Distributed hydrologic modeling with satellite precipitation data

Phu Nguyen, Soroosh Sorooshian

Kuolin Hsu, Amir AghaKouchak, Andrea Thorstensen

June 12, 2017

Presentation Outline

- Introduction
- Research Objectives
- Development of HiResFlood-UCI
- Calibration of HiResFlood-UCI
- Statistical Metrics
- Implementation of HiResFlood-UCI for ELDO2
- Testing HiResFlood-UCI with Synthetic Precipitation
- Validating HiResFlood-UCI using NEXRAD Stage 4 Data
- Application of HiResFlood-UCI for flood forecasting
- Summary and Future Direction

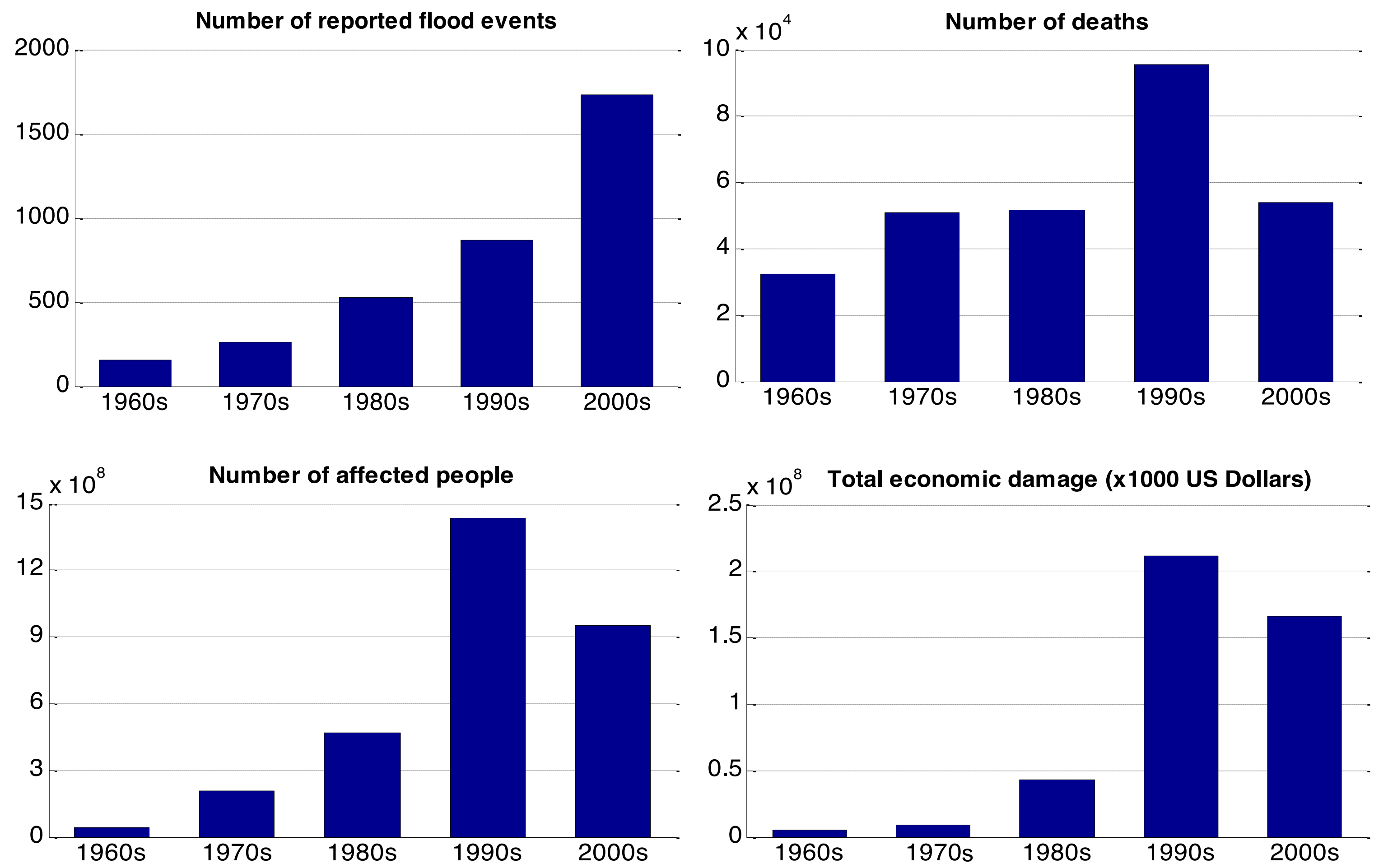
Introduction

Definitions of flood and flash flood

Flood: A flood happens when prolonged rainfall over several days, intense rainfall over a short period of time, or an ice or debris jam causes a river or stream to overflow and flood the surrounding area.

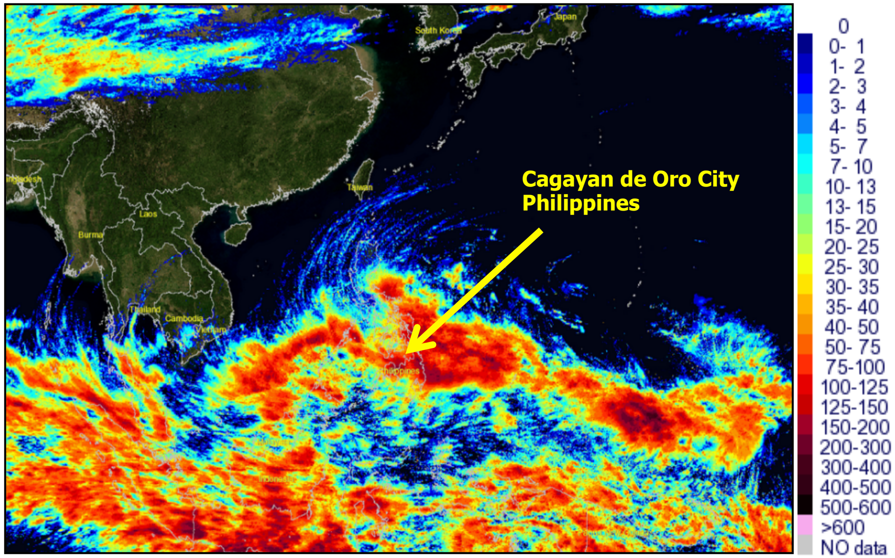
Flash flood: A flood caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours.

Introduction



Flood statistics from 1950 to 2010 using data from Center for Research on the Epidemiology of Disasters (CRED)

Introduction



(left) Tropical storm Washi monitored on CHRS G-WADI PERSIANN-CCS Server (mm) from 00:00 12/15/2011 to 00:00 12/18/2011 UTC; (right) Cagayan de Oro City, Philippines (December 2011) washed out by the flash flood (AP 2011), 1,268 fatalities

Improving flood warnings in regions prone to hydrologic extremes is one highest priority of watershed managers to prevent/mitigate loss of lives and adverse economic impacts caused by this type of natural hazards.

Introduction

Modeling floods

Hydrologic models

Lumped

- Lumped with routing
- Lumped with some spatial representation

Empirical

- Simple equations: Regression, Tanh, ARMA
- Empirical model: IHACRES

Conceptual

- Simple conceptual: Simple bucket, SFB
- SIMHYD, AWBM
- Complex conceptual: HYDROLOG, Sacramento, Stanford

Distributed

MIKE-SHE
HL-RDHM
VIC
PCR-GLOB
CHyM

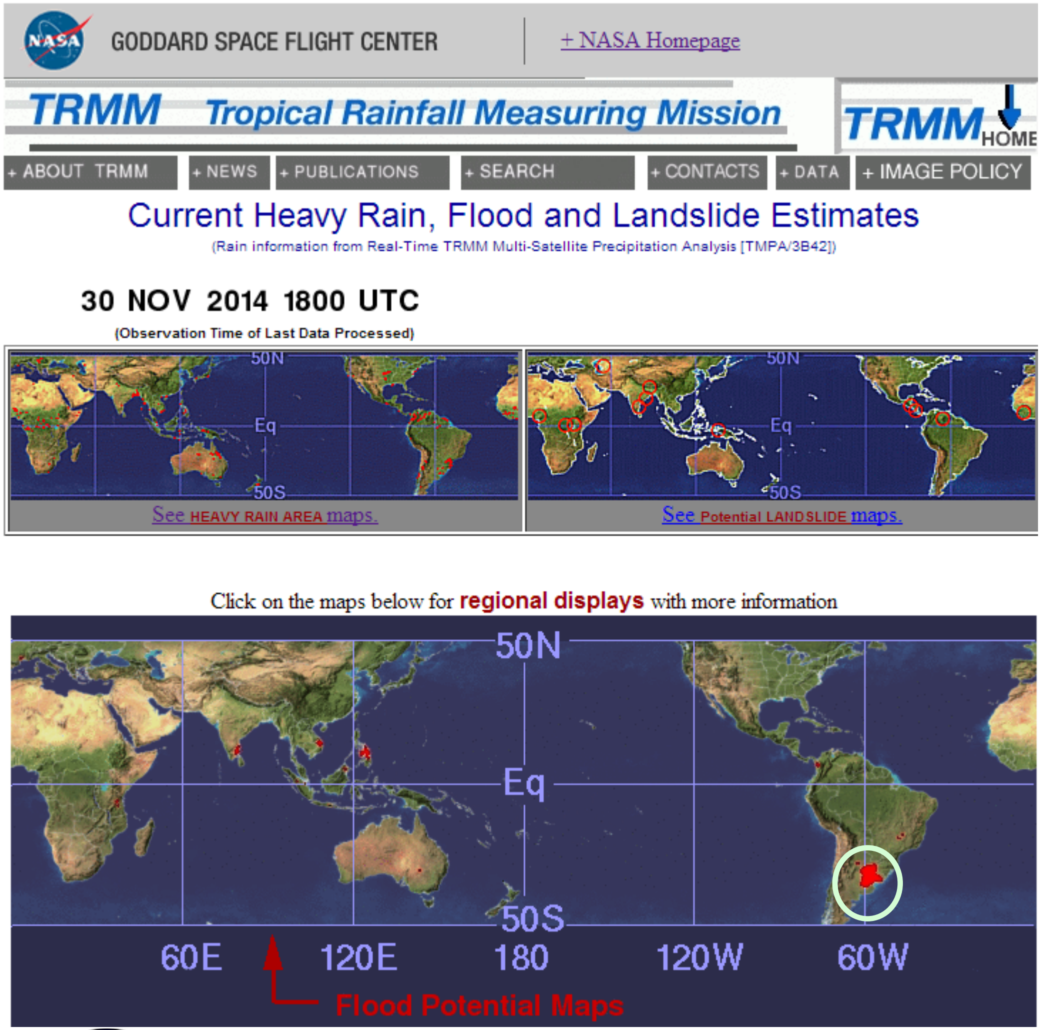
Simple → More physically - based

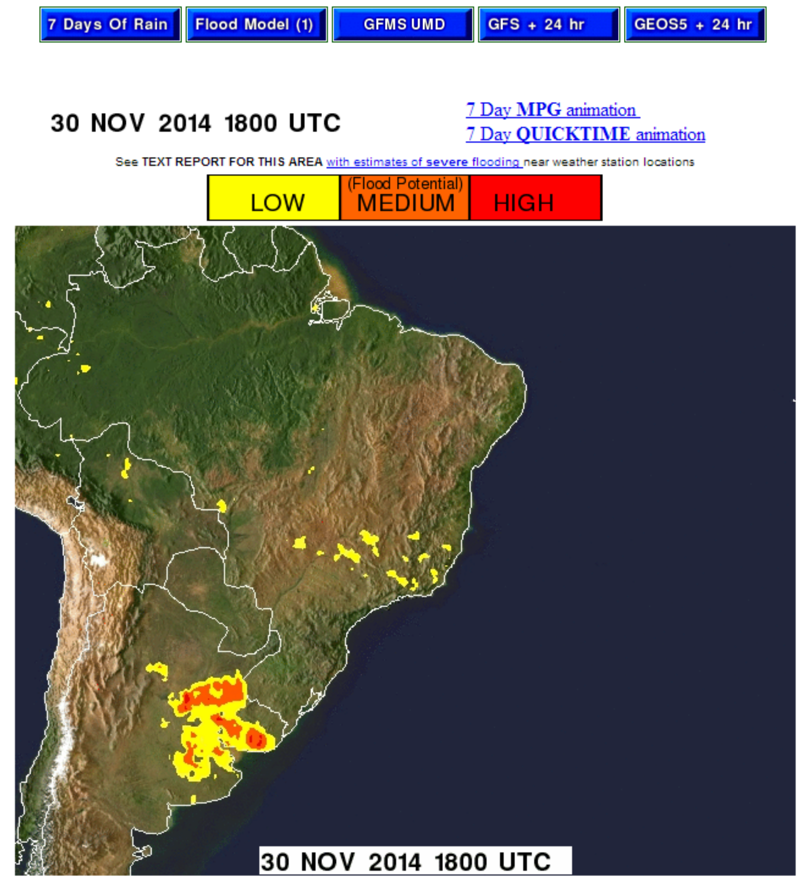
Hydraulic models

Muskingum | Chanel shape method | Rating curve | Finite element

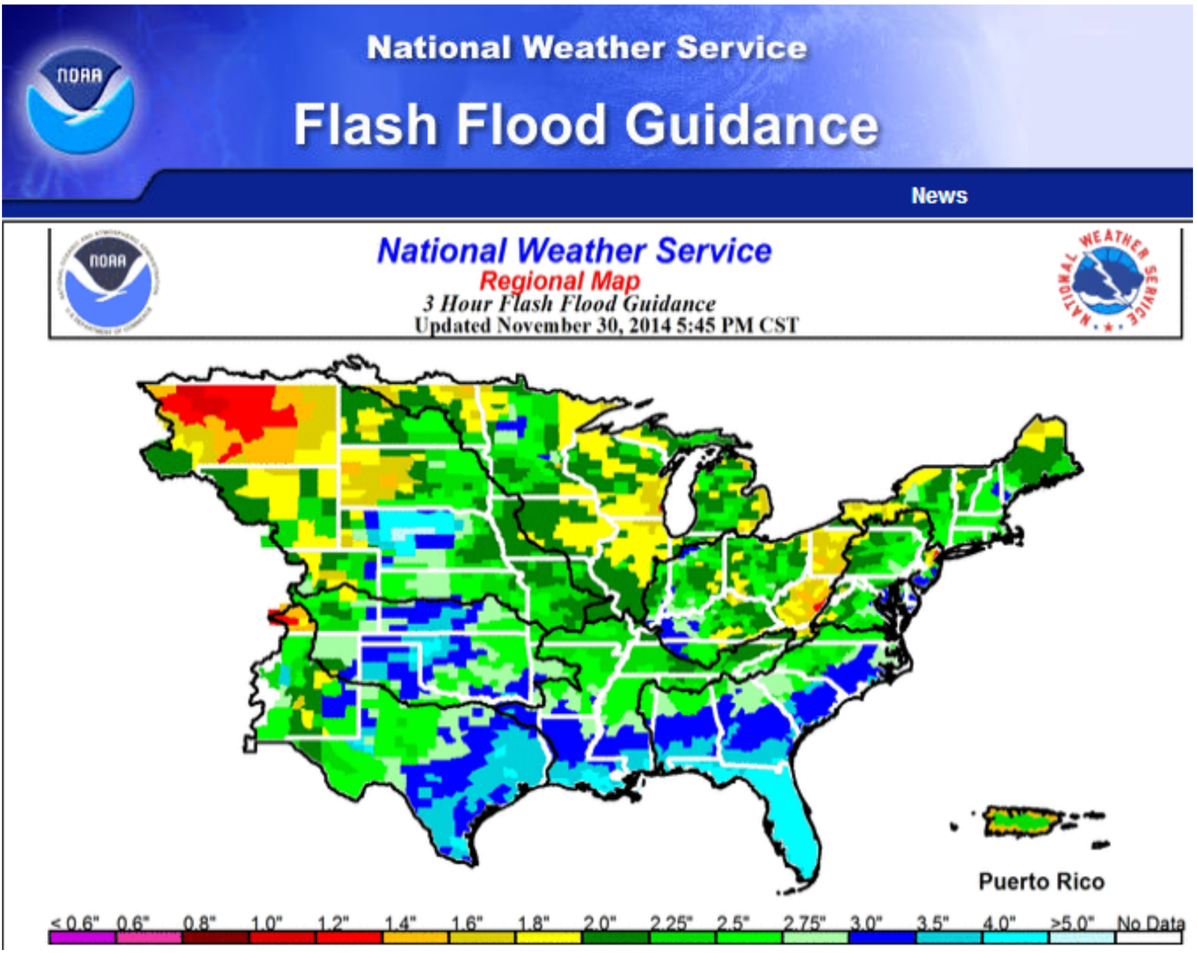
Introduction

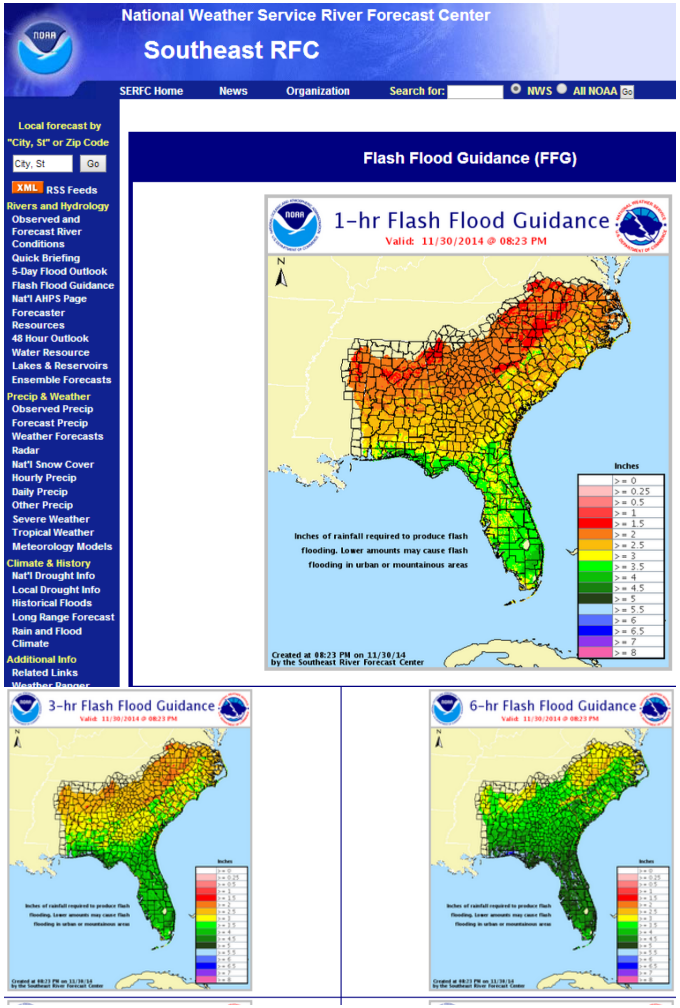
NASA's Natural Hazard Monitoring





NWS's Flash Flood Guidance

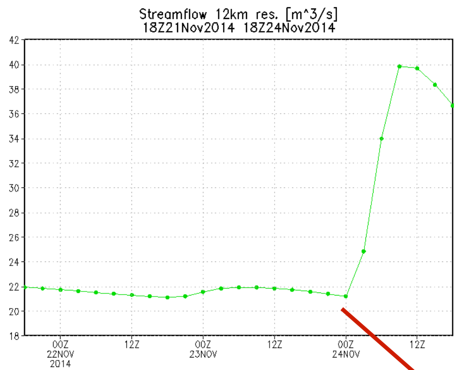


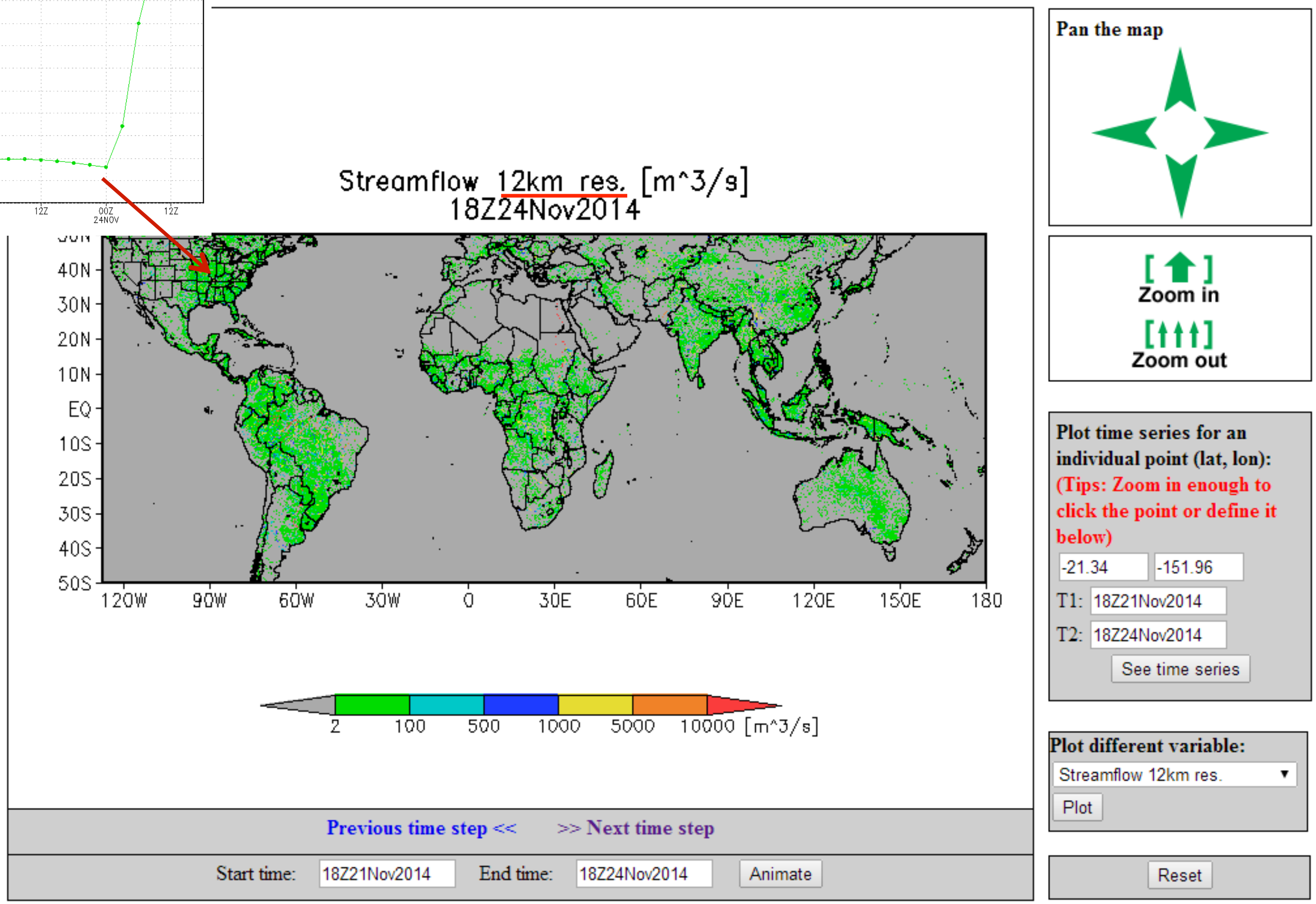


Global Flood Monitoring System (GFMS)

University of Maryland

Flood.umd.edu





Research Objectives

- Developing HiResFlood-UCI for flood modeling purposes.
- Developing a semi-automated technique of efficient unstructured mesh generation for HiResFlood-UCI.
- Testing the sensitivities of HiResFlood-UCI with synthetic precipitation data.
- Validating HiResFlood-UCI for both streamflow and flooded maps for real extreme precipitation events.
- Applying HiResFlood-UCI for flood forecasting using near real-time remote sensing precipitation data.

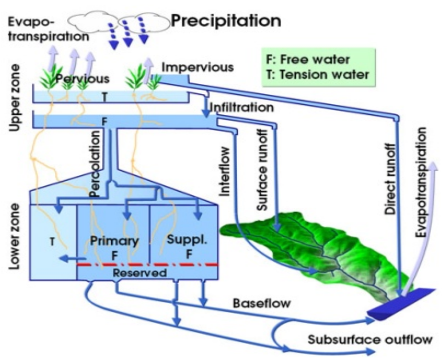
Development of HiResFlood-UCI

Model Heritage

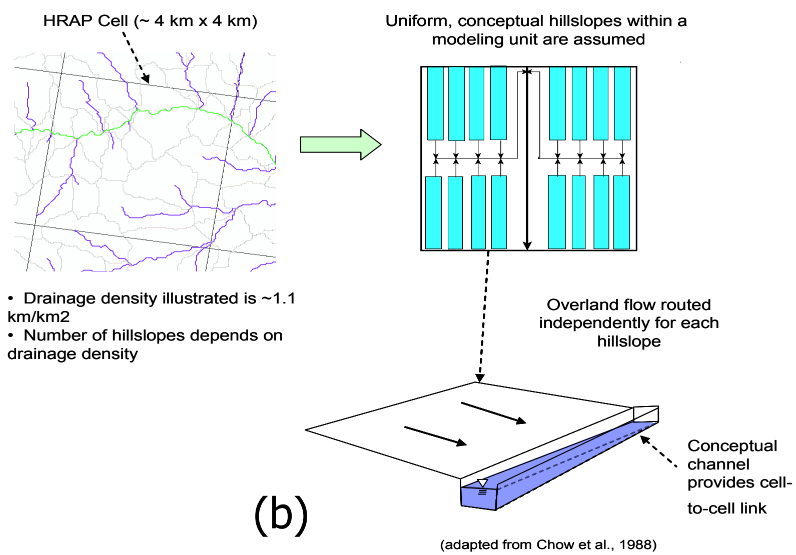
HL-RDHM

HL-RDHM involves four main components: snow-17, SAC-SMA, Continuous API and Overland and Channel Routings (Rutpix7, Rutpix9).

HL-RDHM was designed and implemented for the entire CONUS at two spatial resolutions of 1 HRAP (~4km) and 1/2 HRAP (~2km).



(a)



(b)

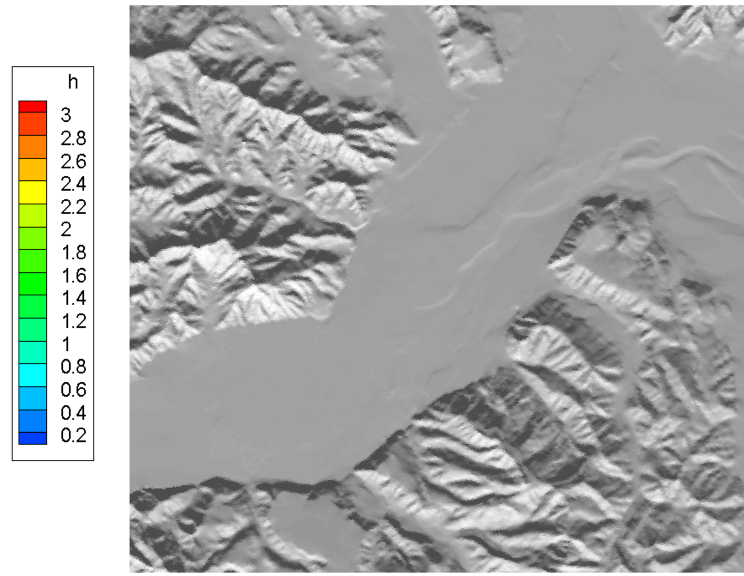
HL-RDHM model: (a) SAC component, (b) Routing scheme

Development of HiResFlood-UCI

Model Heritage

BreZo

Hydraulic model solving the shallow-water equations using a Godunov-type finite volume algorithm that has been optimized for wetting and drying applications involving natural topography and runs on an unstructured grid of triangular cells



Demo of BreZo simulation

Development of HiResFlood-UCI

Coupling HL-RDHM with BreZo

Rainfall, Temperature data

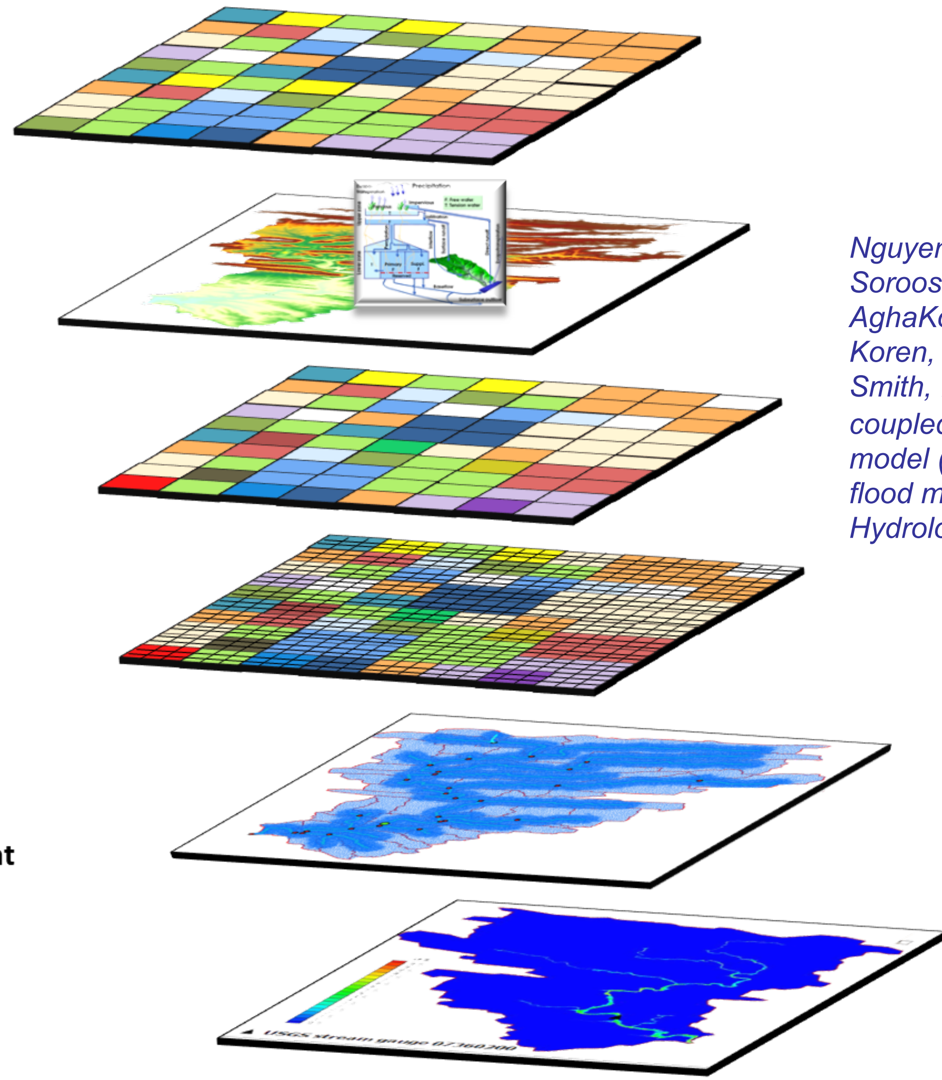
HL-RDHM Rainfall-Runoff generation

Runoff

Regridding Runoff

Zoning Runoff to Subcatchment Point Source

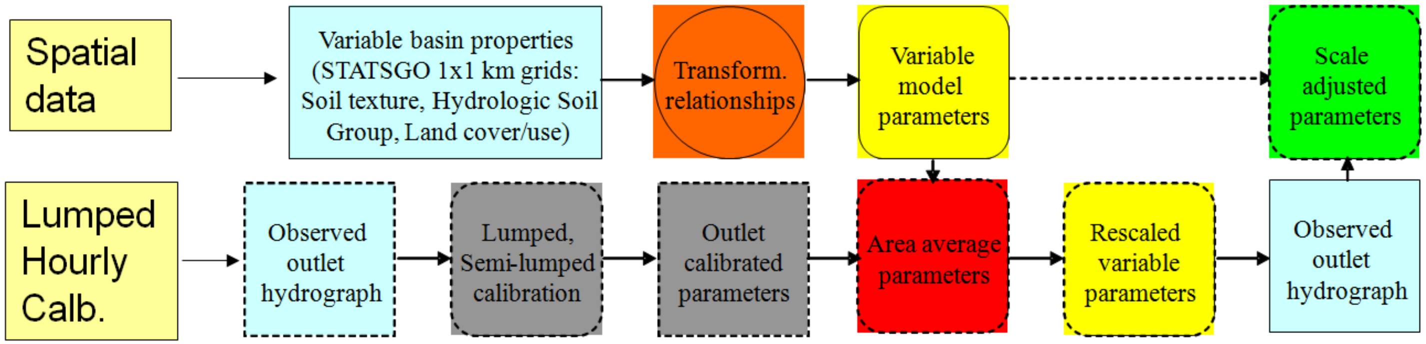
BreZo Simulation



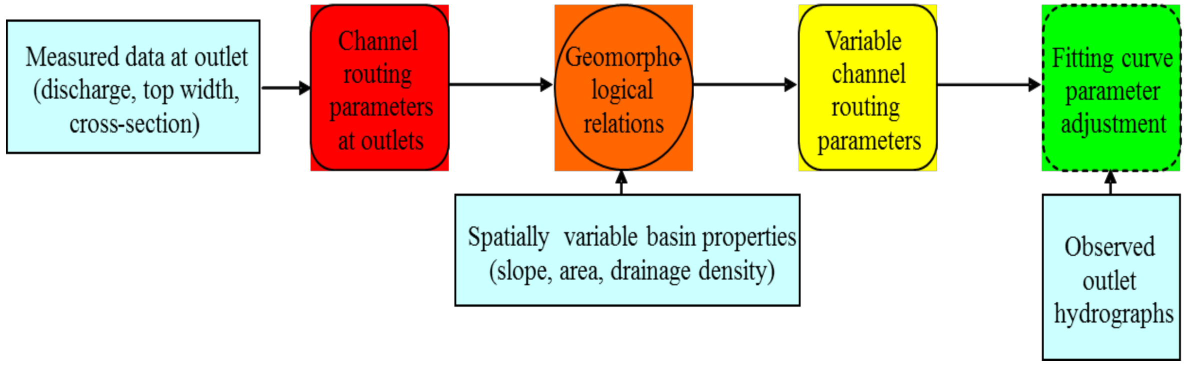
Nguyen, P., A. Thorstensen, S. Sorooshian, K. Hsu, A. AghaKouchak, B. Sanders, V. Koren, Z. Cui, and Michael Smith, 2015. A high resolution coupled hydrologic-hydraulic model (HiResFlood-UCI) for flash flood modeling. Journal of Hydrology. 2015.

Calibration of HiResFlood-UCI

Calibration of HL-RDHM Component



Schematic diagram of SAC-SMA parameter calibration process (Smith *et al.*, 2006)



Schematic diagram of channel routing parameter calibration process (Smith et al., 2006)

Calibration of HiResFlood-UCI

Calibration of BreZo

$$NSE = 1 - \frac{\sum_{t=1}^{n}(q_s(t) - q_o(t))^2}{\sum_{t=1}^{n}(q_o(t) - \overline{q_o})^2}$$

where **n** is the total number of observations, $\mathbf{q_o}$ is the observed discharge (m^3/s), and $\mathbf{q_s}$ is the simulated discharge (m^3/s) for each time step **t**.

Statistical Metrics

Point Comparison

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(q_o(t) - q_s(t)\right)^2}$$

$$\mathrm{BIAS} = \frac{\sum_{t=1}^{n}\left(q_s(t) - q_o(t)\right)}{\sum_{t=1}^{n} q_o(t)}$$

$$\mathrm{CORR} = \frac{\sum_{t=1}^{n}\left(q_o(t) - \bar{q}_o\right)\sum_{t=1}^{n}\left(q_s(t) - \bar{q}_s\right)}{\sqrt{\sum_{t=1}^{n}\left(q_o(t) - \bar{q}_o\right)^2}\sqrt{\sum_{t=1}^{n}\left(q_s(t) - \bar{q}_s\right)^2}}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{n}\left(q_s(t) - q_o(t)\right)^2}{\sum_{t=1}^{n}\left(q_o(t) - \overline{q_o}\right)^2}$$

where **n** is the total number of observations, $\mathbf{q_o}$ is the observed discharge (m^3/s), and $\mathbf{q_s}$ is the simulated discharge (m^3/s) for each time step **t**.

Statistical Metrics

Spatial Comparison

		AWiFS image	
		Flooded	Not flooded
Predicted by HiResFlood-UCI	Flooded	Hit	False alarm
	Not flooded	Miss	-

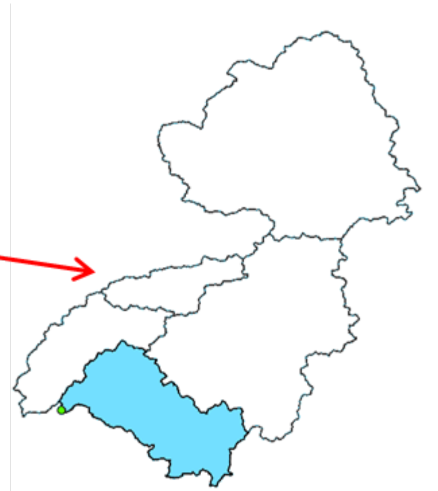
$$\text{Probability of Detection POD} = \frac{\text{hits}}{\text{hits} + \text{misses}}$$

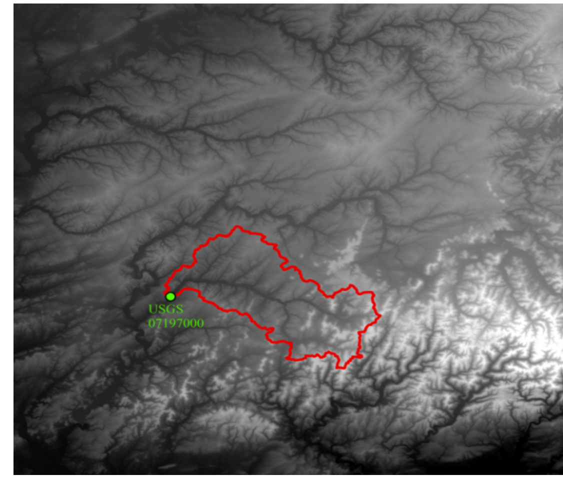
$$\text{False Alarm Ratio FAR} = \frac{\text{false alarms}}{\text{hits} + \text{false alarms}}$$

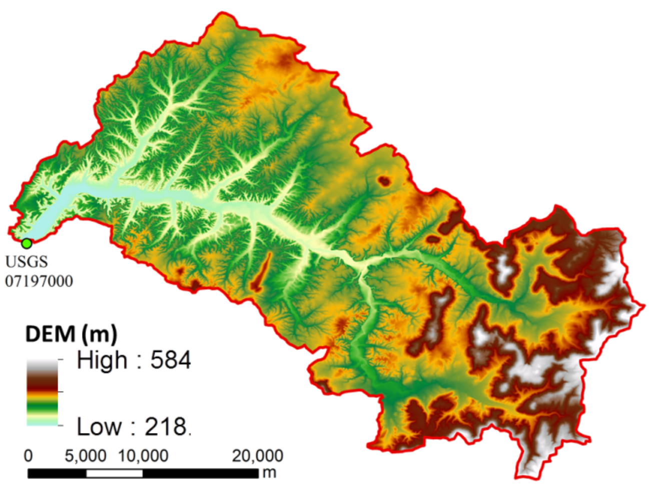
$$\text{Critical Success Index CSI} = \frac{\text{hits}}{\text{hits} + \text{misses} + \text{false alarms}}$$

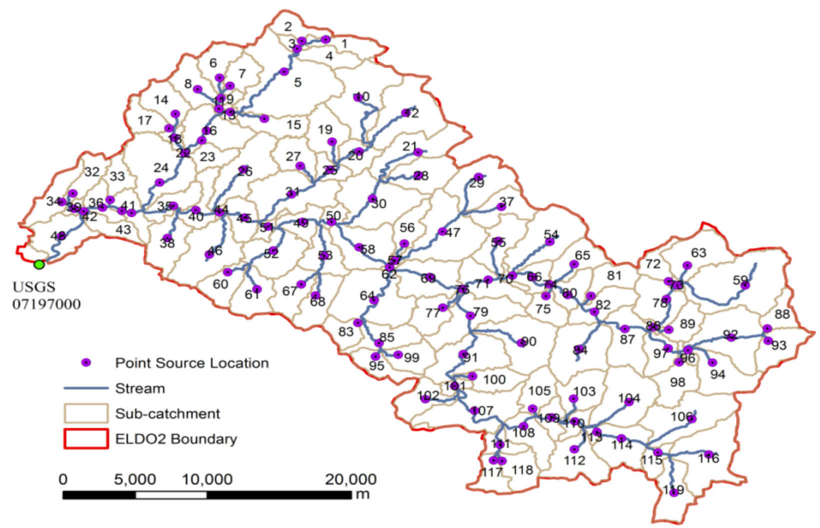
Implementation of HiResFlood-UCI for ELDO2

Watershed Delineation



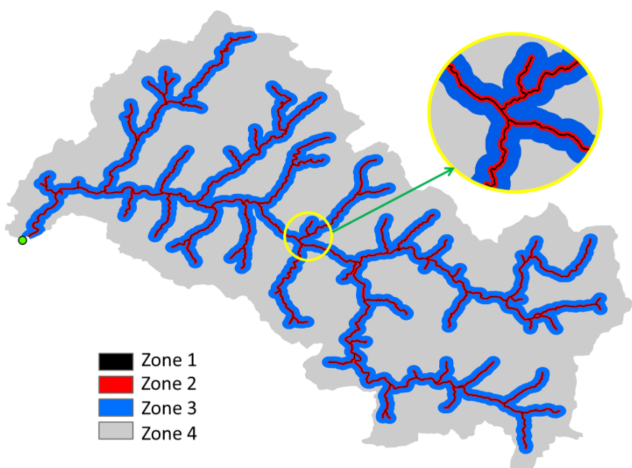


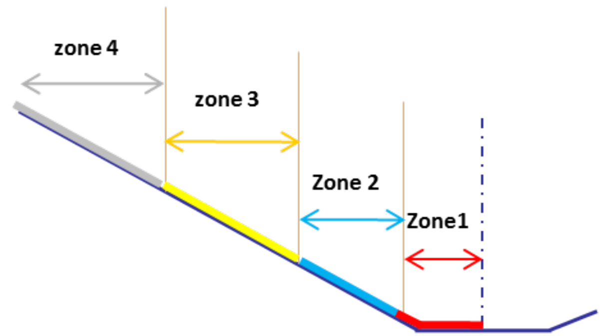




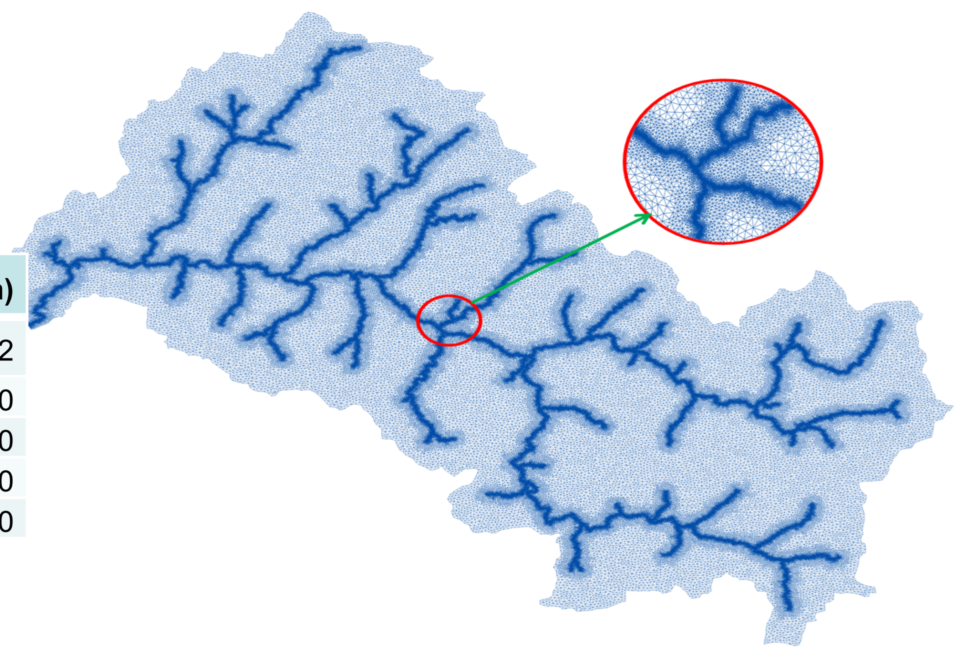
Implementation of HiResFlood-UCI for ELDO2

Mesh Design using ArcGIS and Triangle (Shewchuk, 1996)





Buffer zone	Distance from Stream (m)	Mesh Resolution (m)	
		Case 1	Case 2
1	25	10	30
2	100	30	50
3	500	100	100
4	5000	200	200



Testing HiResFlood-UCI with Synthetic Input

Testing HiResFlood-UCI with Synthetic Input

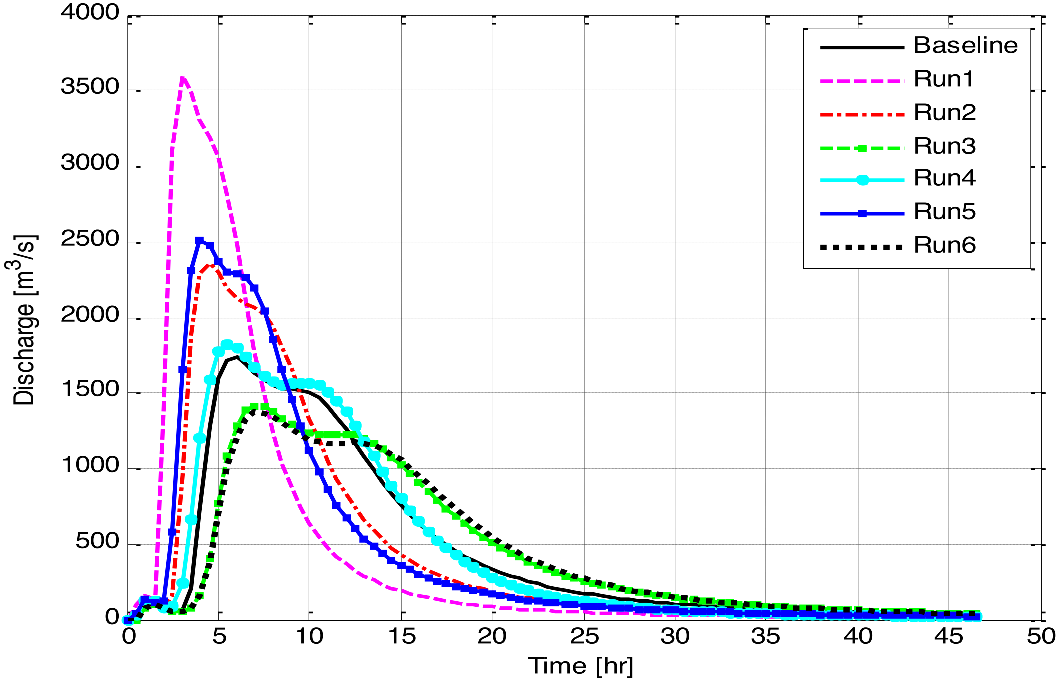
87.38 mm/hr from the partial duration series (PDS)-based precipitation frequency estimates with 90% confidence intervals for 2 hours, 1% probability at USGS 7197000.

Scenario Description

Simulation	Manning value – Channel	Manning value – Floodplain	HL-RDHM	DEM	Mesh Resolution
Baseline	0.0925	0.0975	Calibrated	10m	Case 1 (10m+)
Run1	0.0350	0.0350	Calibrated	10m	Case 1 (10m+)
Run2	0.0638	0.0663	Calibrated	10m	Case 1 (10m+)
Run3	0.1213	0.1288	Calibrated	10m	Case 1 (10m+)
Run4	0.0350	0.1600	Calibrated	10m	Case 1 (10m+)
Run5	0.1500	0.0350	Calibrated	10m	Case 1 (10m+)
Run6	0.1500	0.1600	Calibrated	10m	Case 1 (10m+)
Run7	0.0925	0.0975	**Default**	10m	Case 1 (10m+)
Run8	0.0925	0.0975	Calibrated	**30m**	Case 1 (10m+)
Run9	0.0925	0.0975	Calibrated	10m	Case 2 **(30m+)**

Testing HiResFlood-UCI with Synthetic Input

Model sensitive to Roughness parameter



Scenario	H_{max} [m]	V_{max} [m/s]	Peak Flow [m³/s]	RMSE [m³/s]	BIAS	NSE	CSI	POD	FAR
Baseline	10.25	5.69	1733.47	-	-	-	0.90	0.90	0.00
Run1	10.26	9.04	3593.42	793.04	0.026	-1.09	0.96	0.96	0.00
Run2	10.19	6.93	2362.20	341.73	0.013	0.61	0.98	1.00	0.02
Run3	10.44	4.22	1414.13	203.55	-0.004	0.86	0.94	0.95	0.01
Run4	10.64	9.04	1822.03	92.07	0.021	0.97	0.96	0.96	0.00
Run5	10.39	6.02	2504.80	435.10	0.011	0.37	0.98	1.00	0.02
Run6	10.59	5.69	1368.55	225.04	-0.004	0.83	0.90	0.90	0.00

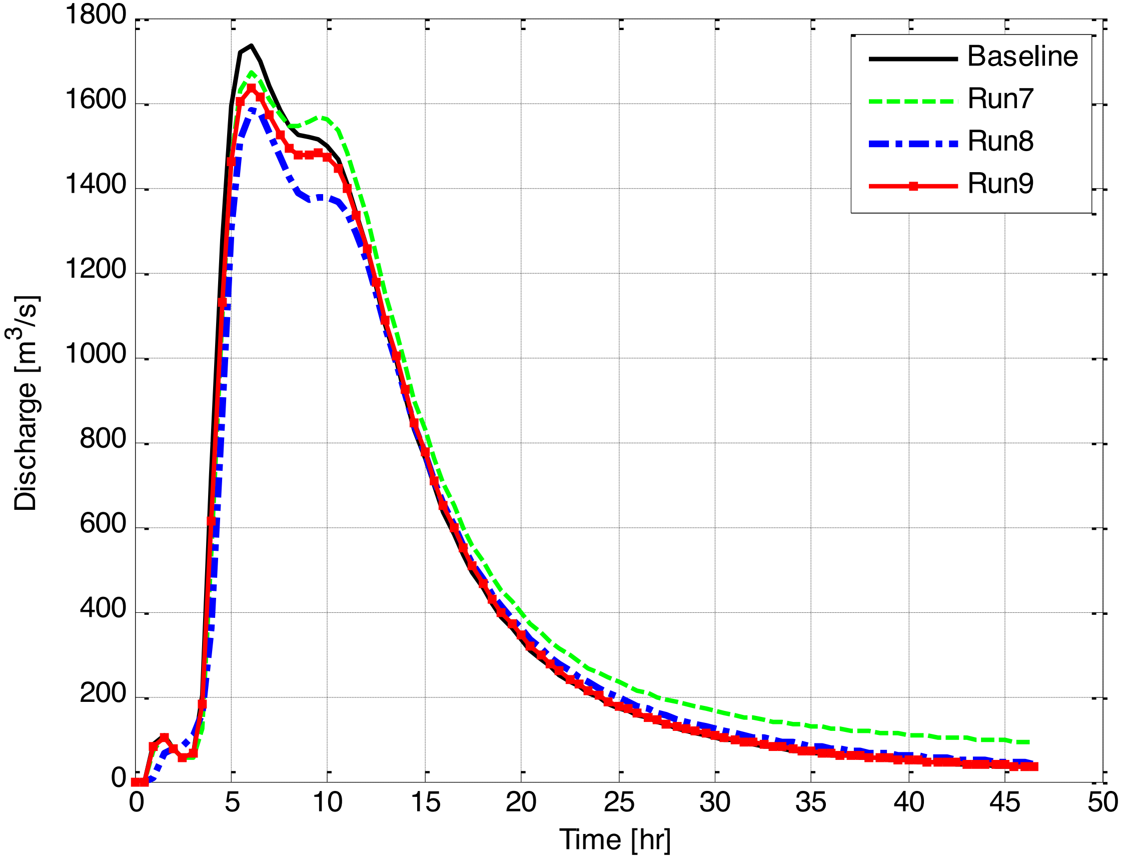
Testing HiResFlood-UCI with Synthetic Input

Testing model with:

* Default HL-RDHM Parameters (Run7)

* DEM Resolution (Run8)

* Mesh Resolution (Run9)

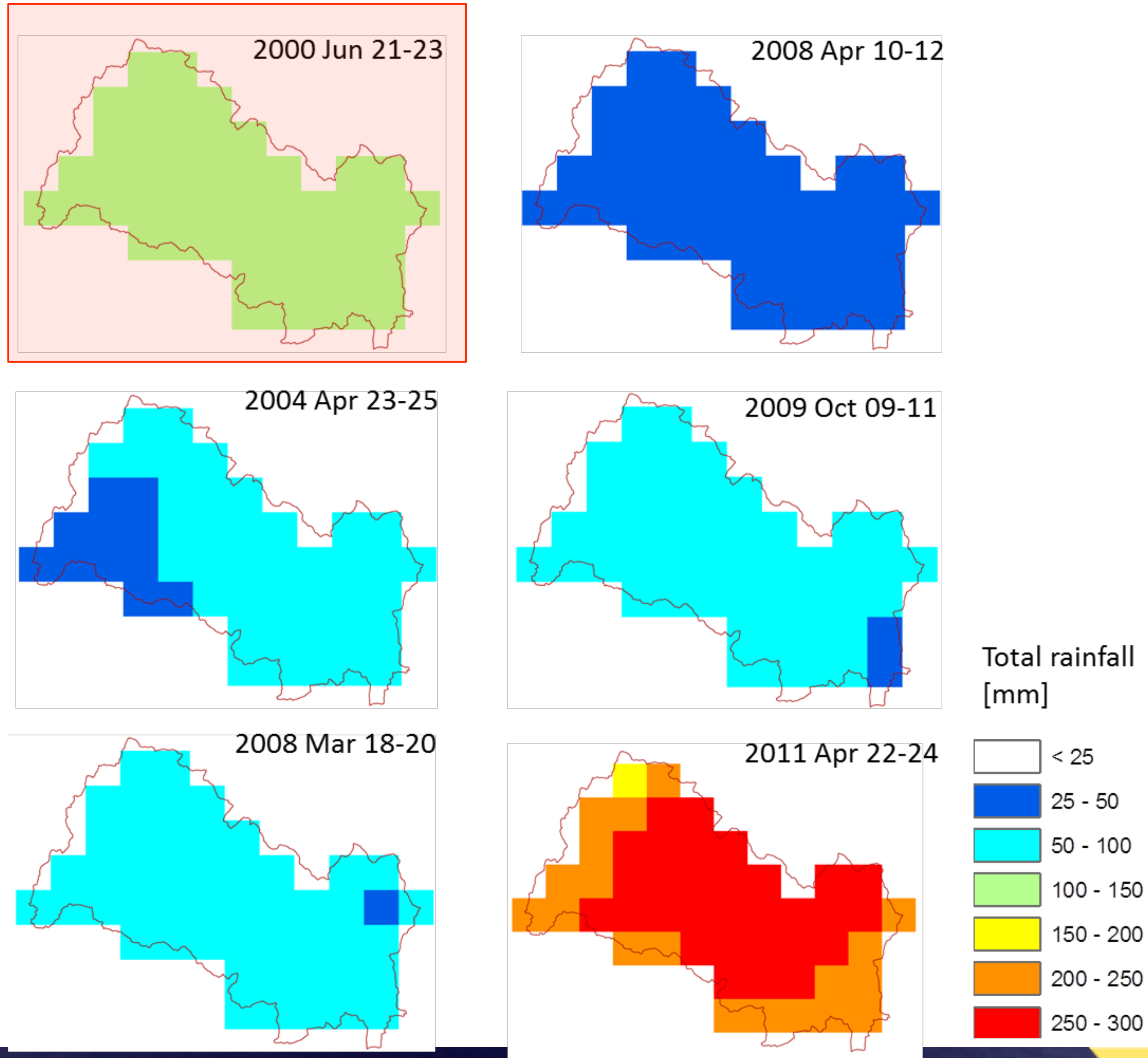


Scenario	H_{max} [m]	V_{max} [m/s]	Peak Flow [m³/s]	RMSE [m³/s]	BIAS	NSE	CSI	POD	FAR
Run7	10.34	5.46	1670.70	65.13	0.09	0.99	0.99	1.00	0.01
Run8	12.43	6.09	1583.30	81.23	-0.04	0.98	0.71	0.85	0.18
Run9	10.07	6.65	1636.67	33.08	-0.02	1.00	0.84	0.99	0.16

Validating HiResFlood-UCI with NEXRAD Stage 4

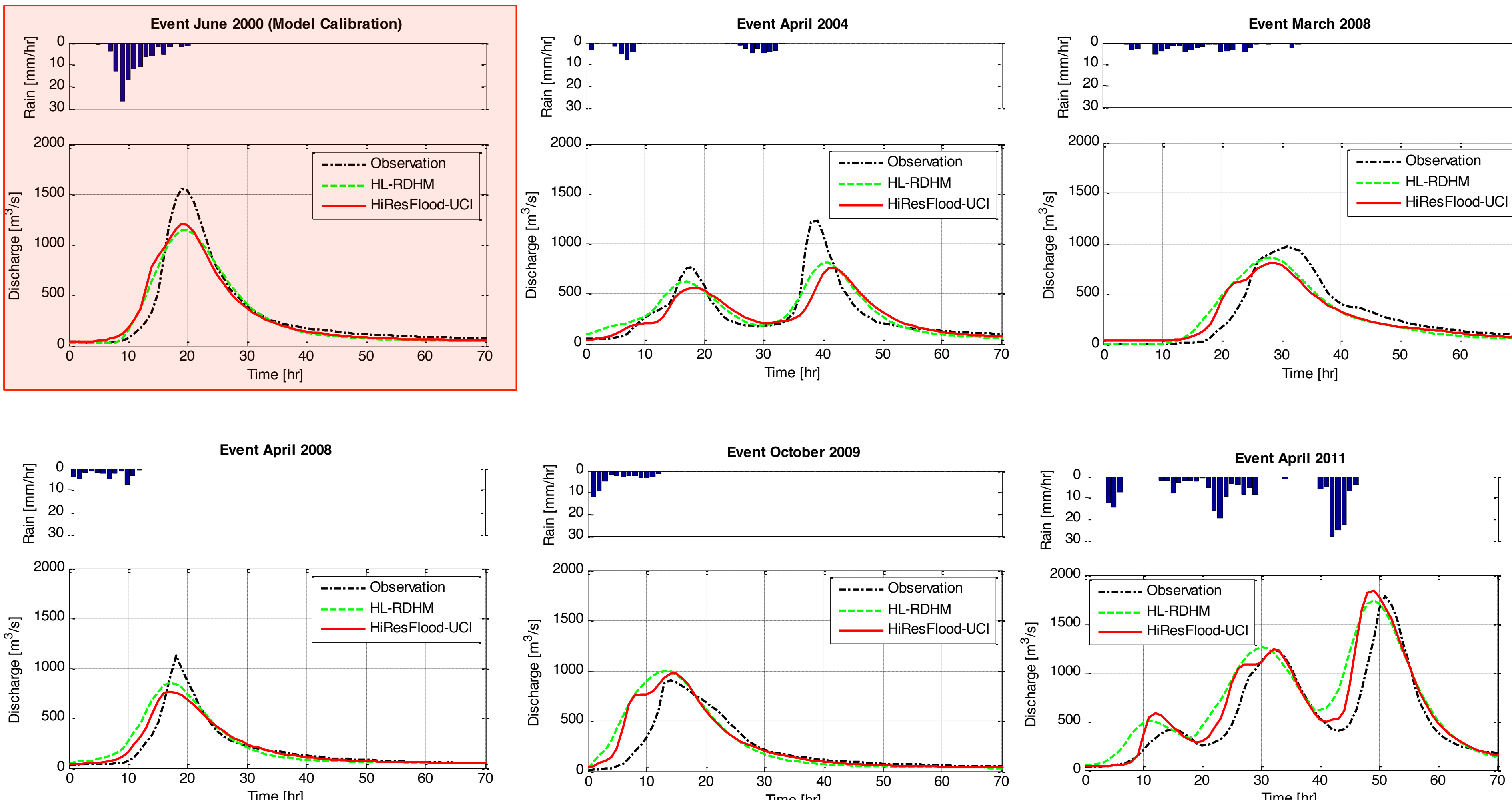
Validating HiResFlood-UCI with NEXRAD Stage 4

Total Rainfall (mm) of extreme events in ELDO2 2000 - 2011



Validating HiResFlood-UCI with NEXRAD Stage 4

Watershed's outlet discharge



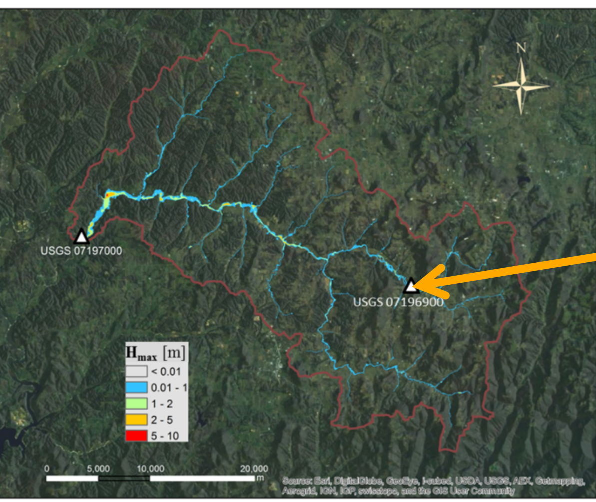
Validating HiResFlood-UCI with NEXRAD Stage 4

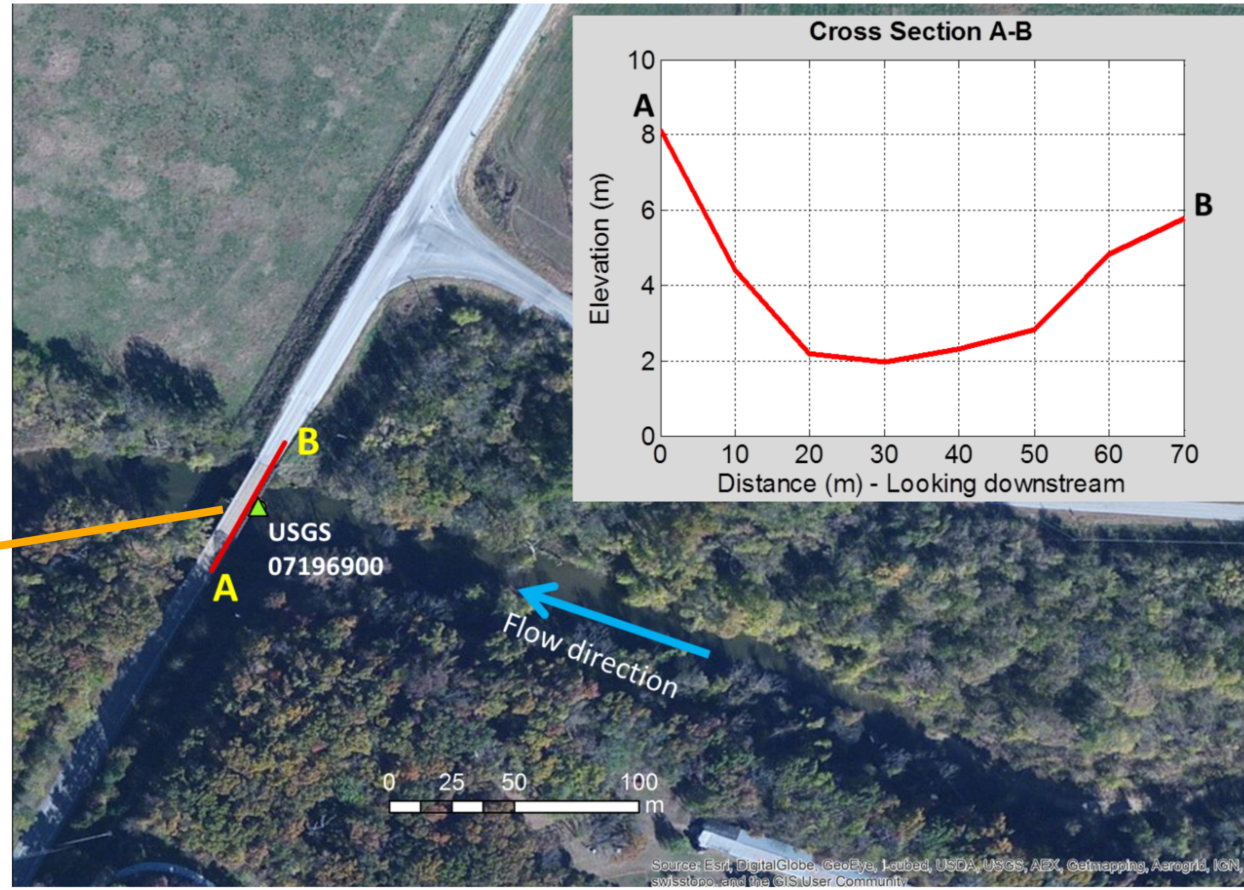
Watershed's outlet discharge

Event	Observation/ Simulation	Peak flow [m³/s]	Peak flow error [%]	Phase error [hr]	RMSE [m³/s]	BIAS [-]	CORR [-]	NSE [-]
June 2000	USGS Observation	1548.90	-	-	-	-	-	-
	HL-RDHM	1144.30	-26.12	1	116.76	-0.09	0.96	0.91
	HiResFlood-UCI	1200.00	-22.53	0	123.03	-0.06	0.95	0.90
April 2004	USGS Observation	1234.60	-	-	-	-	-	-
	HL-RDHM	808.40	-34.52	-1	124.99	0.04	0.90	0.80
	HiResFlood-UCI	756.27	-38.74	-3	170.27	-0.07	0.80	0.63
March 2008	USGS Observation	971.27	-	-	-	-	-	-
	HL-RDHM	862.79	-11.17	-3	129.58	-0.06	0.90	0.80
	HiResFlood-UCI	813.00	-16.30	-3	121.49	-0.08	0.92	0.83
April 2008	USGS Observation	1121.30	-	-	-	-	-	-
	HL-RDHM	851.63	-24.05	-1	100.87	0.07	0.91	0.83
	HiResFlood-UCI	762.00	-32.04	-1	80.47	-0.04	0.95	0.89
October 2009	USGS Observation	911.80	-	-	-	-	-	-
	HL-RDHM	996.37	9.28	-1	179.10	0.17	0.83	0.51
	HiResFlood-UCI	976.00	7.04	1	146.04	0.14	0.88	0.67
April 2011	USGS Observation	1781.10	-	-	-	-	-	-
	HL-RDHM	1740.10	-2.30	-2	260.11	0.25	0.89	0.67
	HiResFlood-UCI	1840.00	3.31	-2	208.97	0.17	0.93	0.78

Validating HiResFlood-UCI with NEXRAD Stage 4

Interior point

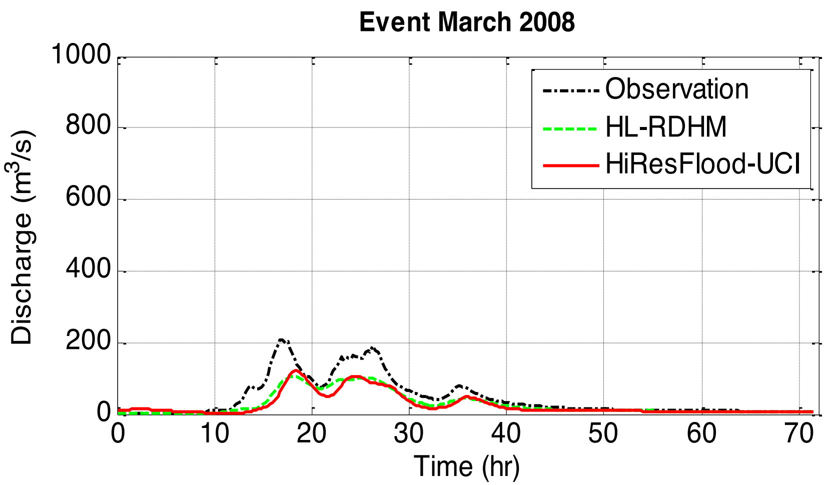


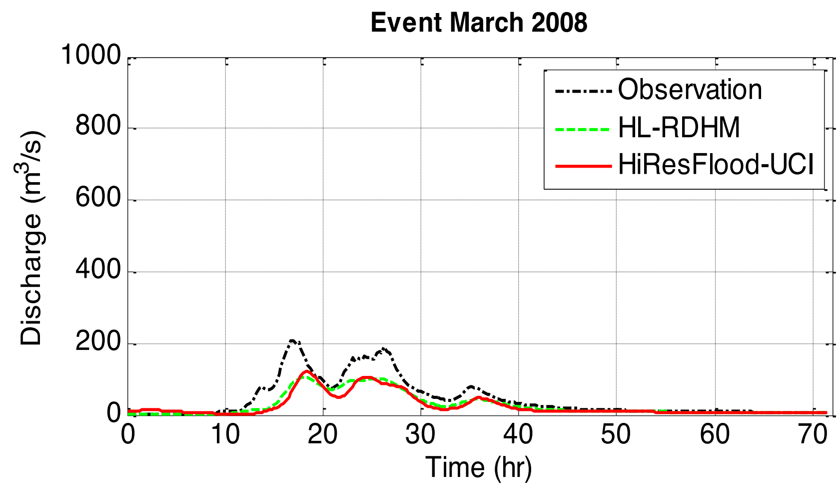


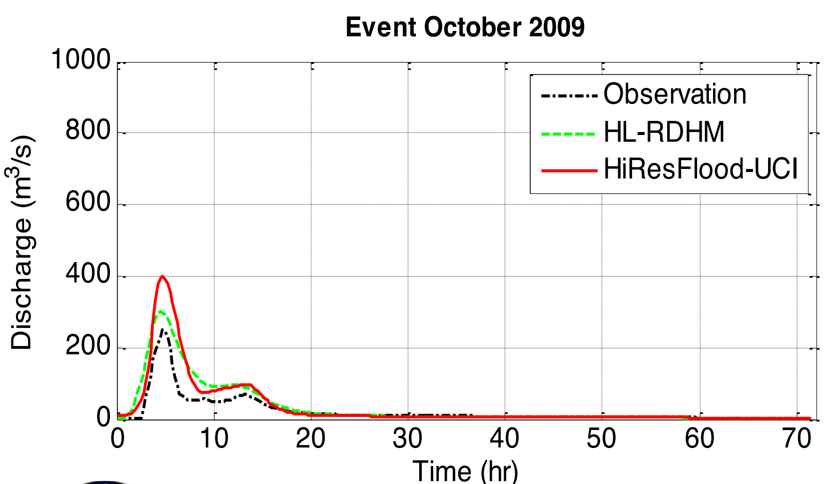
USGS 07196900 gauge station site

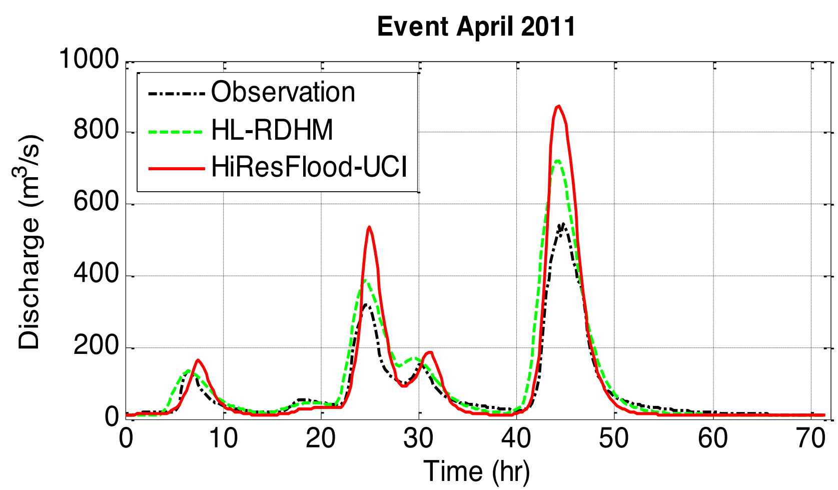
Validating HiResFlood-UCI with NEXRAD Stage 4

Discharge at Interior point USGS 07196900



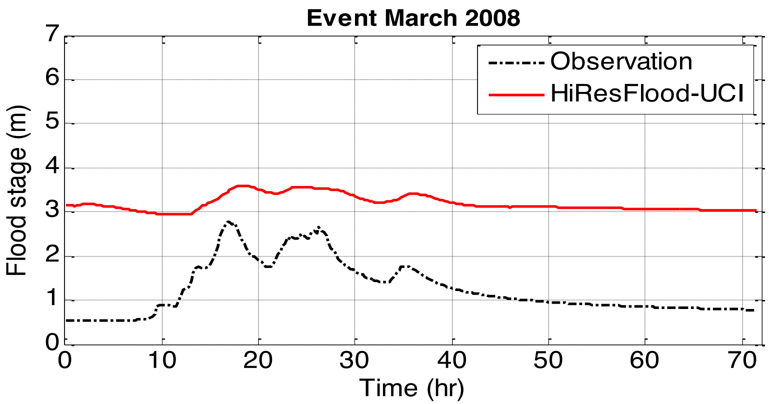


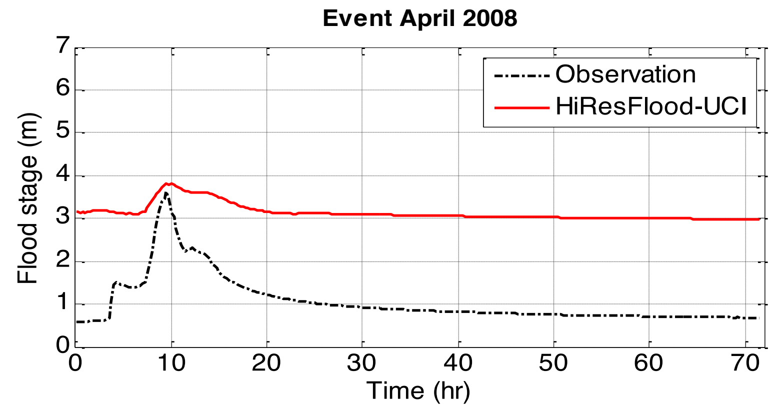


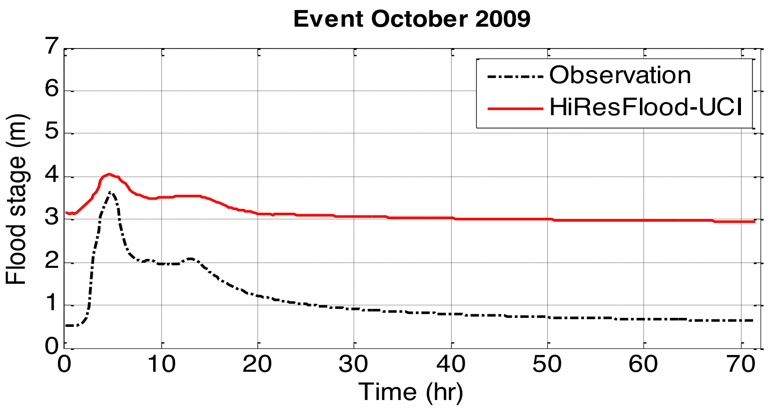


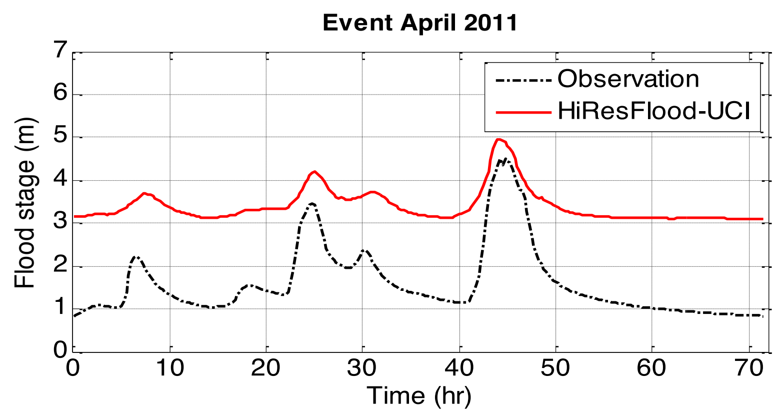
Validating HiResFlood-UCI with NEXRAD Stage 4

Water level at Interior point USGS 07196900





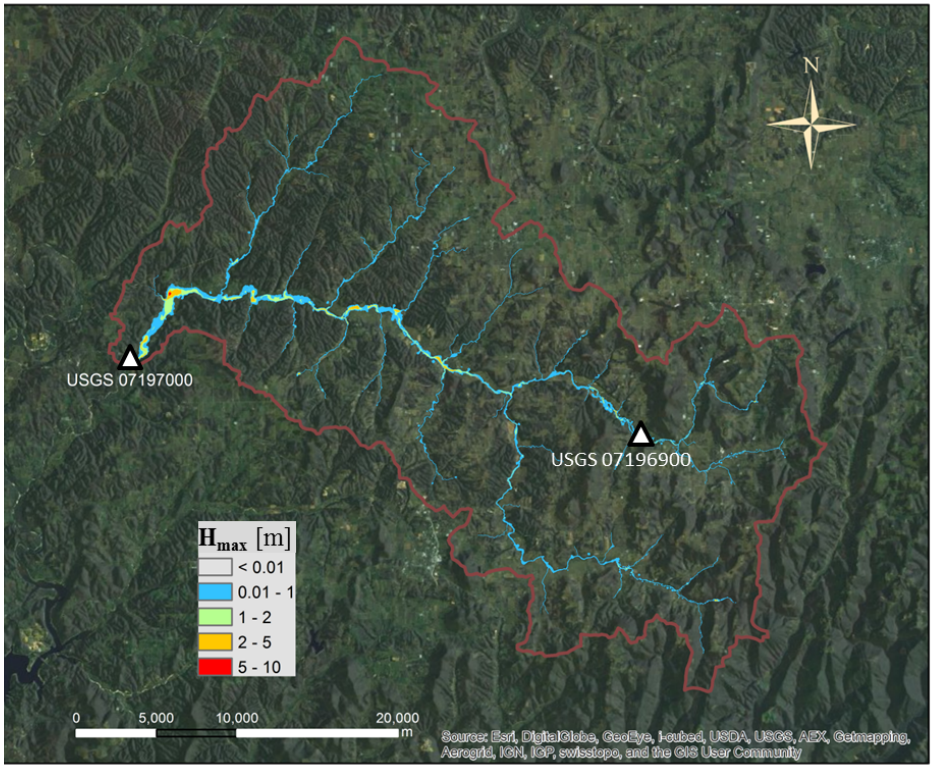




Maximum flood stage error: 0.82m

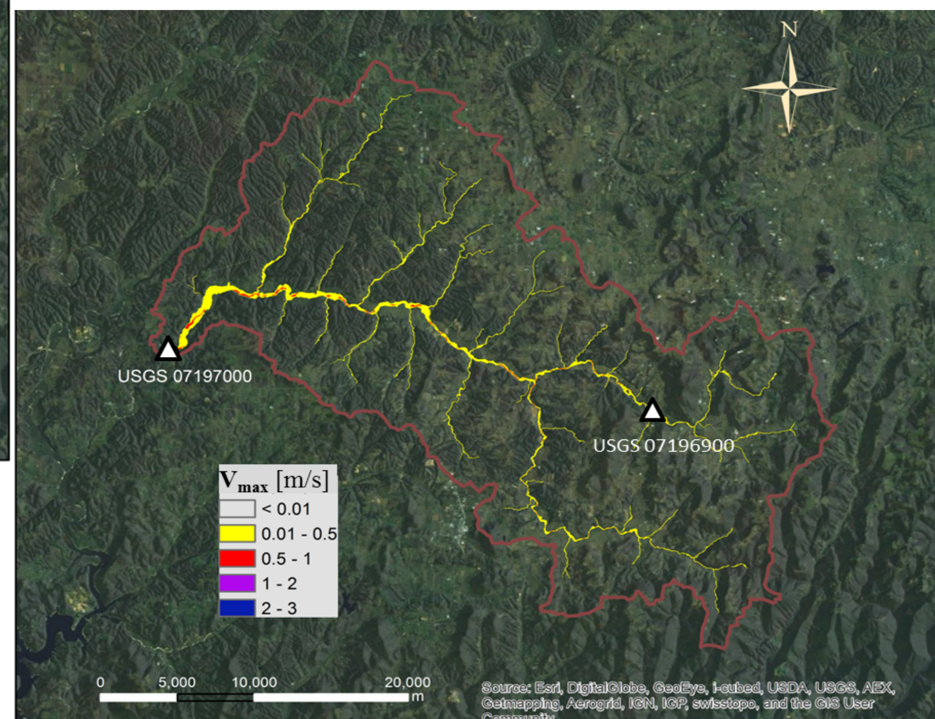
Validating HiResFlood-UCI with NEXRAD Stage 4

Flooded map and Flow velocity



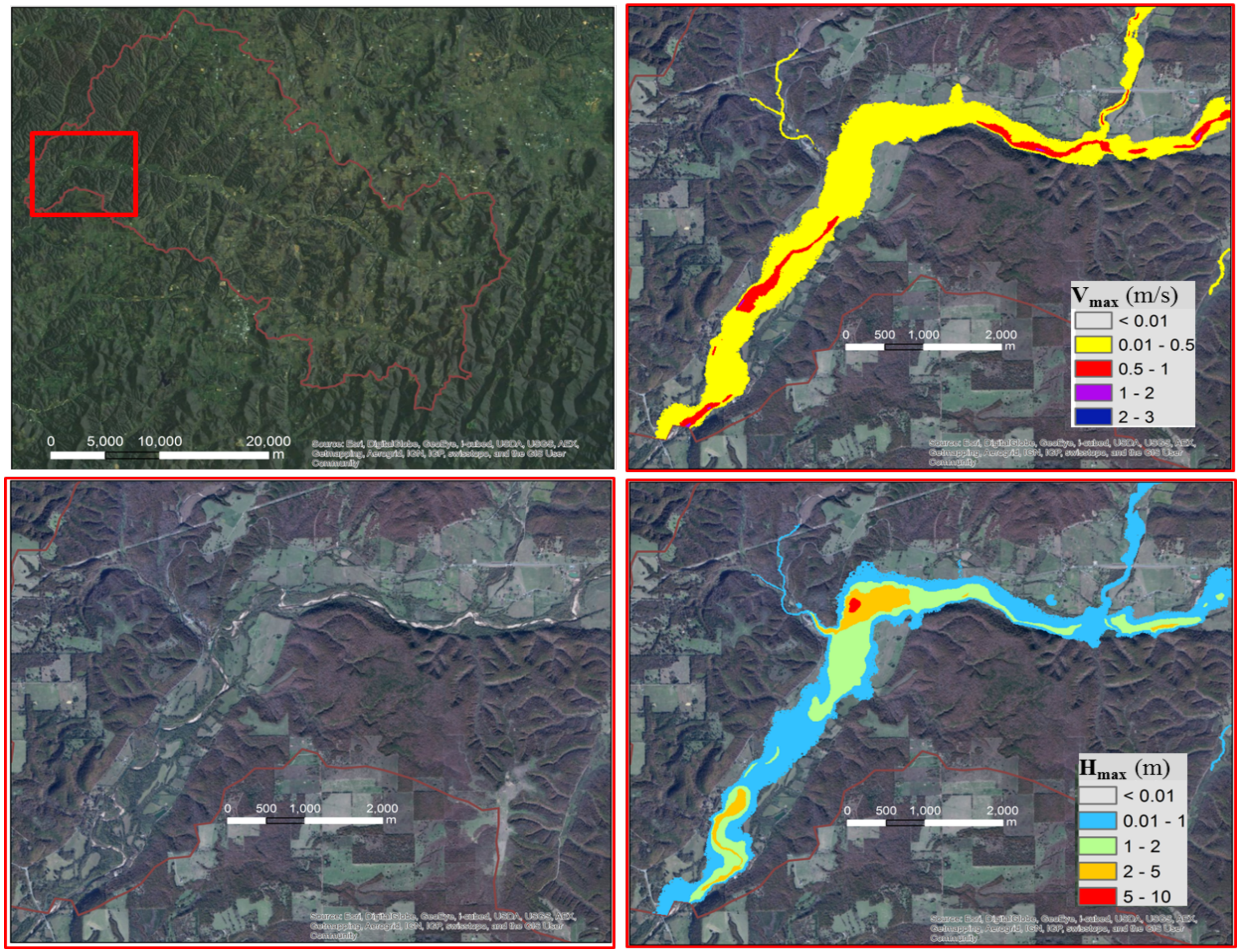
Flooded map - April 2011 event

Flow velocity - April 2011 event



Validating HiResFlood-UCI with NEXRAD Stage 4

Flooded map and Flow velocity



Details of flooded map and flow velocity - April 2011 event

Application of HiResFlood-UCI for flood forecasting

Nguyen, P., A. Thorstensen, S. Sorooshian, K. Hsu, and A. AghaKouchak, 2015: Flood Forecasting and Inundation Mapping Using HiResFlood-UCI and Near-Real-Time Satellite Precipitation Data: The 2008 Iowa Flood. J. Hydrometeor, 16, 1171–1183. DOI http://dx.doi.org/10.1175/JHM-D-14-0212.1.

Application of HiResFlood-UCI for flood forecasting

Cedar River 2008 Flood

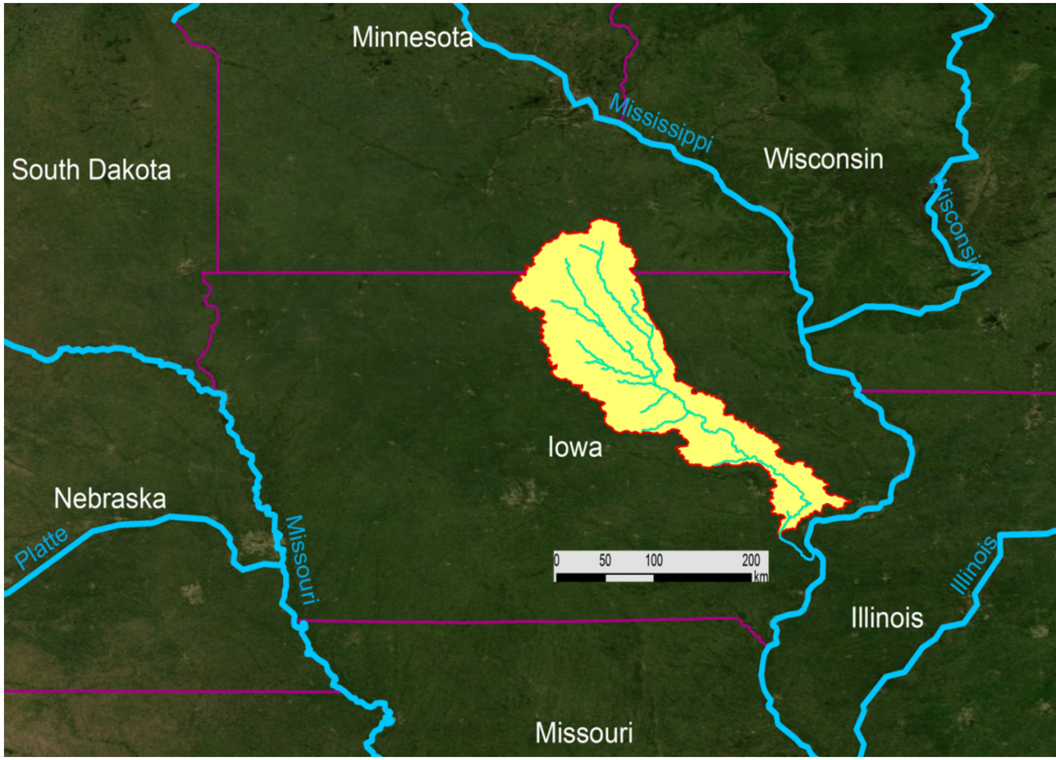
- Some areas flooded beyond 500-year flood level
- 20,000 evacuated
- 3,900 homes under water

Credit: Ron Mayland/Reuters

Application of HiResFlood-UCI for flood forecasting

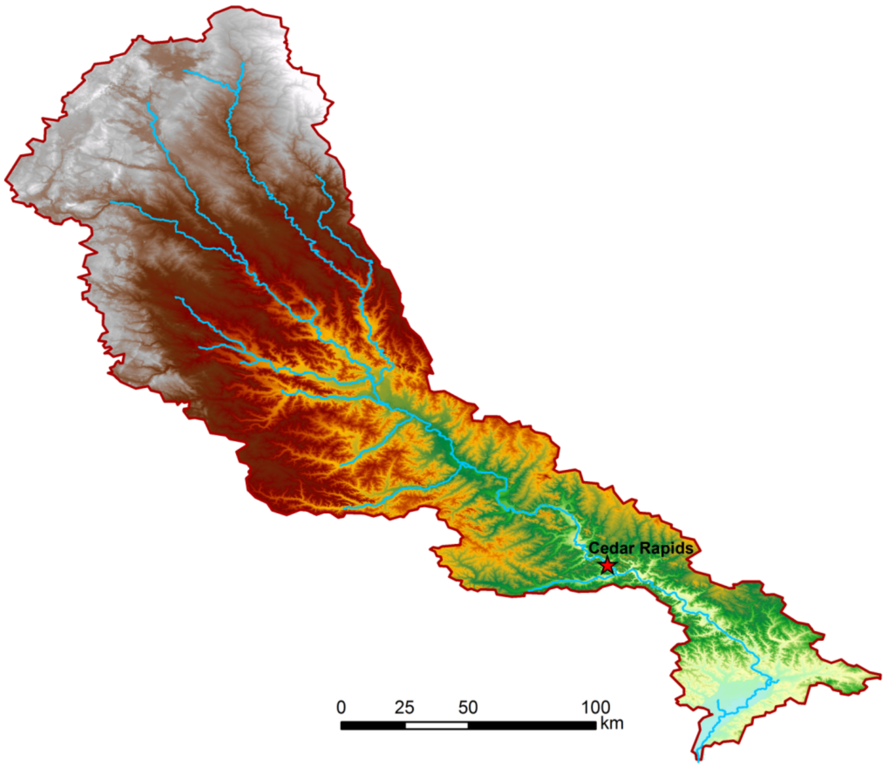
Cedar River Watershed

- Northeastern Iowa
- Tributary to the Mississippi
- 544 km river
- 20,000 km^2 basin
- Primarily cropland



Application of HiResFlood-UCI for flood forecasting

Model implementation



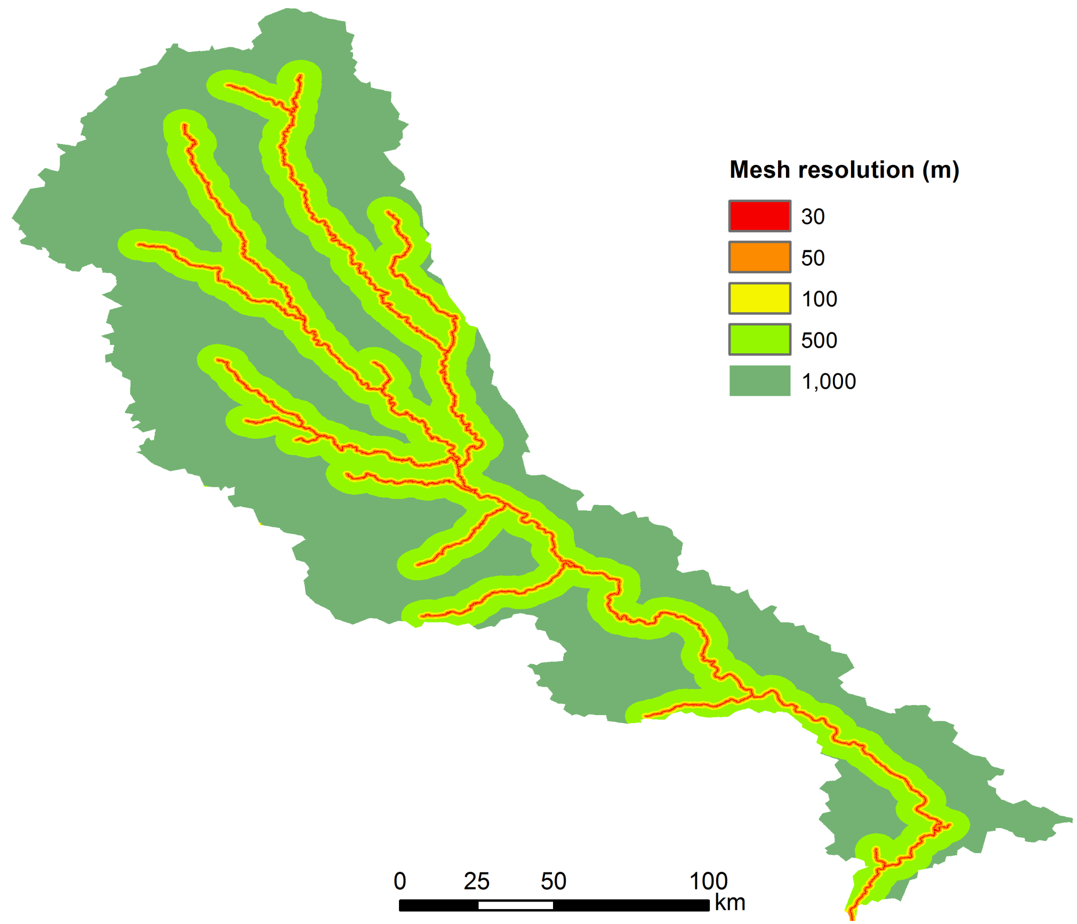
30m DEM

Watershed delineation results

Application of HiResFlood-UCI for flood forecasting

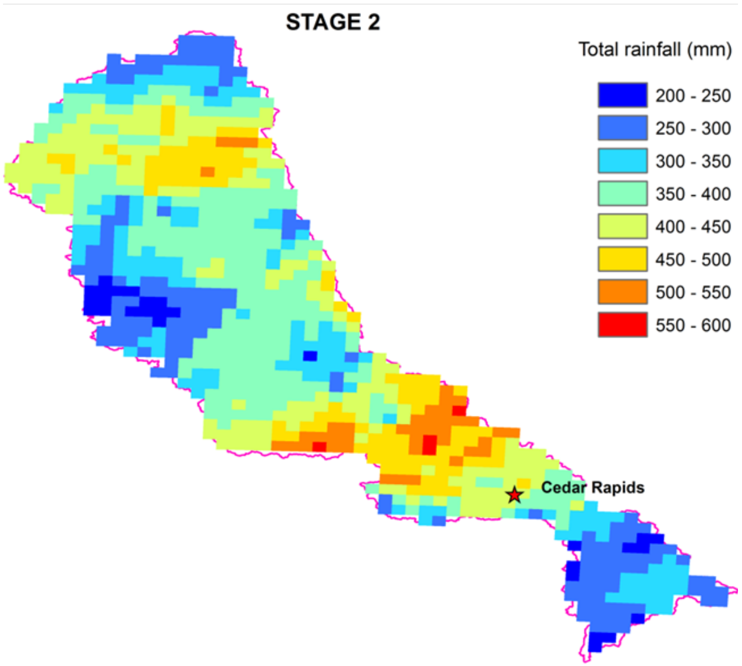
Model implementation

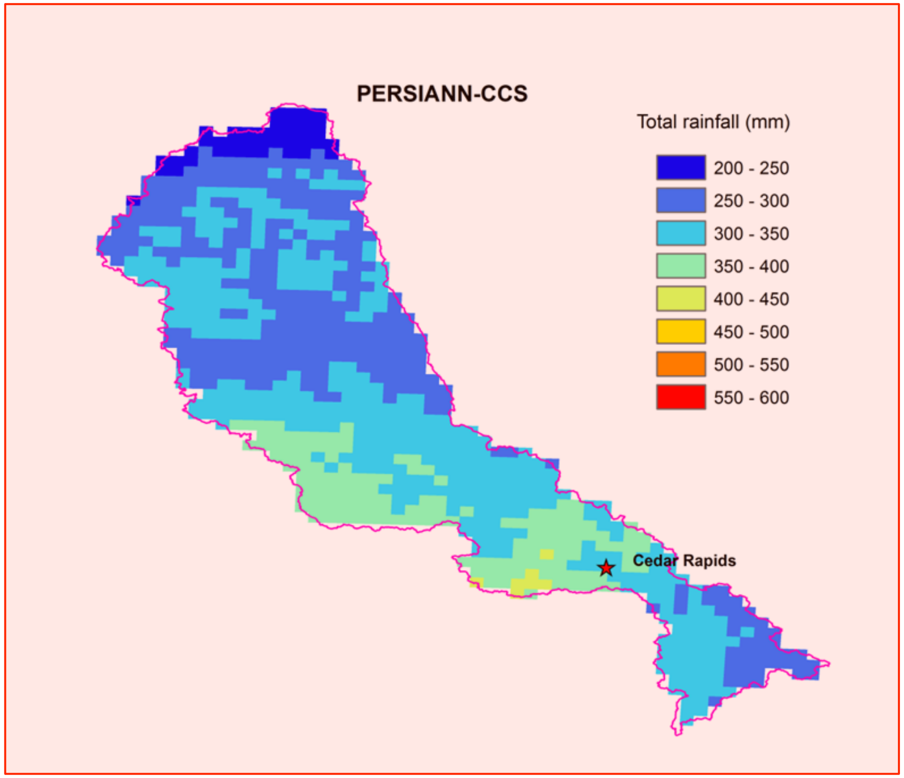
Buffer zone	Distance from river (m)	Mesh resolution	
		Size (m)	Area (m^2)
1	100	30	450
2	500	50	1,250
3	1,000	100	5,000
4	5,000	500	125,000
5	20,000	1,000	500,000



Application of HiResFlood-UCI for flood forecasting

Near real-time precipitation data





Total precipitation during the event from 29 May 00:00 to 25 June 23:00 2008

http://chrsdata.eng.uci.edu

Data Portal

Inspiring research on hydroclimate and water resources

Home | Info | Tutorial | Products | About Us

Lat: 7.015, Lon: -161.212

PERSIANN | **PERSIANN-CCS** | **PERSIANN-CDR**

The current operational PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) system developed by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI) uses neural network function classification/approximation procedures to compute an estimate of rainfall rate at each 0.25° x 0.25° pixel of the infrared brightness temperature image provided by geostationary satellites. An adaptive training feature facilitates updating of the network parameters whenever independent estimates of rainfall are available. The PERSIANN system was based on geostationary infrared imagery and later extended to include the use of both infrared and daytime visible imagery. The PERSIANN algorithm used here is based on the geostationary longwave infrared imagery to generate global rainfall. Rainfall product covers 60°S to 60°N globally. Further reading.

Data Period: March 2000 - Present

Coverage: 60°S to 60°N

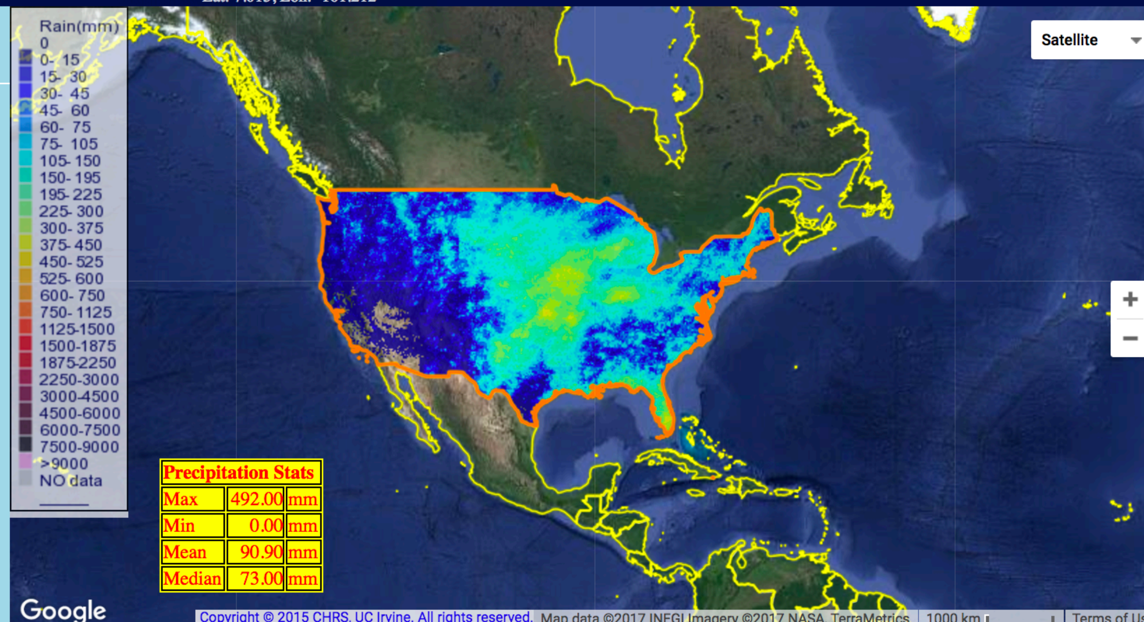
Resolutions: 0.25° x 0.25°

Timesteps: 1, 3, 6 hourly, daily

FTP Download (full): 1 hourly, 3 hourly, 6 hourly, Daily, Monthly, Yearly

Latest Update: Near real-time with 2 day delay

Selected References:



Precipitation Stats		
Max	492.00	mm
Min	0.00	mm
Mean	90.90	mm
Median	73.00	mm

Dataset PERSIANN-CCS **Time Step** Monthly **Domain** Country

Visualization | Download | Comparison

DateTime 2008-06 Visualize | Clear Image **Legend** ON

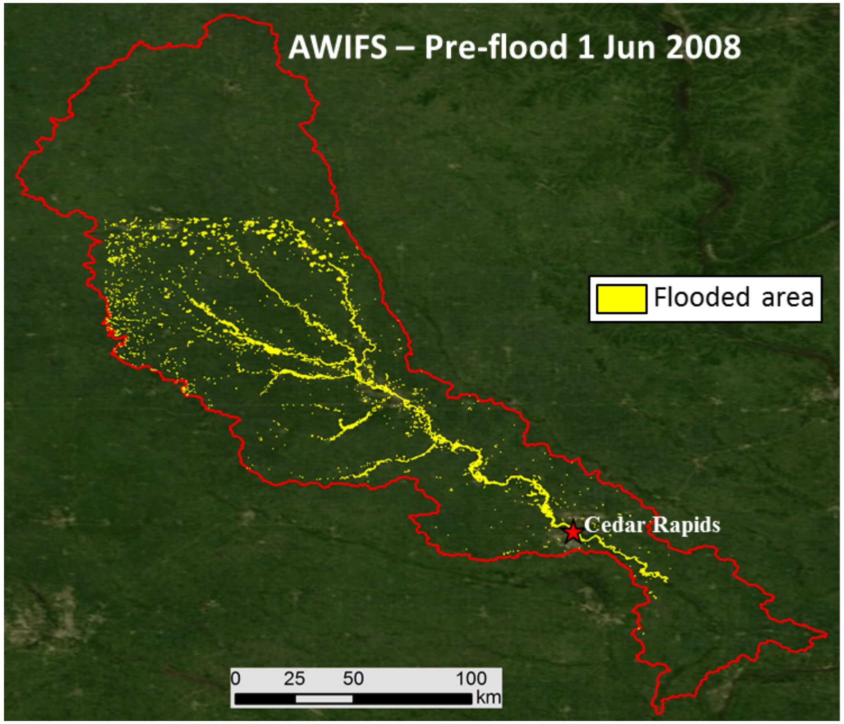
News | **FAQ**

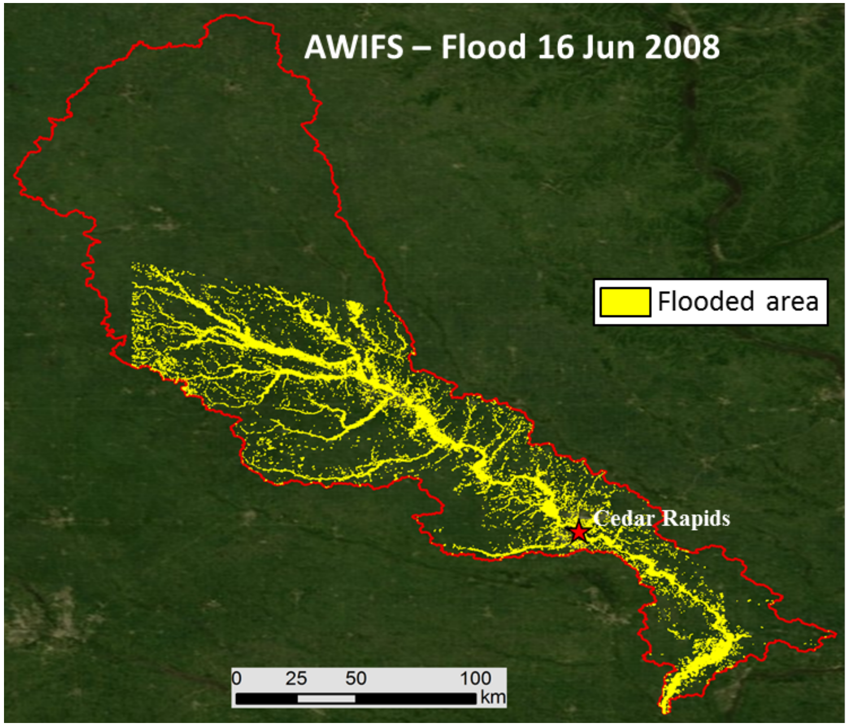
Hurricane Matthew
Houston Flooding Rainfall
Hurricane Patricia
RainMapper

News & Recent Events

Application of HiResFlood-UCI for flood forecasting

Advanced Wide Field Sensor (AWiFS) flooded maps

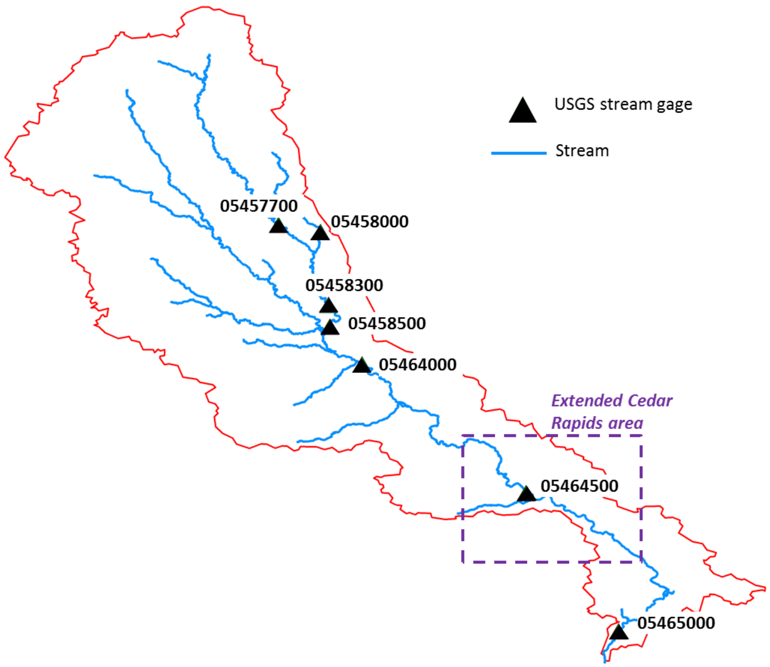


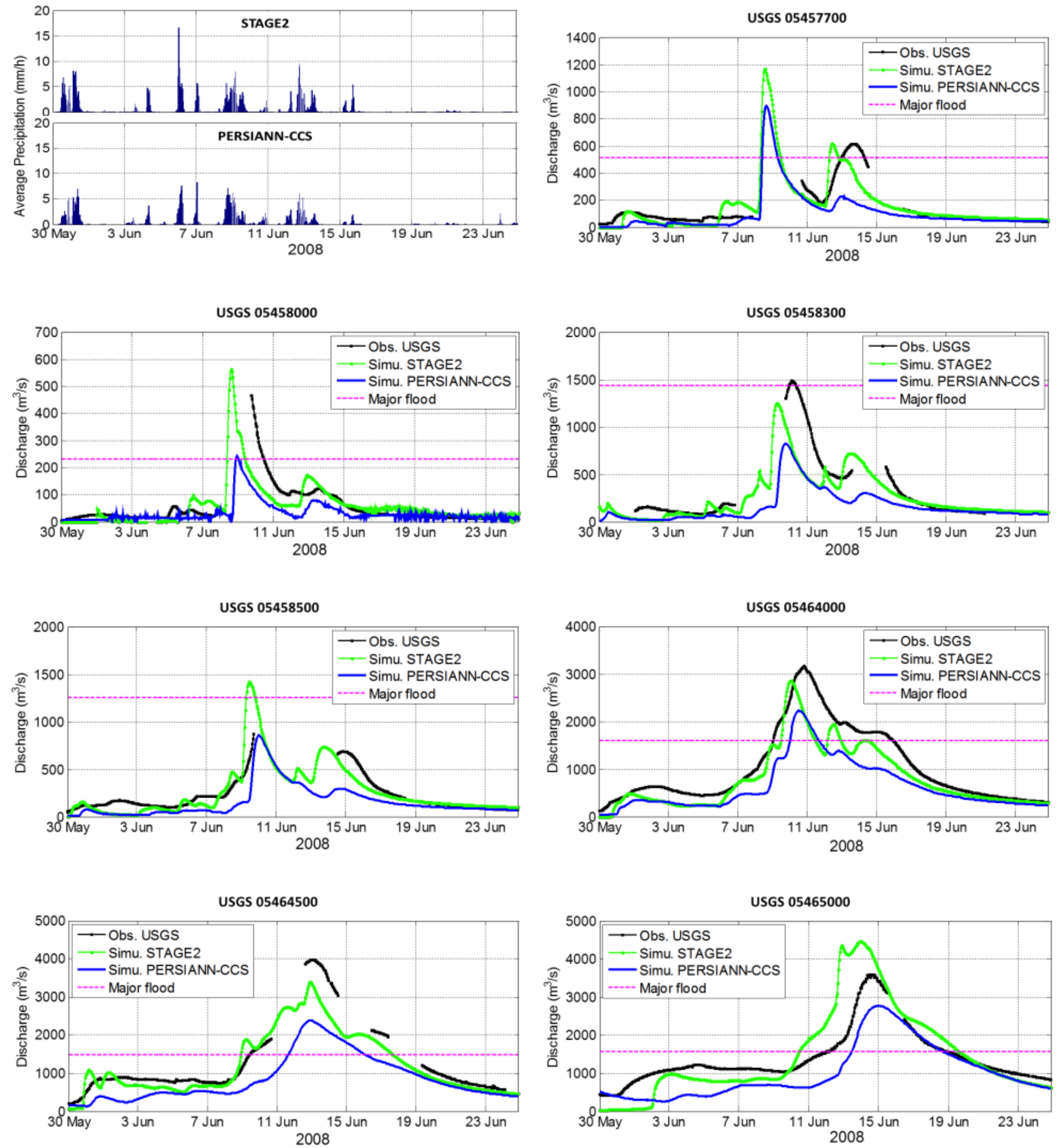


AWiFS areal images of pre-flood (1 June 2008) and flood (16 June 2008)

Application of HiResFlood-UCI for flood forecasting

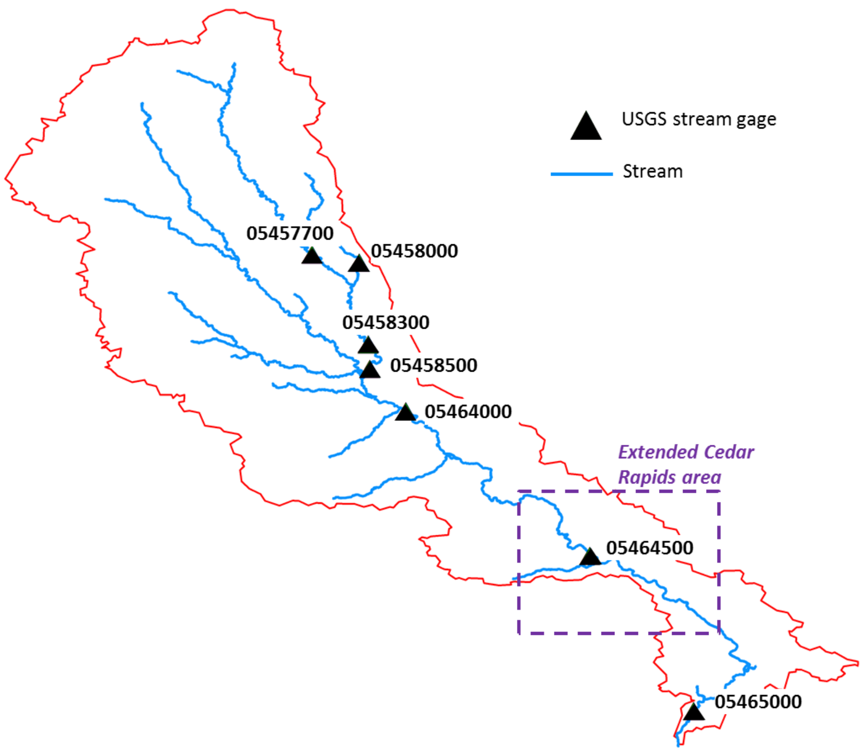
Discharge





Application of HiResFlood-UCI for flood forecasting

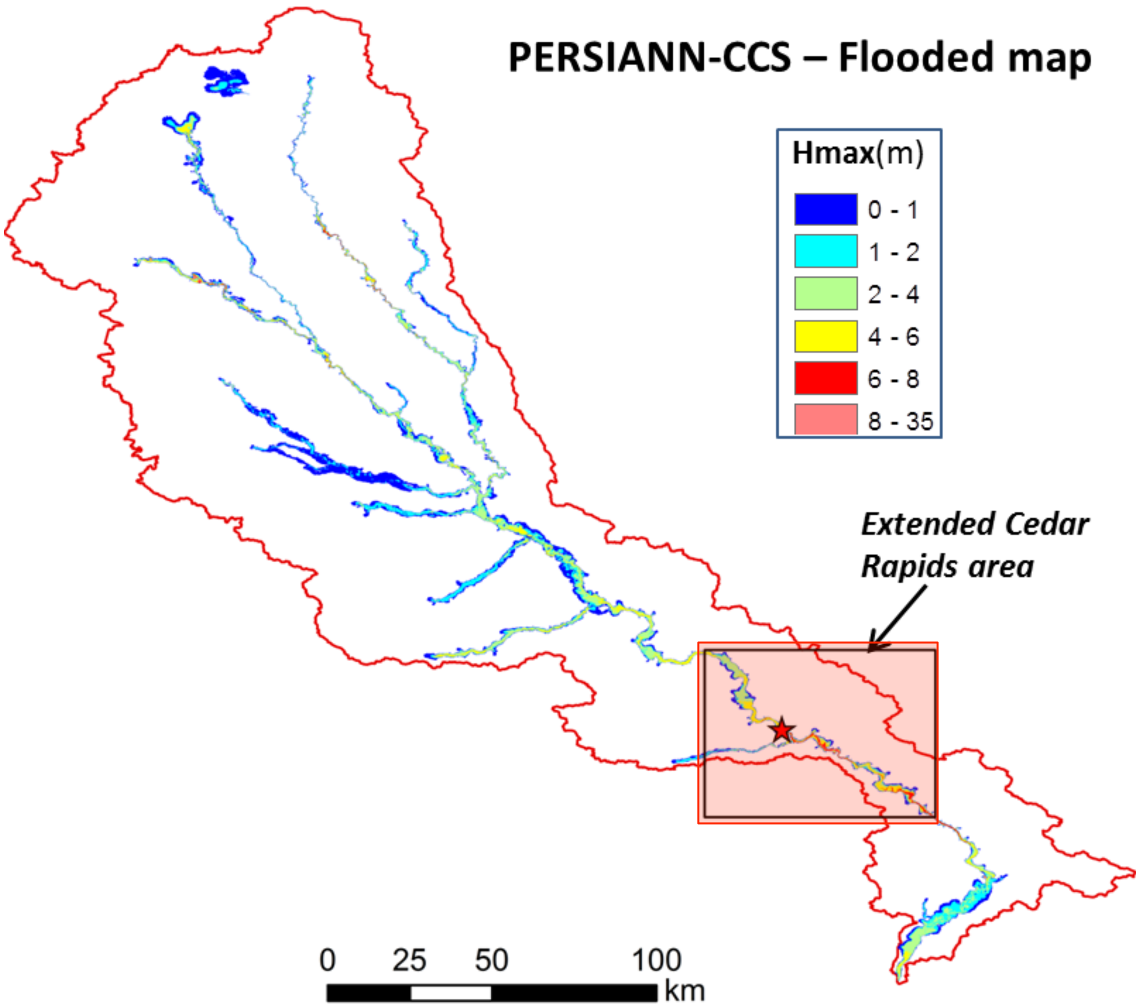
Discharge



USGS Streamflow Gauge	Precipitation Input	RMSE (m^3/s)	BIAS	CORR
05457700	Stage 2	77.79	-0.08	0.85
	PERSIANN-CCS	119.84	-0.51	0.87
05458000	Stage 2	46.50	-0.14	0.72
	PERSIANN-CCS	54.06	-0.50	0.87
05458300	Stage 2	233.32	-0.28	0.87
	PERSIANN-CCS	256.97	-0.48	0.97
05458500	Stage 2	139.07	-0.05	0.79
	PERSIANN-CCS	151.43	-0.54	0.86
05464000	Stage 2	353.32	-0.22	0.95
	PERSIANN-CCS	493.58	-0.39	0.99
05464500	Stage 2	328.10	-0.13	0.96
	PERSIANN-CCS	631.54	-0.42	0.97
05465000	Stage 2	609.22	0.05	0.91
	PERSIANN-CCS	518.85	-0.31	0.89

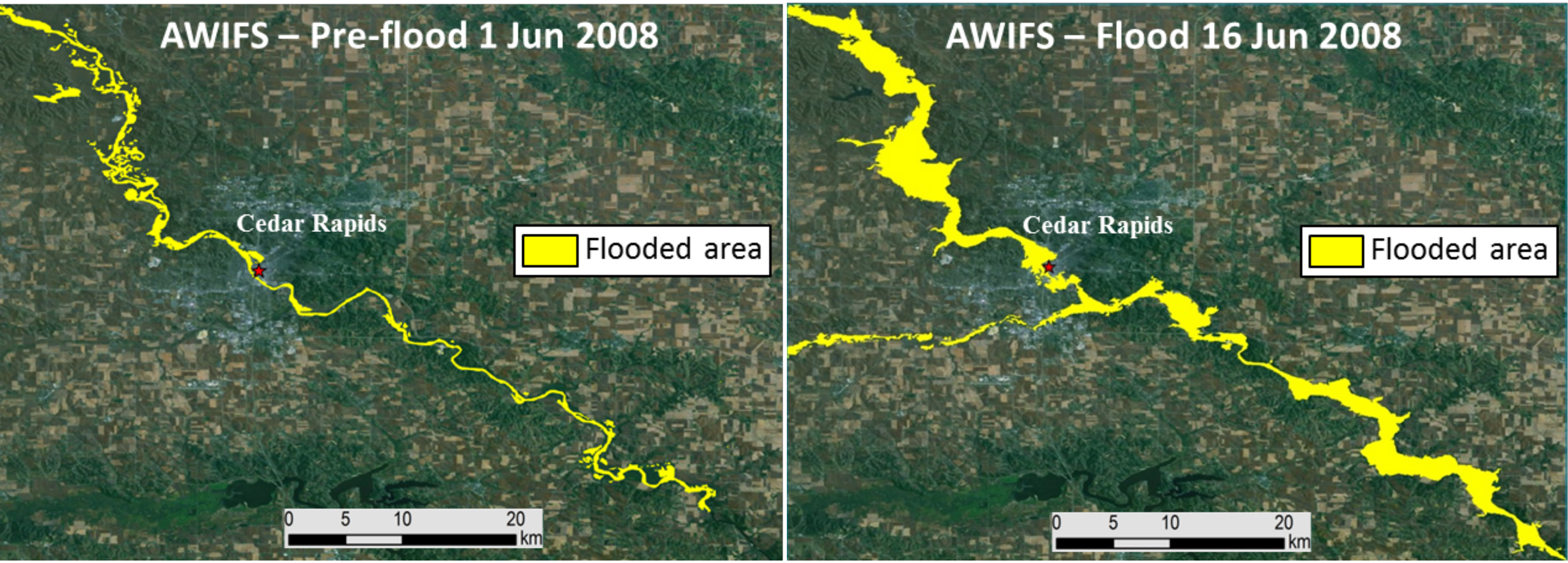
Application of HiResFlood-UCI for flood forecasting

Flooded map



Application of HiResFlood-UCI for flood forecasting

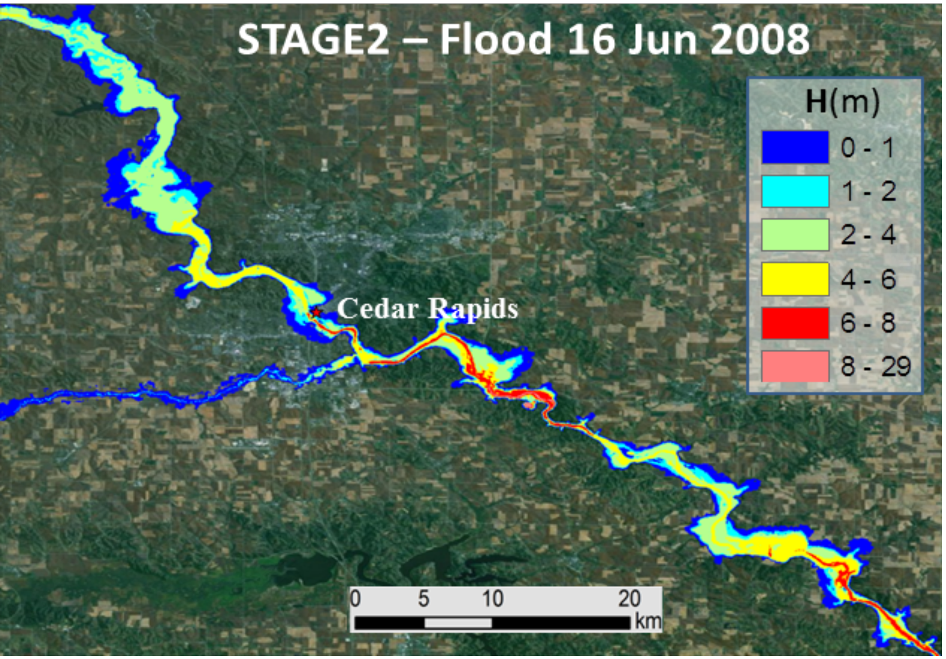
Flooded map

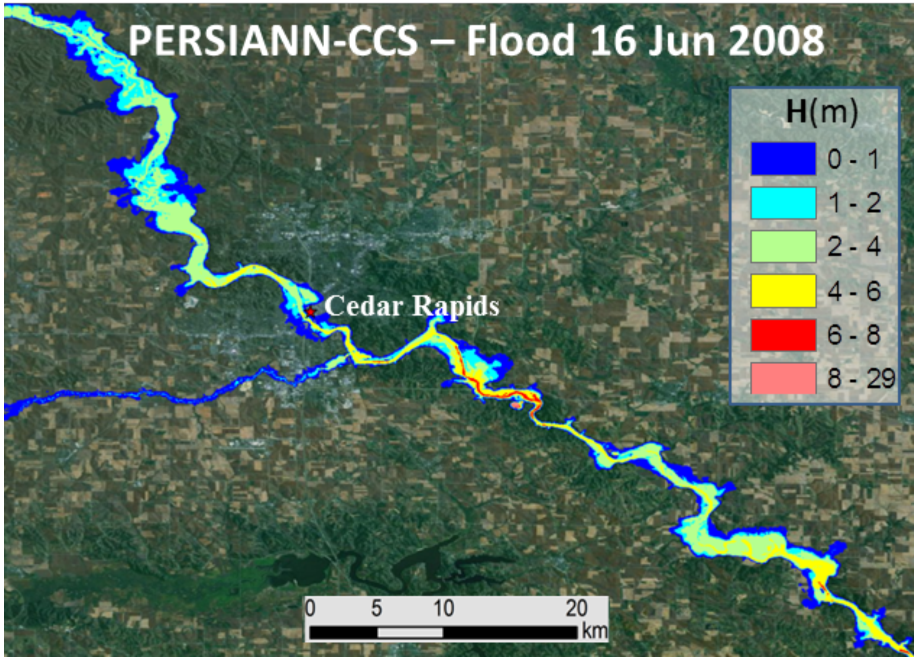


Cleaned flooded maps of pre-flood and flood over the extended Cedar Rapids area

Application of HiResFlood-UCI for flood forecasting

Flooded map



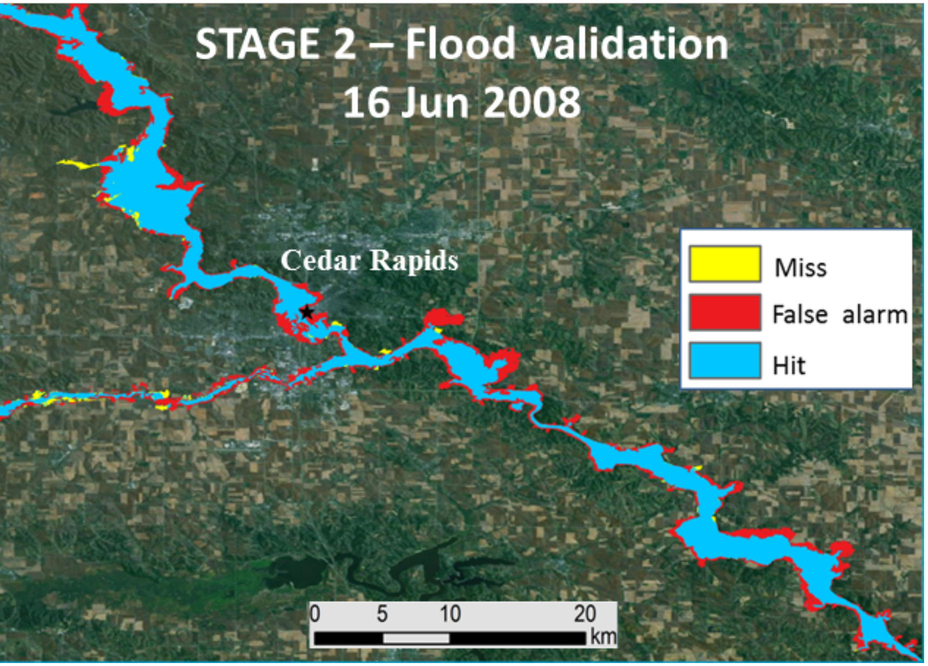


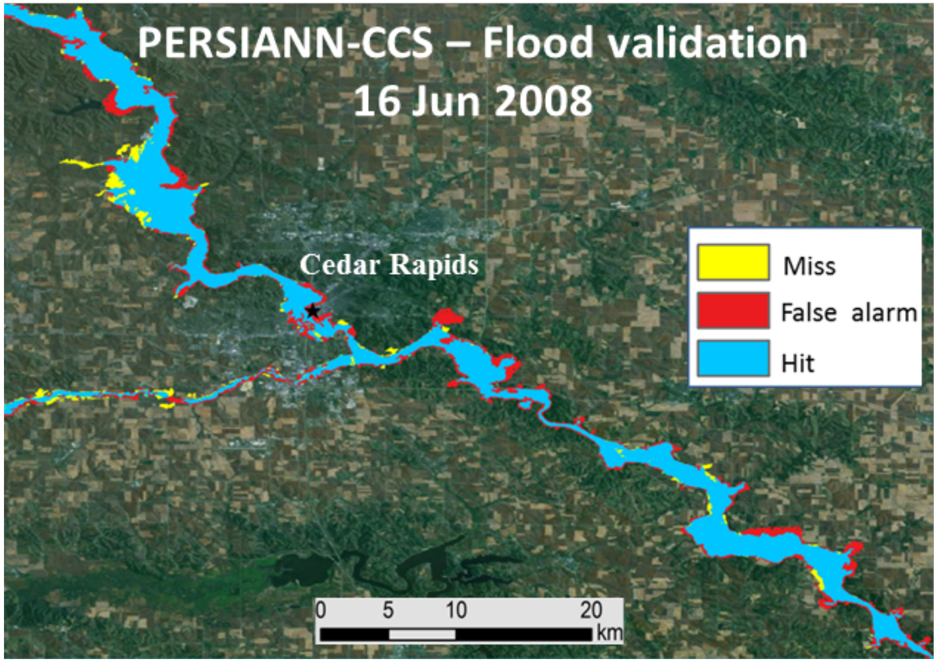
Modeled flood depth maps with Stage 2 and PERSIANN-CCS precipitation data

Application of HiResFlood-UCI for flood forecasting

Flooded map

Precip. input	CSI	POD	FAR
STAGE 2	0.672	0.965	0.311
PERSIANN-CCS	0.727	0.925	0.227





Validations of flooded maps from the model (with STAGE2 and PERSIANN-CCS precipitation) using AWiFS areal imagery

Summary

- HiResFlood-UCI was developed by coupling the NWS's hydrologic model (HL-RDHM) with the hydraulic model (BreZo) for flood modeling at decameter resolutions.

- A semi-automated technique of efficient unstructured mesh generation using ArcGIS and Triangle was developed.

- HiResFlood-UCI is highly sensitive to roughness values. HiResFlood-UCI can produce reasonable results with the *a priori* parameter set of HL-RDHM in the CONUS.

- It is more imperative to have a high quality, high resolution DEM to derive the mesh, even if the mesh resolution is slightly coarser.

Summary

- HiResFlood-UCI is able to produce spatially distributed, high resolution flow information without forgoing the quality outlet hydrograph simulation at both watershed outlet and interior point already produced by HL-RDHM.
- Through application of the newly developed HiResFlood-UCI model, paired with near real-time, remotely sensed precipitation data, this study demonstrates the ability to recreate detailed flood information in a forecasting setting.
- Results from this work demonstrate the potential benefits to humanity, especially in regions with poorly monitored data.

Thank you for your attention!

Questions?