainfall	NOAA	Spatial, Temporal
Topography	USGS, State, Local	Spatial
Land Use\Land Cover	NLCD (USGS)	Spatial
Soils	NRCS, Local	Spatial
River Gage	USGS, NOAA, Local	Spatial, Temporal
Levee\Dam	USACE	Spatial
Infrastructure	HSIP, State, Local	Spatial

- Spatial & Temporal Resolution
- Dynamic Data Feeds

**MTON8 Forest River at Minto (North Dakota)**

Current Hydrologic Observations for North Dakota provided by the National Weather Service - Advanced Hydrologic Prediction Service

**Observation - MTON8 - Forest River at Minto (North Dakota)**

Flood Stage: 6 ft

Latest Observation: 1.38 ft  
 Observation Time: Dec 12, 2011 04:15 PM CST

AHPS Hydrologic Service Area Homepage:  
<http://water.weather.gov/ahps2/index.php?vfo=fgf>

<http://water.weather.gov/ahps2/rss/obs/mton8.rss>

**LITA4 Arkansas River at Little Rock (Arkansas)**

Current Hydrologic Forecasts for Arkansas provided by the National Weather Service - Advanced Hydrologic Prediction Service

**Forecast - LITA4 - Arkansas River at Little Rock (Arkansas)**

Flood Stage: 23 ft

Latest Observation: 7.76 ft  
 Observation Time: Dec 12, 2011 01:00 PM CST

Highest Forecast Within Next 48 Hours: 7.7 ft  
 Highest Forecast Time: Dec 14, 2011 12:00 PM CST

Last Forecast: 7.5 ft  
 Last Forecast Time: Dec 17, 2011 06:00 AM CST

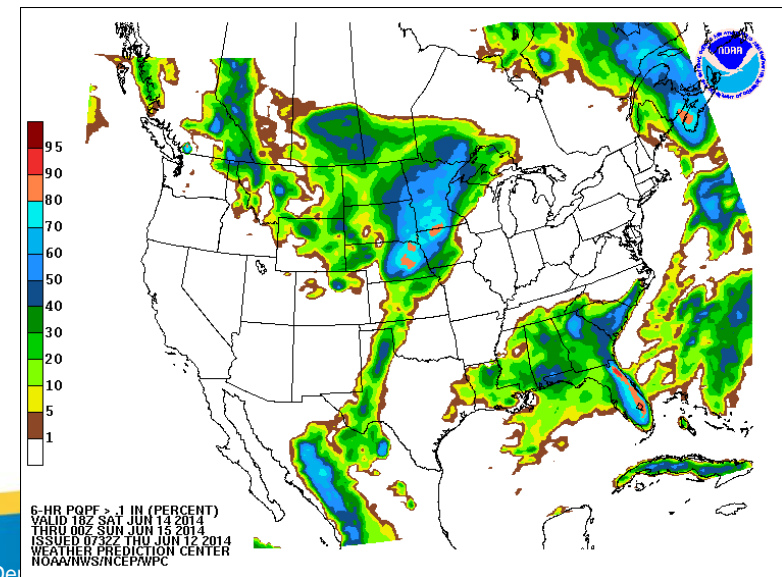
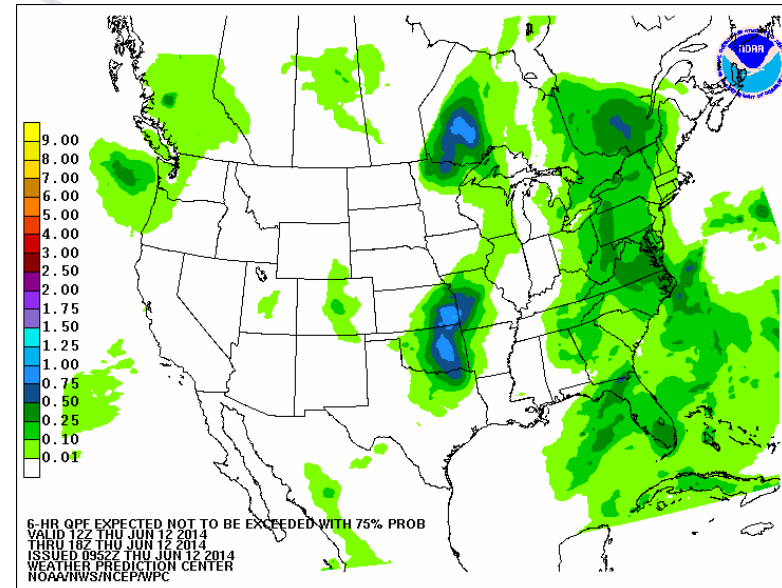
AHPS Hydrologic Service Area Homepage:  
<http://water.weather.gov/ahps2/index.php?vfo=lak>

<http://water.weather.gov/ahps2/rss/fcst/lita4.rss>

## Forecast vs. Observation

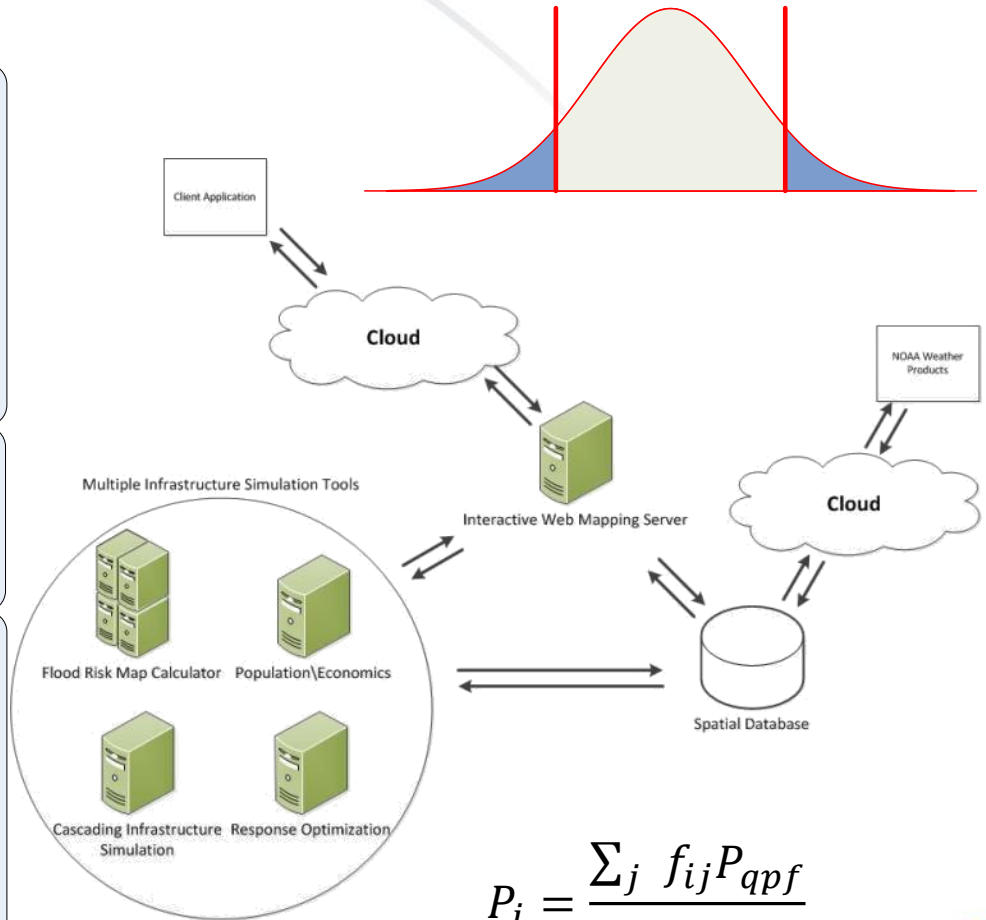
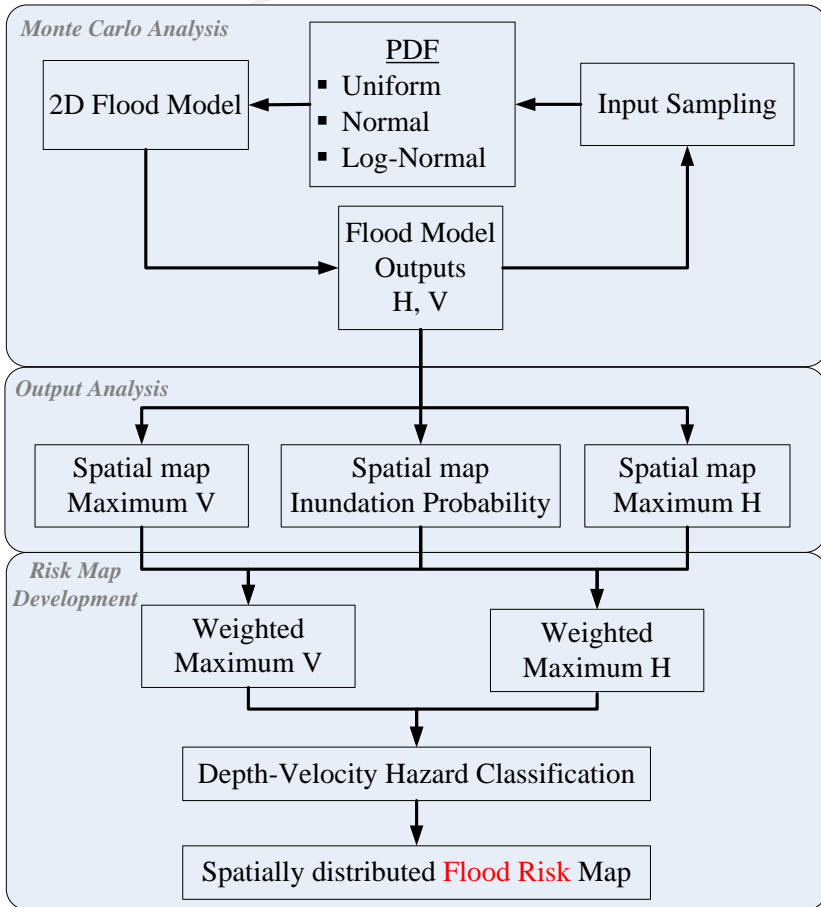
# Probabilistic Precipitation

- PQPF (NOAA HPC)
  - “Give users an idea of where to begin to focus mitigation services before an event”
  - 72-hour forecast, 6-hour time intervals
- Datasets Available:
  - Percentiles of non-exceedance (%):
    - 5, 10, 25, 50, 75, 90, 95
  - Probability of exceeding threshold (inches):
    - 0.01, 0.1, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3



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# PQPF Integration in Flood M&S

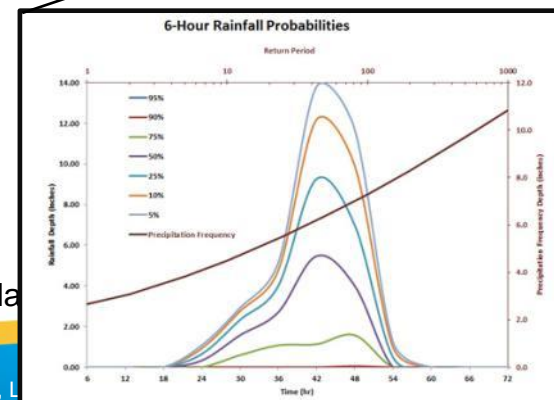
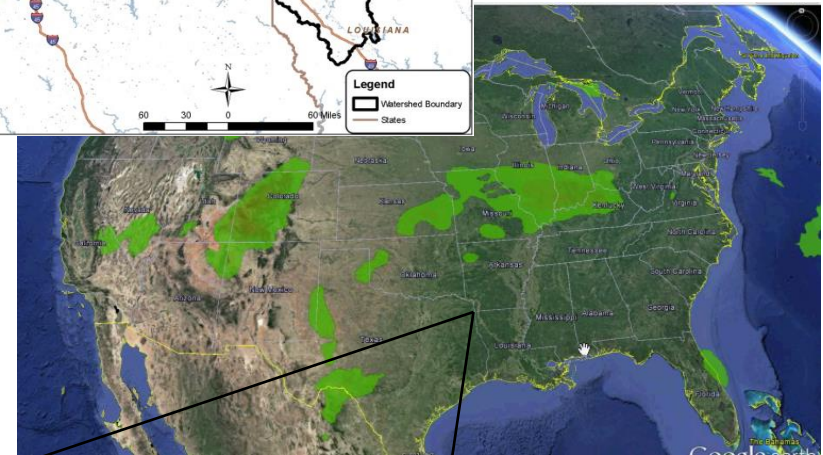
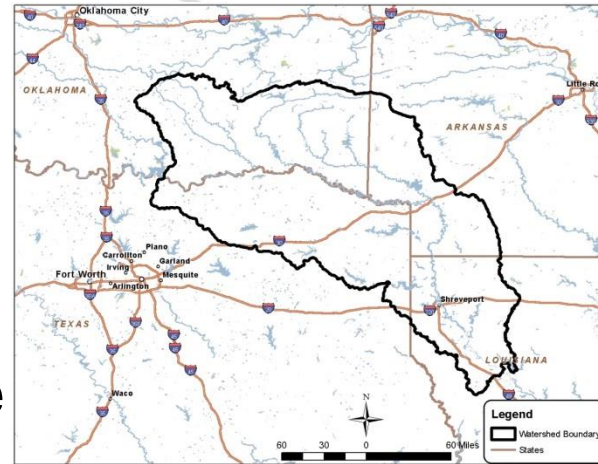


$$P_i = \frac{\sum_j f_{ij} P_{qpf}}{\sum_j P_{qpf}}$$

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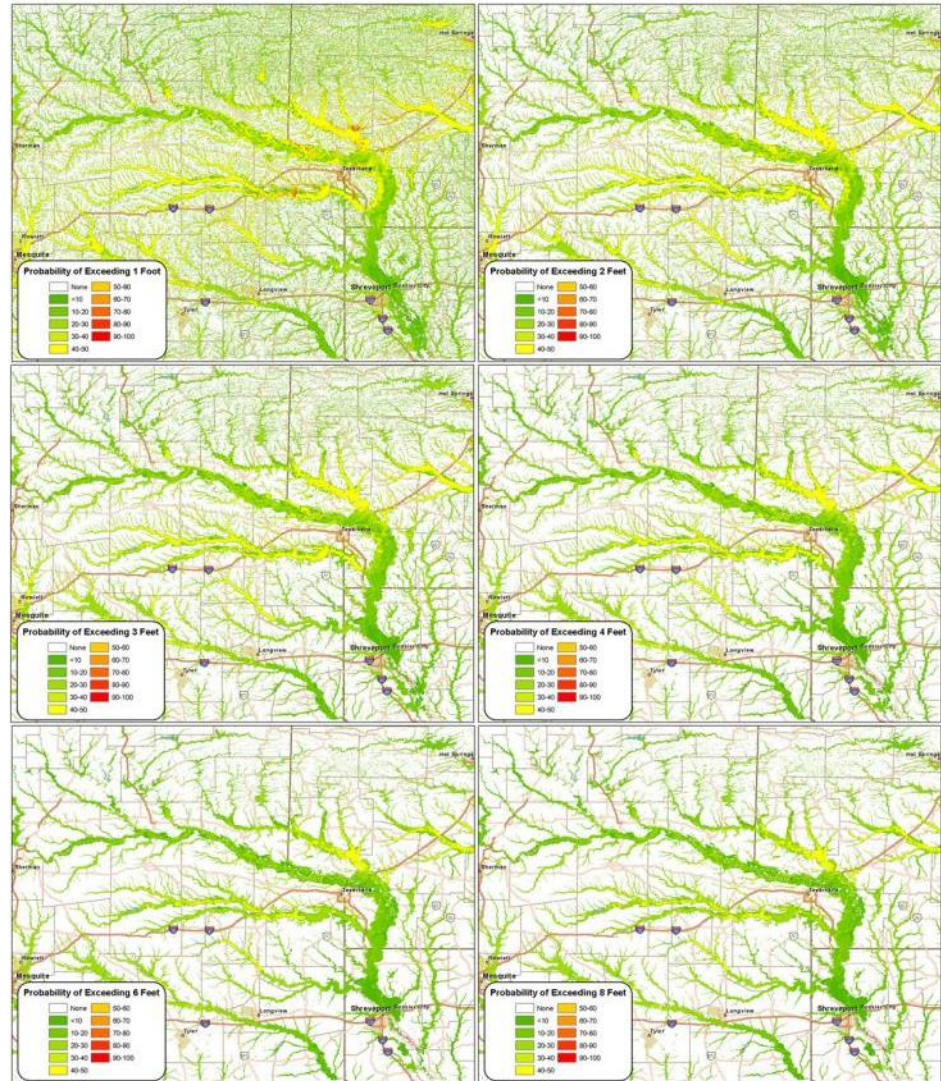
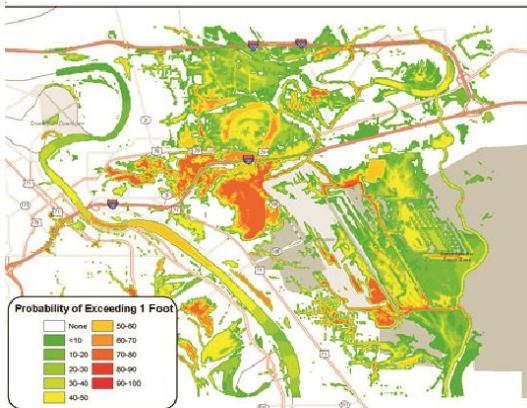
# PQPF Case Study

- Watershed
  - Lower Red sub-basin (HUC 1114)
  - Red River, tributary of the Mississippi
  - Forms border between Texas and Arkansas
  - Area: 2,400 mi<sup>2</sup>
  - Elevation: 1320 to 574 ft above MSL
- PQPF
  - “Modified” event



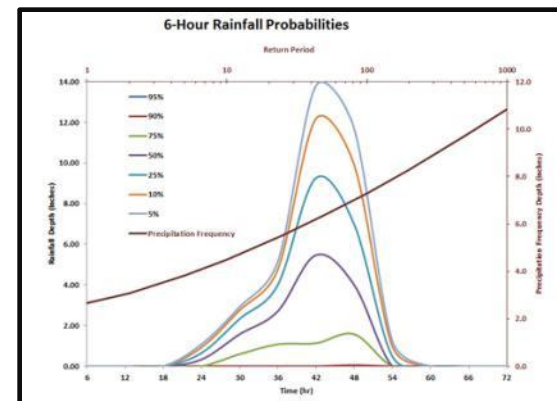
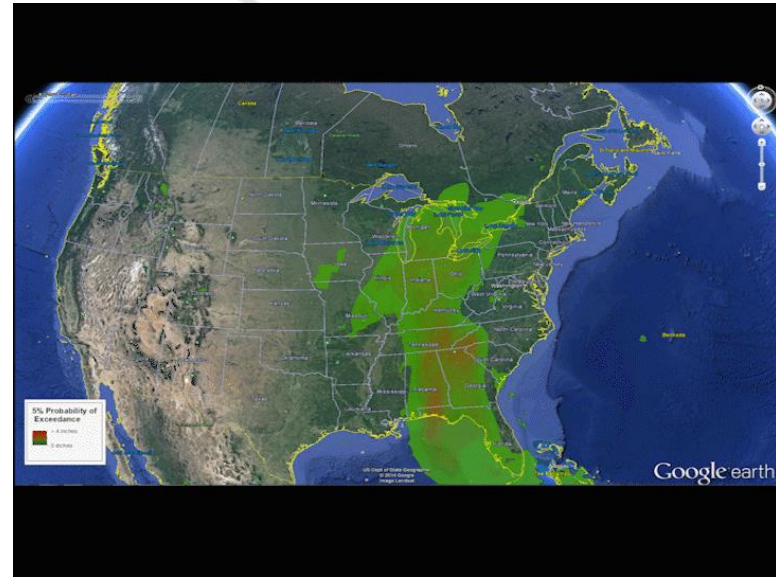
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# PQPF to Flood Depth Exceedance Maps



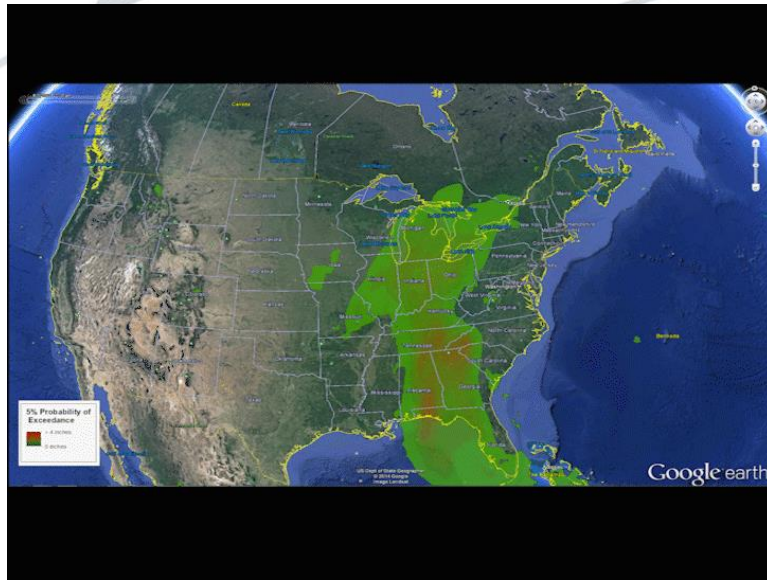
# Situational Awareness

- PQPF Challenges
  - When should a PQPF be considered for simulation?
- PQPF Analysis
  - Comparison of forecasted PQPF against precipitation frequency distribution curves (show map here).
  - Notification when event crosses return period threshold (e.g., 50 year)

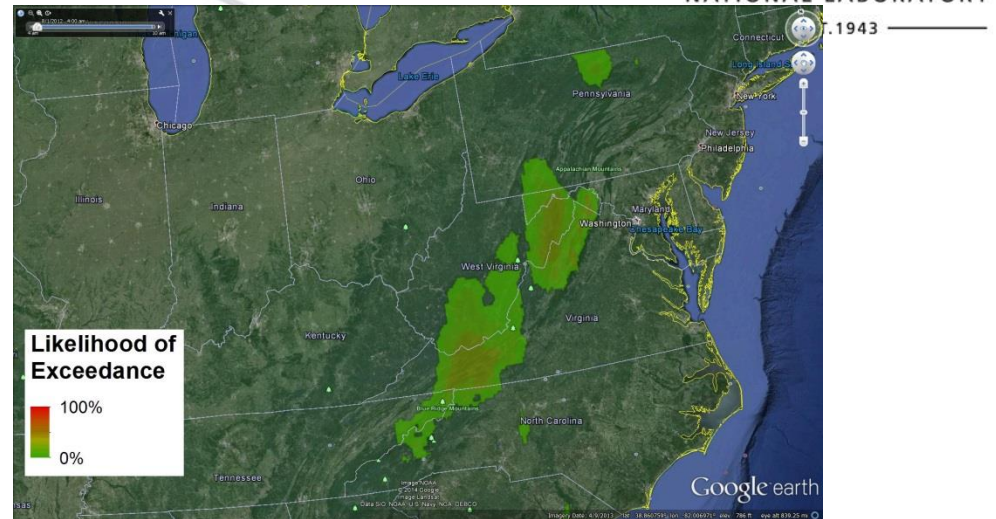


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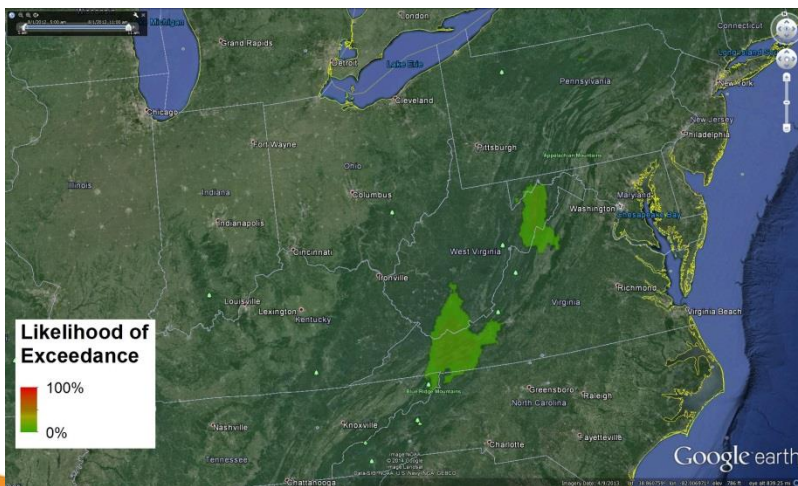
# Situational Awareness



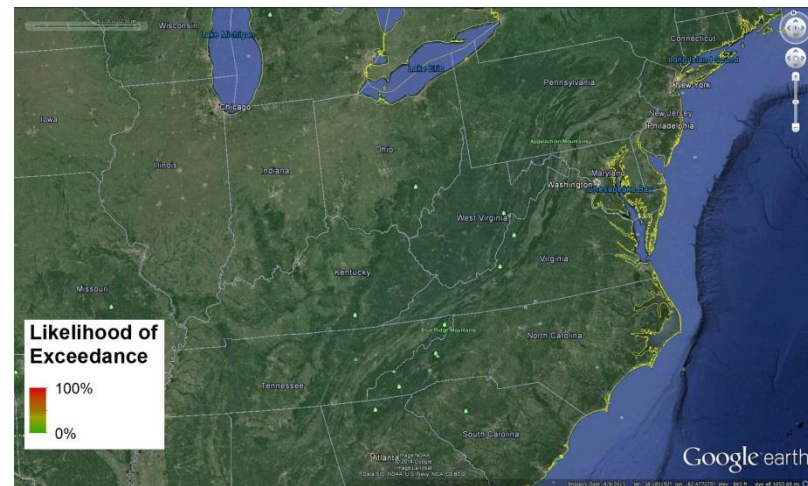
Raw PQPF



1-Yr Event



2-Yr Event



Unclassified

25-Yr Event