A CyberGIS Integration and Computation Framework for High-Resolution Continental-Scale Flood Inundation Mapping

Yan Y. Liu, David R. Maidment, David G. Tarboton, Xing Zheng, Shaowen Wang

Paper submitted to the Journal of American Water Research Association (JAWRA), Feature Collection of 2016 National Water Center Summer Institute

June 19, 2017

Outline

- Background
- Computational model
- Continental coverage of Height Above Nearest Drainage (HAND)
- Hydraulic property table and inundation mapping
- Conclusion and discussion

Team

- UT Austin
  - David Maidment – methodology development; PI
  - Xing Zheng – HAND methodology; hydro model coupling
  - Justine Yu – Hydro model integration
- Utah State University
  - David Tarboton - methodology development; TauDEM development
  - Nazmus Sazib – TauDEM integration test; HAND methodology
  - Pabitra Dash – HydroShare web
  - Tony Castronova - JupyterHub
- University of Illinois at Urbana-Champaign (UIUC)
  - Yan Liu – coordination; computation; workflow integration
  - Ahmet Yildirim (left) – Inlet identification; block-wise data decomposition in TauDEM; future d8 and dinf algorithm integration
  - Kornelijus Survila – breakthrough of the new flow direction algorithm in TauDEM
  - Nathan Casler, Xingchen Hong, Kiumars Soltani, Dandong Yin, Hao Hu – scalable data storage, query, visualization, JupyterHub environment
- USGS
  - Larry Stanislawski – NHD and methodology consulting
  - NHDPlus team
  - 3DEP national elevation program
- ESRI
  - Steve Kopp, Dean Djokic, Daniel Siegel – TX inundation mapping; commercial solutions
- RENCI
  - Ray Idaszak – iRODS sharing with HydroShare
- NCAR
  - Channel geometry calculation
- NOAA NWS
  - Nation Water Center (NWC) - summer institute

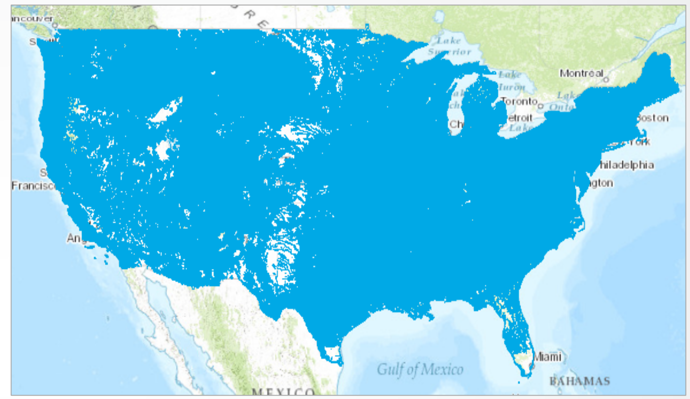
Real-Time Flood Inundation Mapping

Existing	Proposed

Existing

130 Stream Gage Reaches

Proposed



All of Medium Resolution NHD

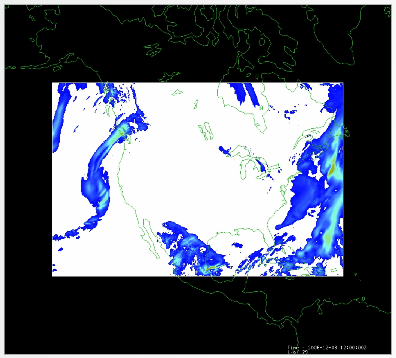
	Existing	Proposed	Ratio
Number of Mapped Reaches	130	2,691,344	
Total Mapped Length (Km)	2256	5,192,824	2302
Average Reach Length (Km)	17.4	1.93	0.11

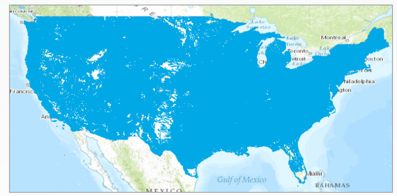
A tremendous application of USGS elevation and hydrography data!

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

National Water Model

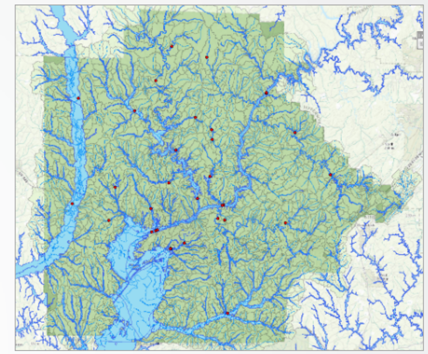
Meteorology

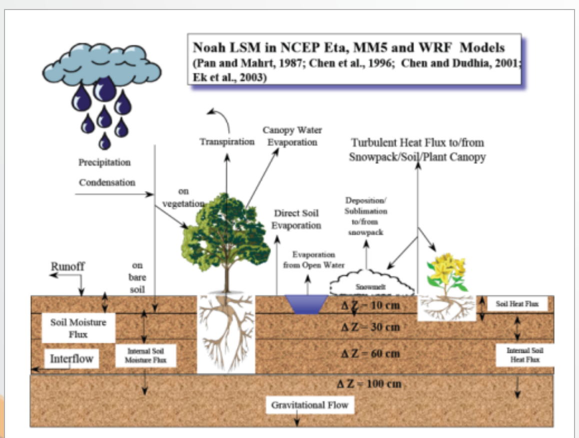




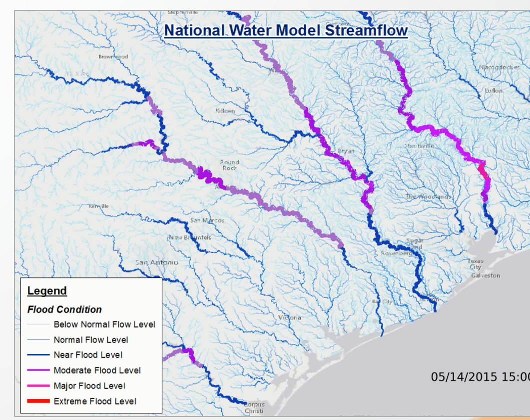
2.7 million catchments

Mapping and Impacts





Hydrology



Hydraulics

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

Cross Section Method

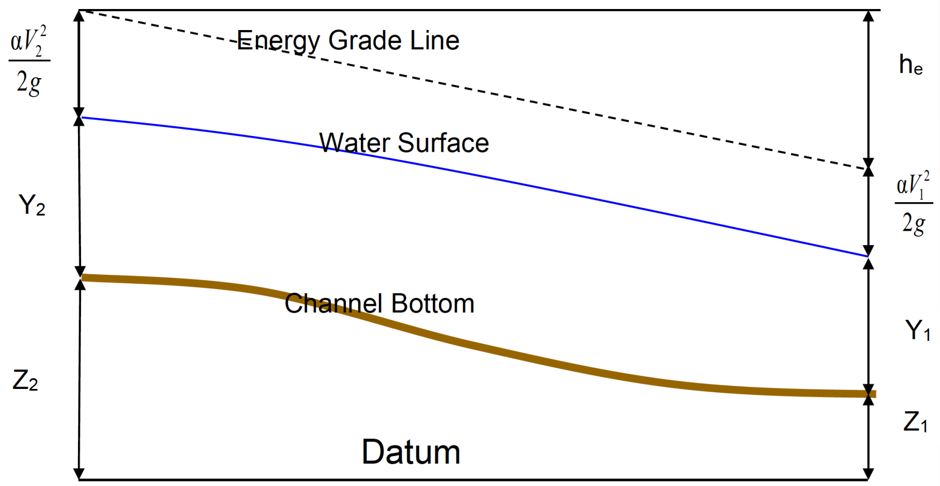


Figure 2-1 Representation of Terms in the Energy Equation

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \quad (2\text{-}1)$$

Where: Z_1, Z_2 = elevation of the main channel inverts

Y_1, Y_2 = depth of water at cross sections

V_1, V_2 = average velocities (total discharge/ total flow area)

a_1, a_2 = velocity weighting coefficients

g = gravitational acceleration

h_e = energy head loss

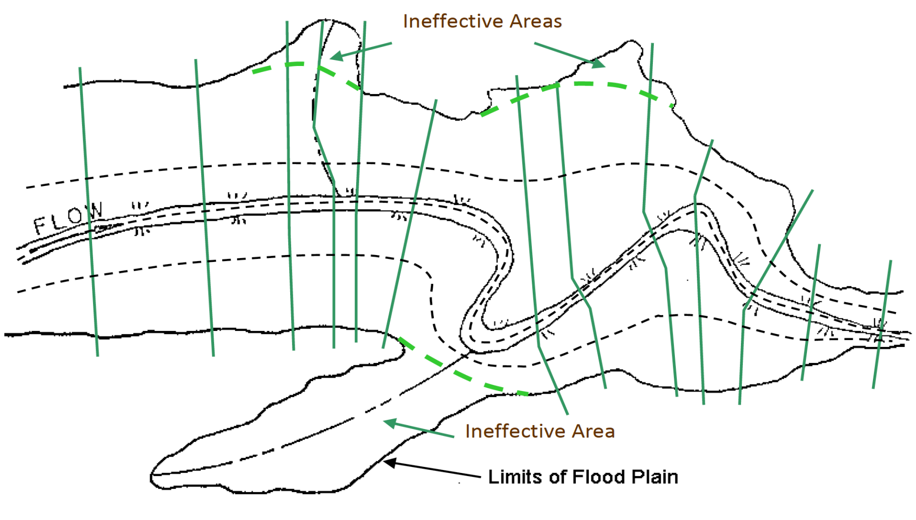
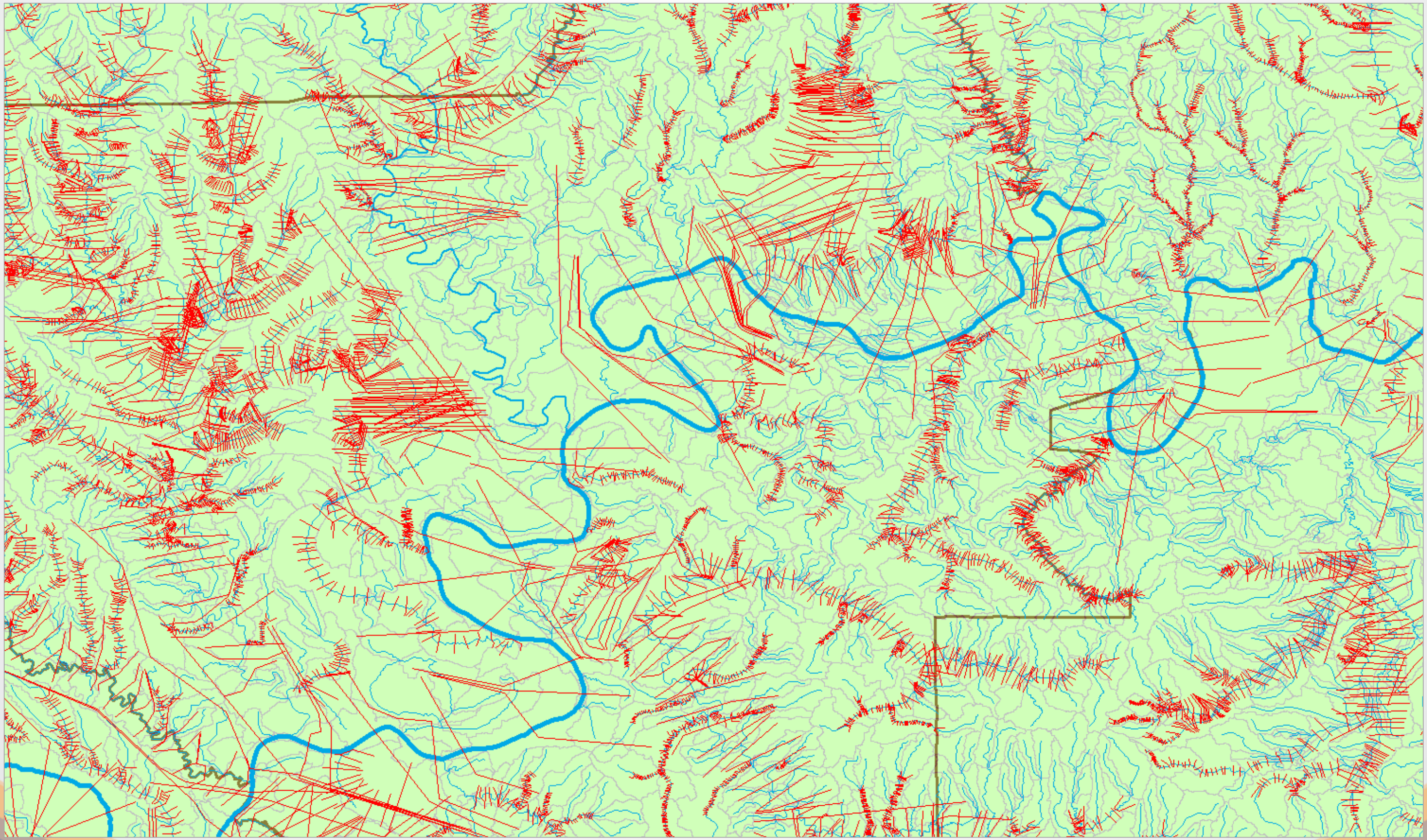


Figure 3-4 Example Cross Section Layout

HEC-RAS 5.0 Reference Manual

Cross Section Method at CONUS Scale

- NHDPlus MR: 5.2 million kilometers rivers and streams

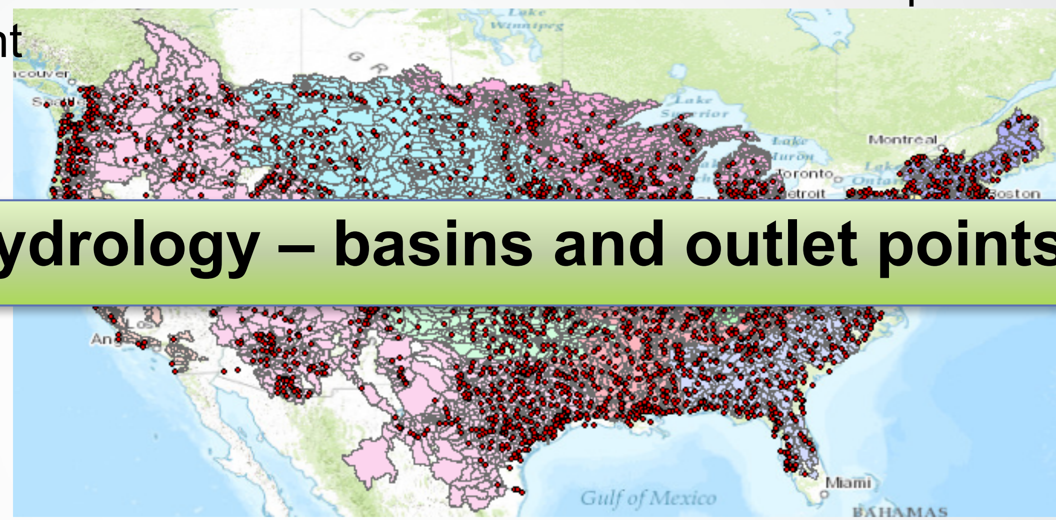


Cross-Sections for Alabama Rivers compiled in NFIE-I

Flow Continuum Model – a national stream network, atmosphere to oceans, coast to coast

Blanco River at Wimberley
Two basins and one forecast point

Current: 6600 basins and 3600 forecast points

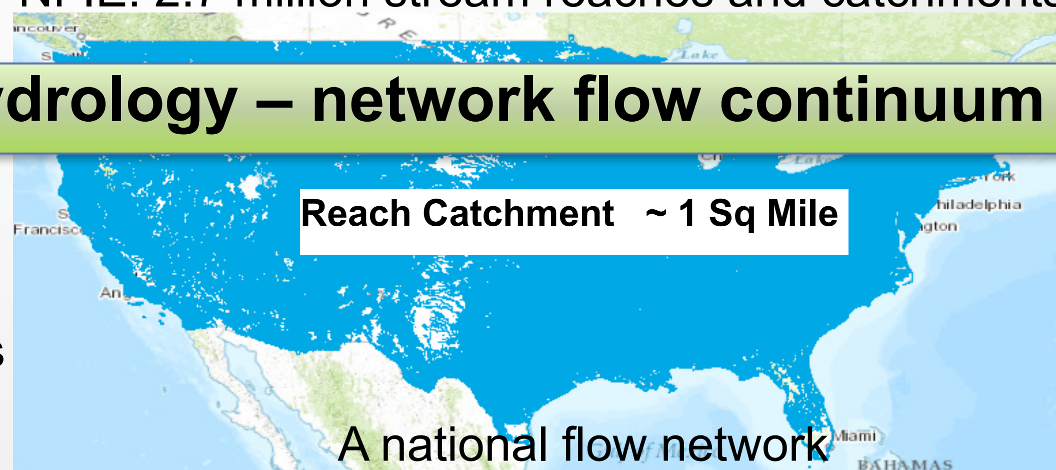


Watershed Hydrology – basins and outlet points

becomes ⇩

NFIE: 2.7 million stream reaches and catchments

Continental Hydrology – network flow continuum



130 Catchments and Flowlines uniquely labelled

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

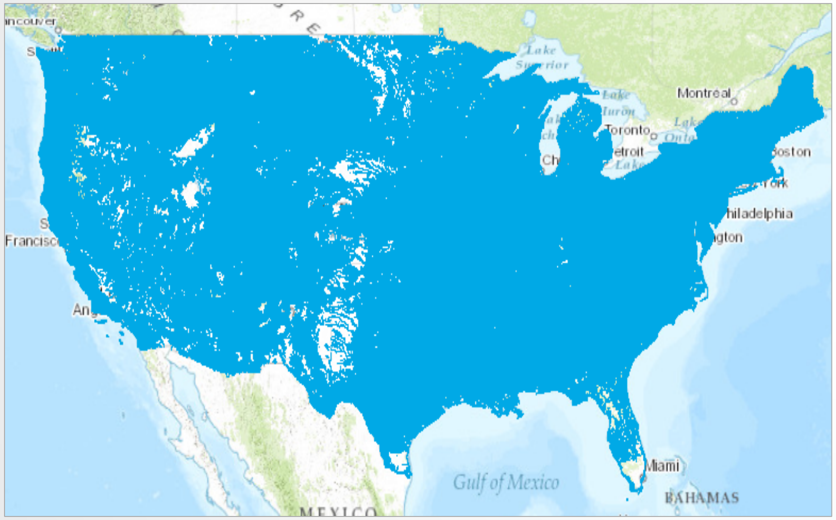
NFIE Continental Flood Inundation Mapping:

Scope of Work

- Vision
  - Big gap between NWM data availability and existing flood inundation mapping work
  - DEM-based hydrologic analysis, with help from NWM, can achieve continental flood inundation mapping
- Continental hydrology and emergency management
  - Vision paper (Maidment *et al.*)
- New flood inundation mapping methodology
  - Height Above Nearest Drainage (HAND) for flood inundation mapping
  - Reach+catchment+HAND+rating curve+discharge
  - Methodology paper (Xing *et al.*)
- Computation
  - A major challenge in implementing the methodology
  - Computation paper (Liu *et al.*)

Experiment for 2016:

Combine hydrography and elevation to define river channel geometry and flood inundation extent for 5 million km of stream reaches over continental US



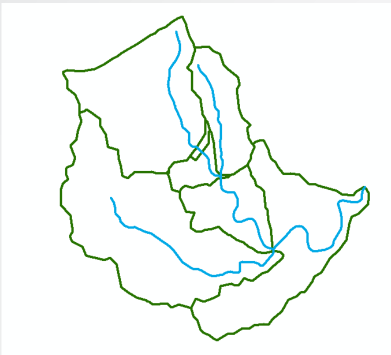
National Hydrography Dataset

National Elevation Dataset

Use the National CyberGIS Facility (ROGER supercomputer) operated by the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign

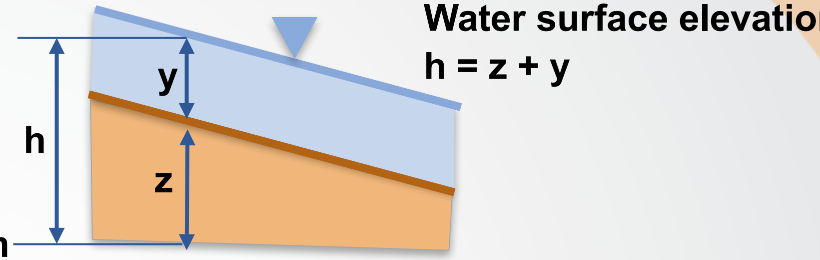
Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

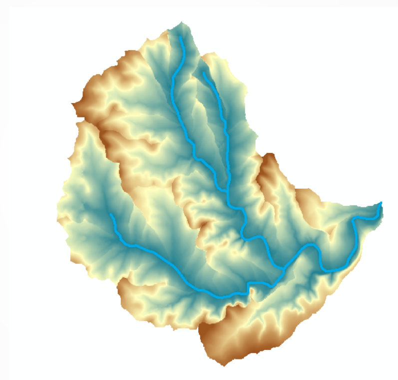
Flood Inundation Mapping – NHDPlus-HAND Method

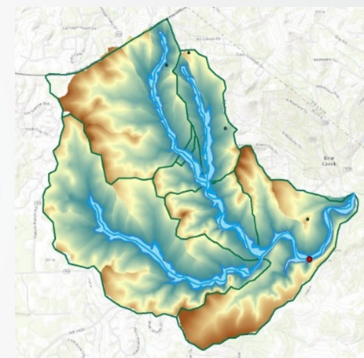


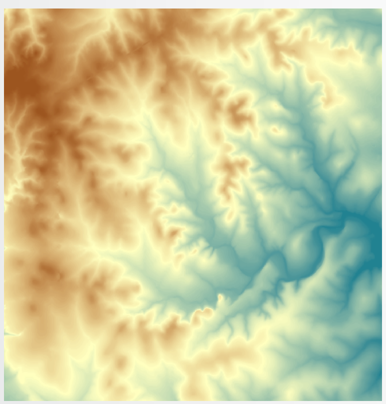
NHDPlus

Catchments and Flowlines









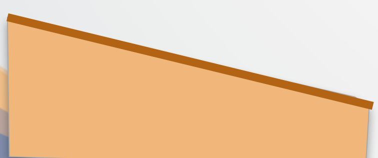
Digital Elevation Model

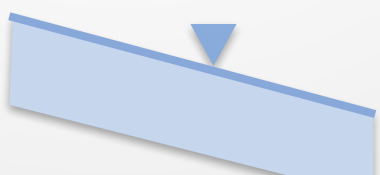
Height Above Nearest Drainage (HAND)

(relative elevation of land surface cell above cell in NHDPlus stream to which it flows)

Inundation map

Height above drainage < 15 ft)





Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

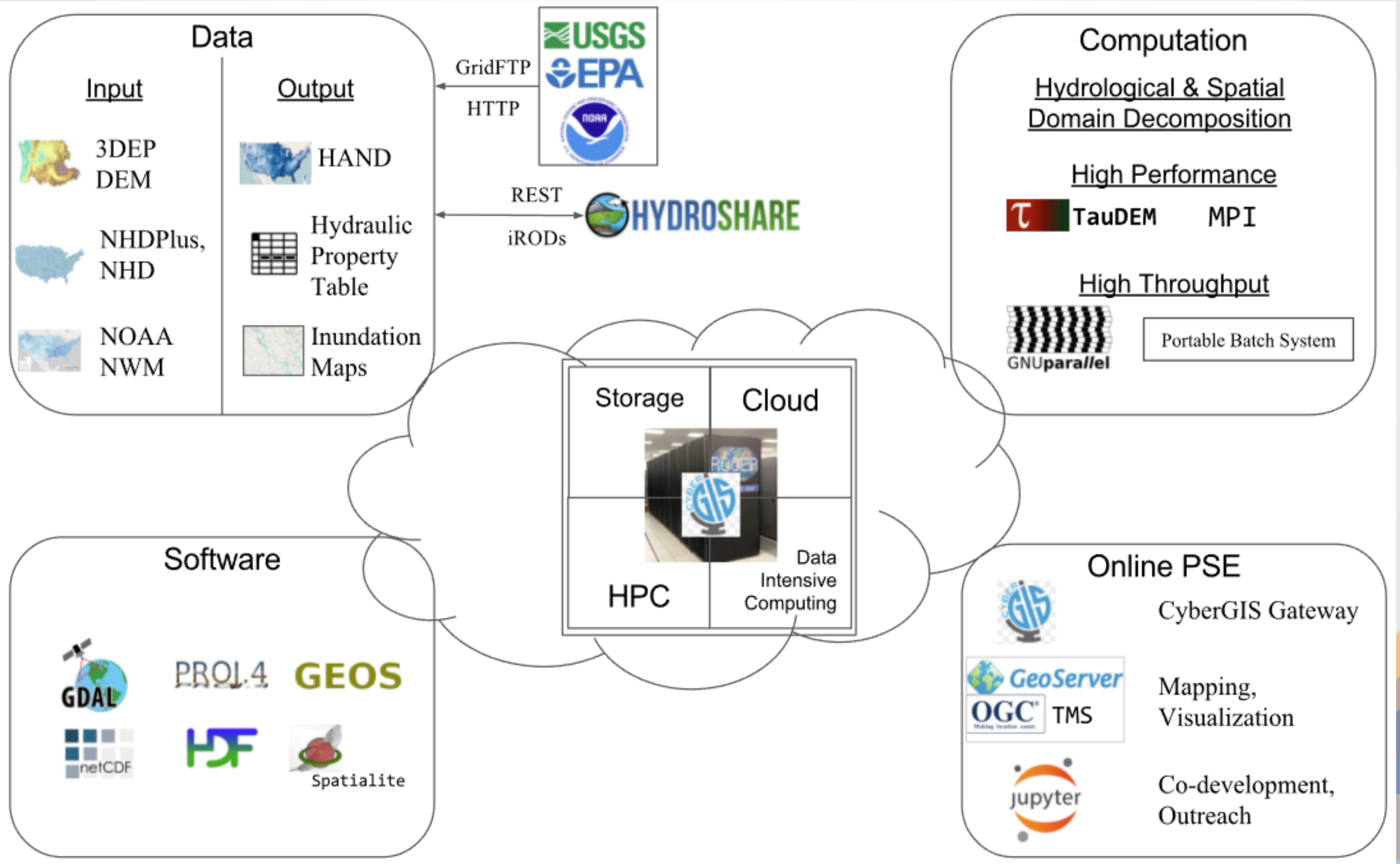
Data Challenge

Data Source	*Resolution & Coverage*	*Size*	*Format*	*Update Frequency*
USGS 3DEP Elevation Dataset	$1/3^{rd}$ arc-second (10m); Entire U.S.	635939 x 282122 (180b cells); 718GB uncompressed	ArcGrid, GeoTIFF	Partial update every 3 months
	$1/9^{th}$ arc-second (3m); Partial U.S.	~10 times larger than $1/3^{rd}$ arc-second	ArcGrid, GeoTIFF	N/A
	$1/27^{th}$ arc-second (1m); Partial U.S.	~100 times larger than $1/3^{th}$ arc-second	ArcGrid, GeoTIFF	N/A
NHDPlus from EPA and USGS	1:100,000; Entire U.S.	~2.69 million reaches; 12 layers;18GB	Esri FileGDB	Version 2.1
	1:24,000 Partial U.S.	~30 million reaches; ~77 layers in pre-release versions	Esri FileGDB	Not released yet
NOAA NWM channel_rt forecast	1:100,000; Entire U.S.	2,699,225 reaches; short range: 15 hourly forecasts medium range: 80 forecasts (3-hr; 10 days)	NetCDF	short range: hourly; medium range: daily

Major Output Datasets

- Height Above Nearest Drainage (HAND)
- Hydraulic property table
- Inundation tables and maps

CyberGIS Integration



Hybrid Supercomputing Architecture

- ROGER
  - HPC: 32 computing nodes, 12 with GPU
  - Cloud (OpenStack): 13 nodes
  - Hadoop: 11 nodes
  - Storage: 5PB usage; GPFS parallel file system
- An advanced end user research computing environment
  - Highly integrated environment
  - Data
    - Access, transfer, archiving, sharing
  - Software
    - Geospatial computing environment
    - Virtualization and containerization
  - Services
    - Databases, mapping, Web, Jupyter, … …

NFIE on ROGER

- HUC-based computation on ROGER HPC
  - NFIE code: /projects/nfie/nfie-floodmap
  - TauDEM development version: /gpfs_scratch/taudem/
  - Software environment
    - GDAL, NetCDF4/HDF5, Python libs, GEOS, PROJ4, ESRI FileGDB, Spatialite/SQLite, MPI
- 3DEP and NHDPlus data deployment on GPFS
  - /gpfs_scratch/usgs/ned{1|3|10}m
  - /gpfs_scratch/usgs/nhd
  - /gpfs_scratch/usgs/wbd
- Data & visualization server in ROGER cloud
  - http://nfie.roger.ncsa.illinois.edu/nfiedata/
- Gateway environment
  - Jupyter interactive analysis environment
    - http://hydroroger.ncsa.illinois.edu/
  - CyberGIS Gateway
    - http://sandbox.cigi.illinois.edu
- iRODS and GridFTP
  - iRODS NCSA vault: cg-hm02.cigi.illinois.edu:/projects/nfie/irods/nfie_vault
  - External access
    - RENCI iRODS
    - TACC Wrangler

Scalable Computing

- Two-level parallelization
  - HUC-level hydrologic and spatial decomposition (High-throughput computing (HTC))
  - Parallel computing for individual HUC units (High-performance computing (HPC))

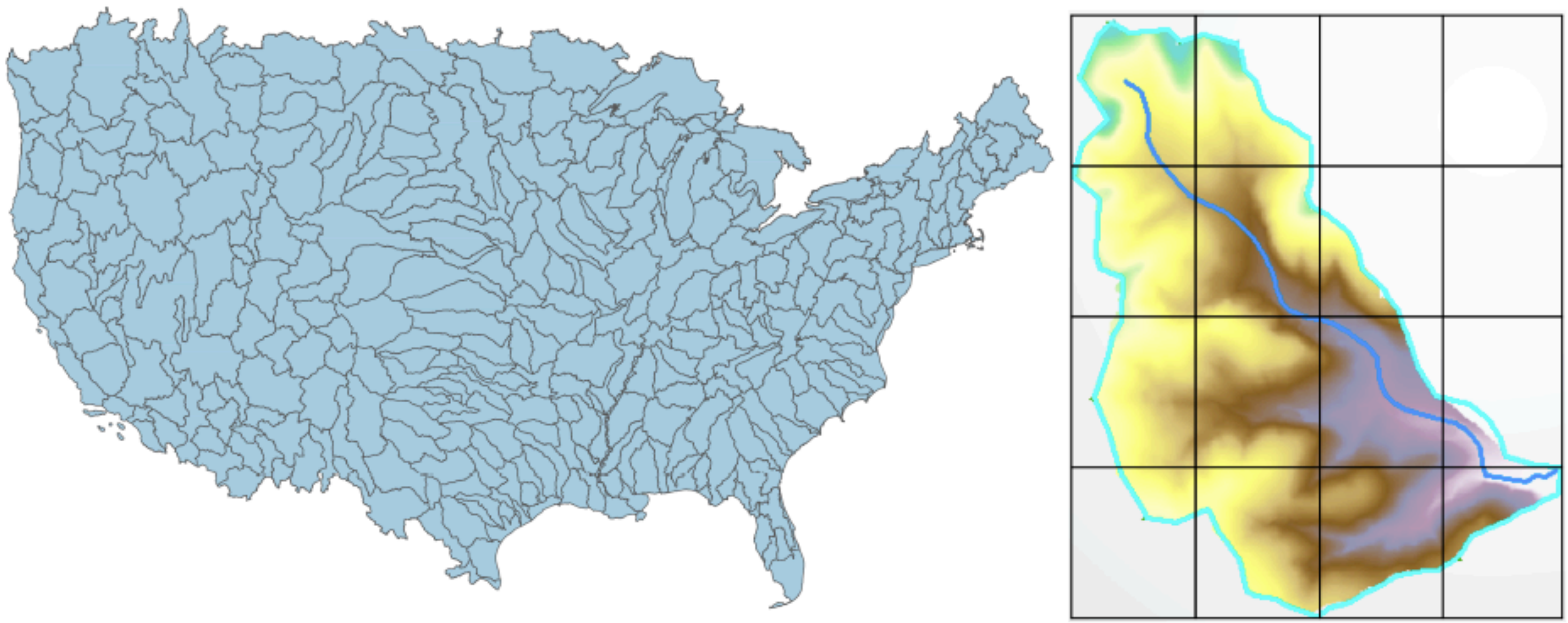


FIGURE 2. Two-level parallelization based on hydrologic and spatial domain decomposition. On the left, the top level parallelization decomposes the U.S. continent based on the well-developed HUC system, resulting in 336 HUC6 units. On the right, each HUC unit is computed in parallel using regular spatial domain decomposition in a single computing job.

Algorithm 1: HAND generation

```
foreach HUC unit h:
    clip DEM from USGS 3DEP and flowline from NHDPlus;
    compute HAND for h;
merge HAND at the HUC level into CONUS.
```

Algorithm 2: Hydraulic property table generation

```
foreach HUC unit h:
    prepare HAND input, reach polygons for h;
    read stage table;
    foreach COMID and stage height:
        compute hydraulic properties including channel geometry and rating curve;
merge hydro property table at the HUC level into CONUS.
```

Algorithm 3: Inundation map generation

```
foreach NOAA NWM forecast:
    foreach COMID:
        Interpolate inundation depth from hydraulic property table and HAND;
    generate forecast table;
    foreach HUC unit h:
        generate inundation map raster from the forecast table;
        generate TMS visualization layer;
    merge inundation map raster and visualization layer for CONUS.
```

Preliminary Computational Intensity Analysis

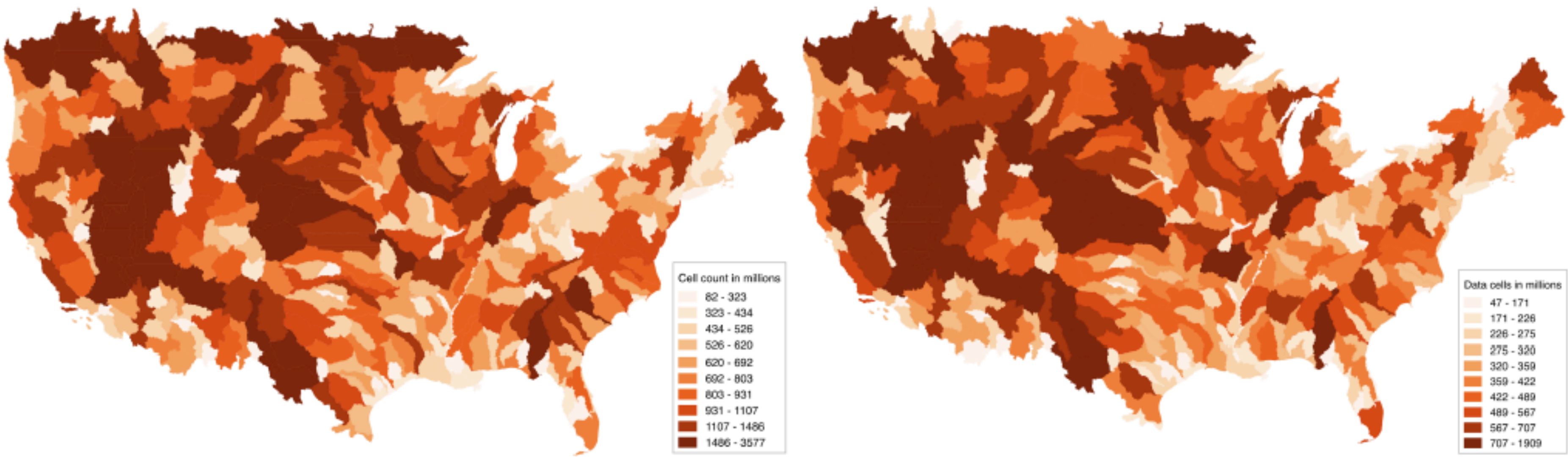
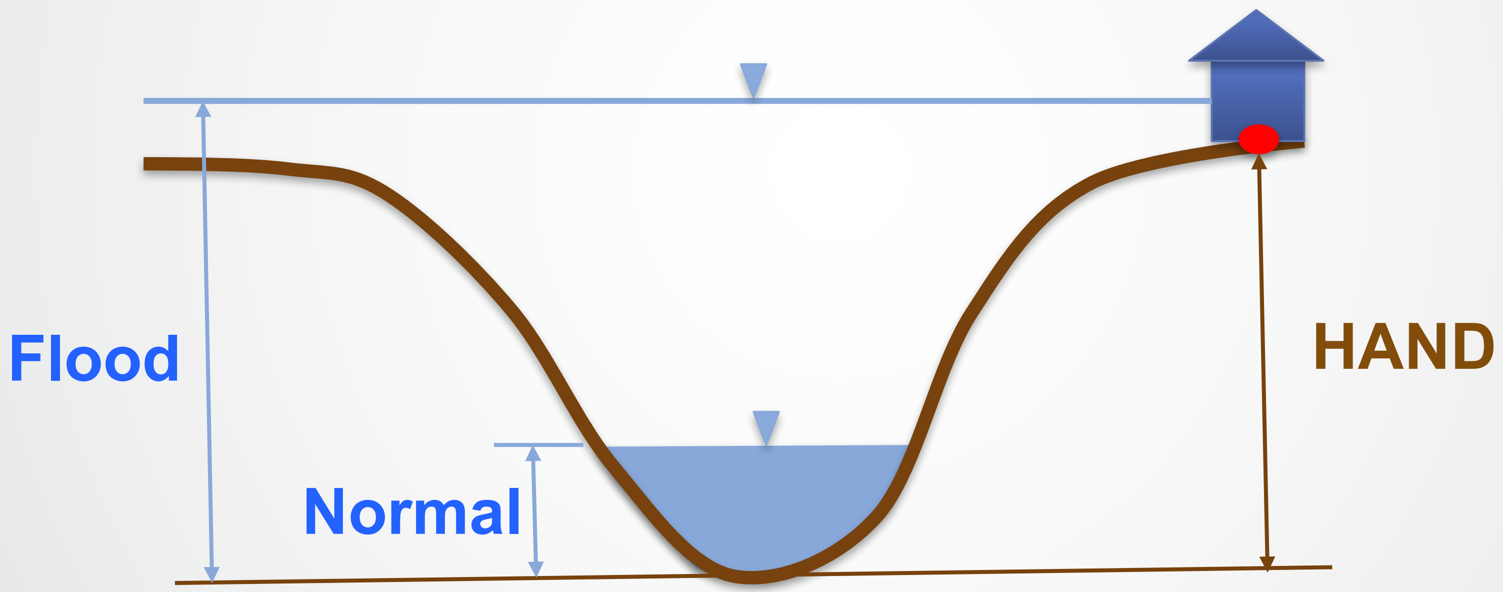


FIGURE 4. Data density map for 331 HUC6 units on CONUS, excluding the five Great Lakes units. The map on the left is the number of grid cells in each unit DEM. The map on the right is the number of data cells, excluding *nodata* cells, in each unit DEM. The map is visualized using equal-count (quantile) symbology. The unit is in millions.

HAND

Method for Determining Flood Risk: Height Above Nearest Drainage (HAND)

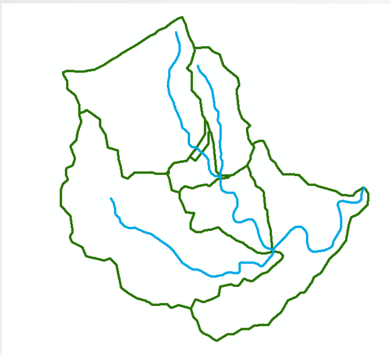
Flooding occurs when Water Depth is greater than HAND



Source: Maidment, NOAA NWS leadership team briefing. 01/09/2017

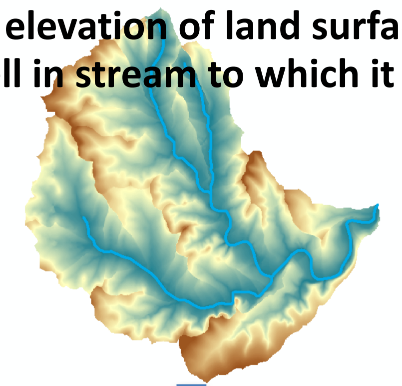
Implementation based on NHDPlus catchments and reaches

Flowlines

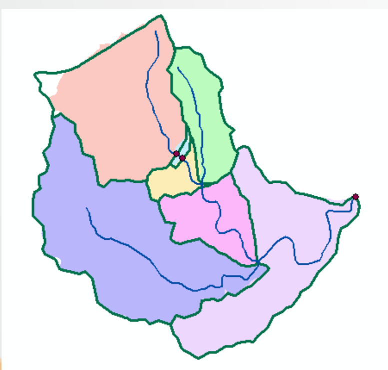


Height above stream

(relative elevation of land surface cell above cell in stream to which it flows)

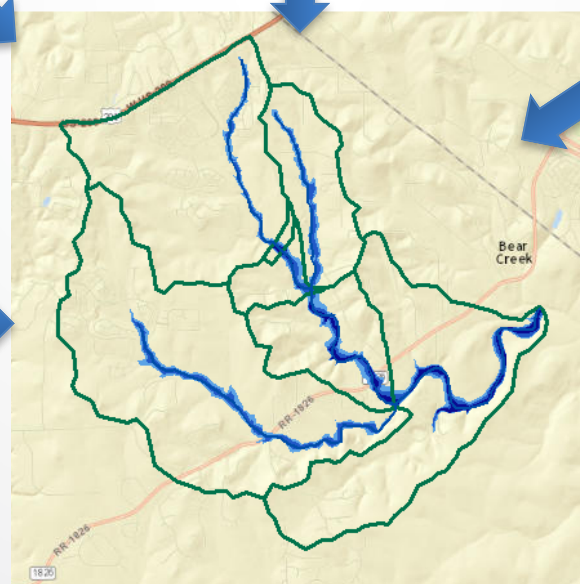


Catchments



Reach Scale Flood Depth

Comid	Depth (ft)
5781365	8
5781381	9
5781405	10
5781401	15
5781399	14
5781383	12
5781933	11

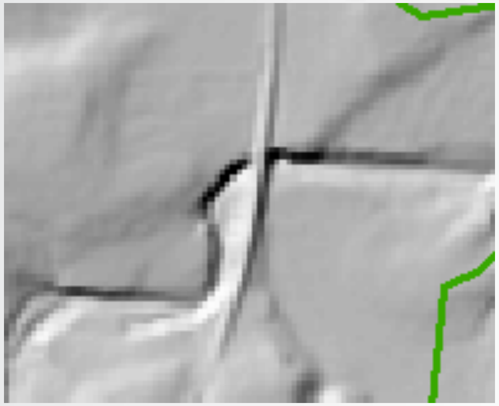


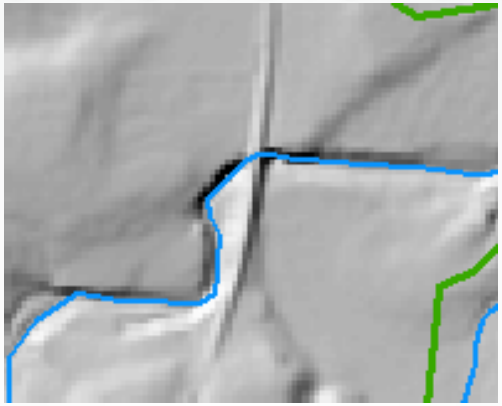
Inundation map

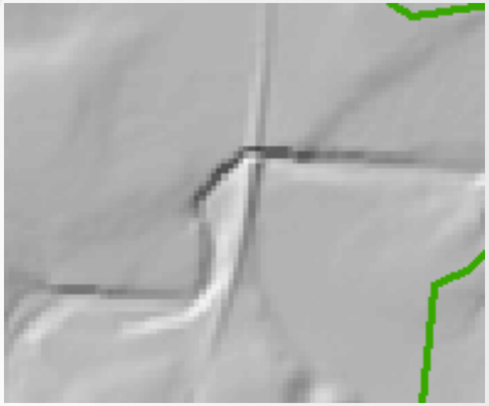
Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

NHD-HAND Workflow

1. Obstacle Removal using NHD HR







48	48	49	48	47
48	46	50	46	45
47	45	51	43	39
44	40	51	47	47
41	45	52	48	48

48	48	49	48	47
48	46	50	46	45
47	45	51	43	39
44	40	51	47	47
41	45	52	48	48

48	48	49	48	47
48	46	50	46	45
47	45	40	40	39
44	40	51	47	47
41	45	52	48	48

Obstacles, like this railroad that are present in DEM are removed tracing down NHD HR streams ensuring that elevation never increases along a stream.

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

2. Remove (Fill) Sinks

Raw DEM (Obstacles removed)

36	35	36	39	42	48	50
39	32	33	35	38	46	51
47	40	36	32	38	43	46
52	48	39	36	31	35	34
52	50	47	38	34	31	30
51	50	49	45	40	35	33
52	51	52	50	47	41	37

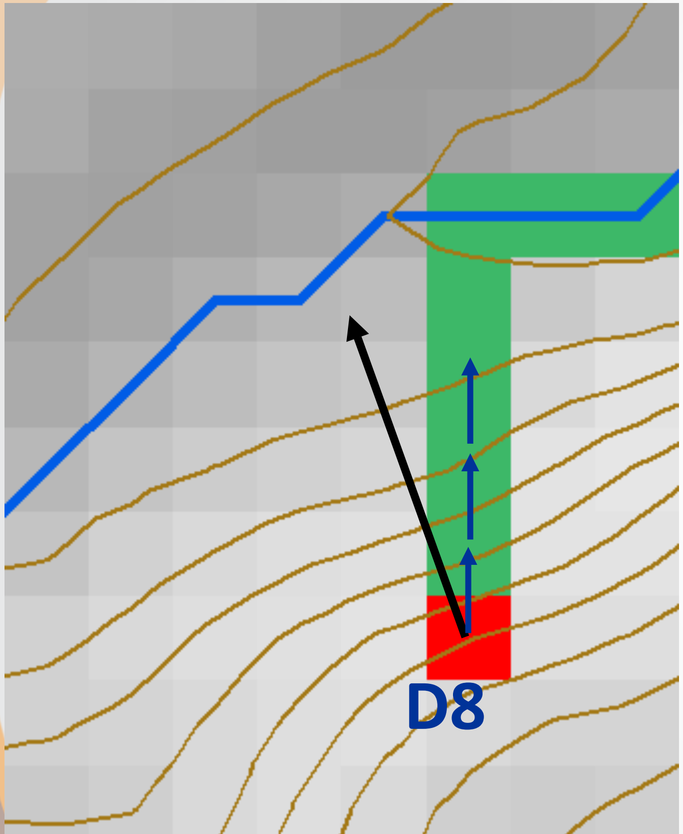
Pit-Removed DEM (Hydrologically conditioned)

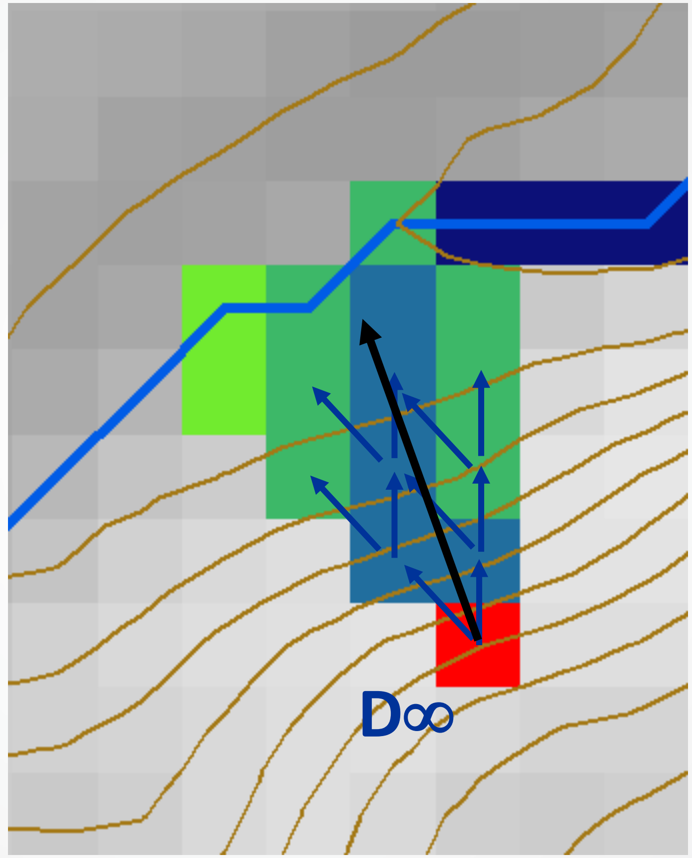
36	35	36	39	42	48	50
39	33	33	35	38	46	51
47	40	36	32	38	43	46
52	48	39	36	31	35	34
52	50	47	38	34	31	30
51	50	49	45	40	35	33
52	51	52	50	47	41	37

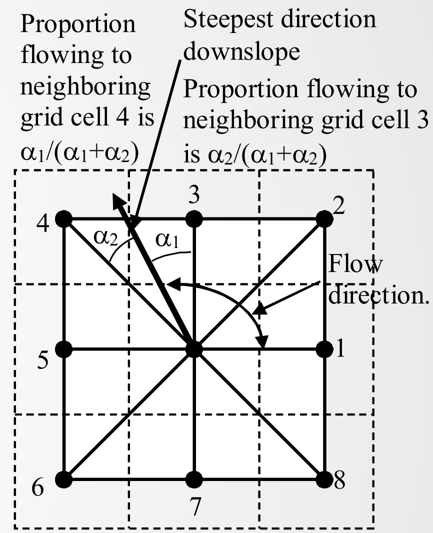
Sinks

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

3. TauDEM Dinfinity Representation of Flow Field







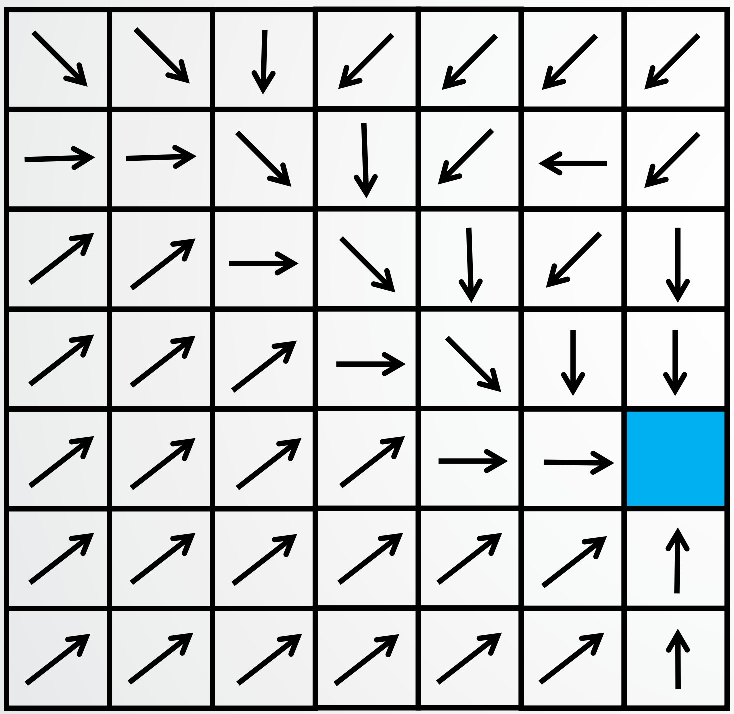
Tarboton, D. G., (1997), "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," Water Resources Research, 33(2): 309-319.)

http://hydrology.usu.edu/taudem

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

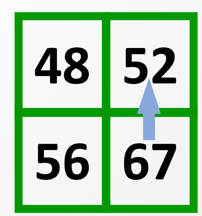
4. D8 Flow Direction

D8 Flow Direction



Flow direction from each grid cell set in the steepest downslope direction to one of eight adjacent neighbors

Routing across flats away from high terrain and towards low terrain (Garbrecht and Martz, 1997)



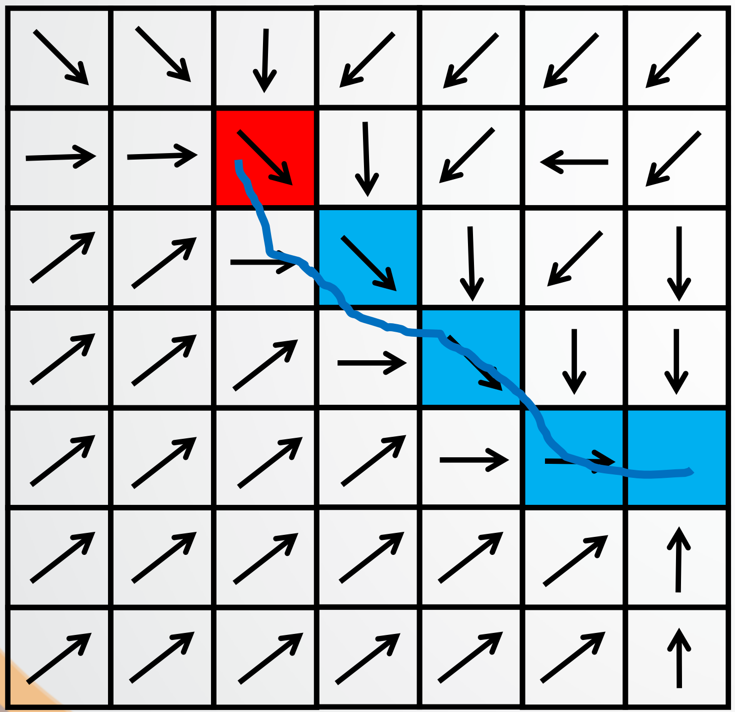
$$\frac{67-52}{30}=0.50 \qquad \frac{67-48}{30\sqrt{2}}=0.45$$

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

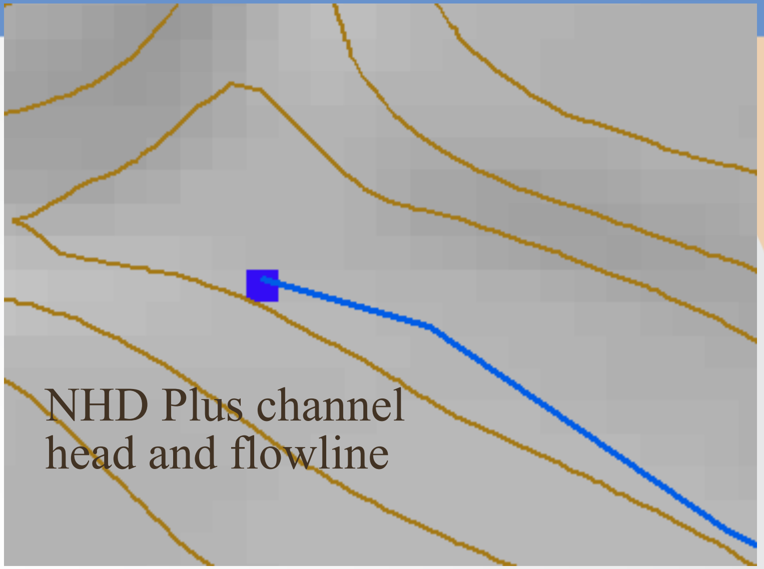
5. Stream Definition

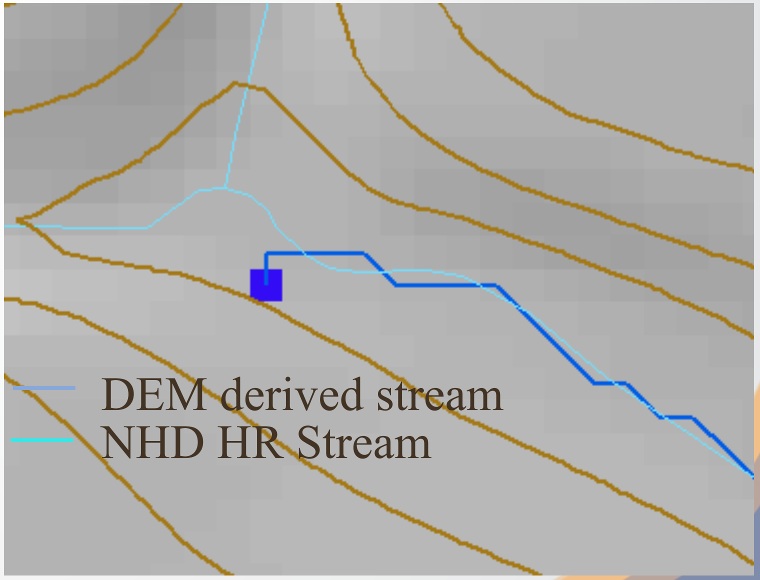
Grids from the NHD Plus channel head cell to the outlet cell are defined as Stream Cells

Channel Head



NHD Plus Flowline

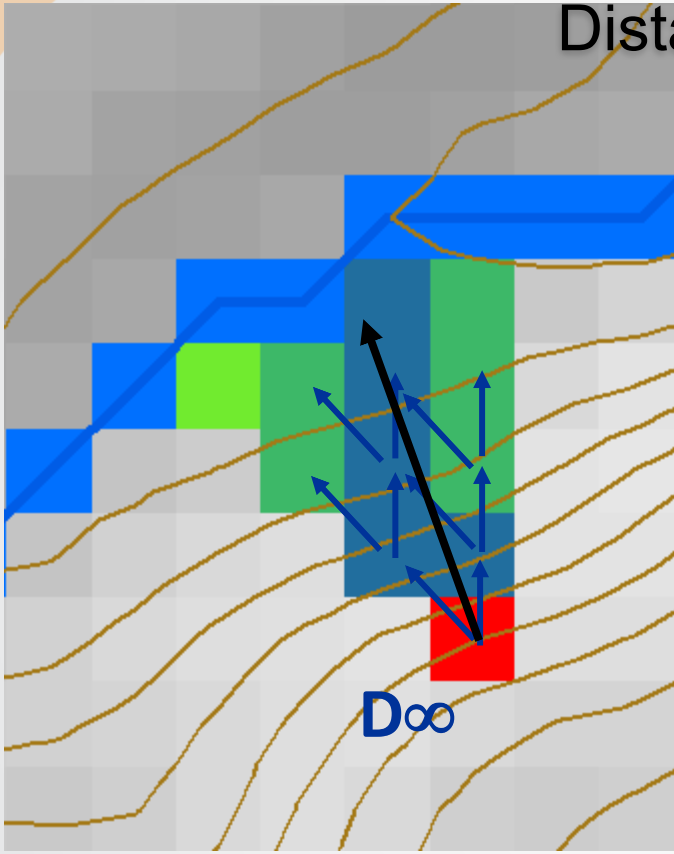




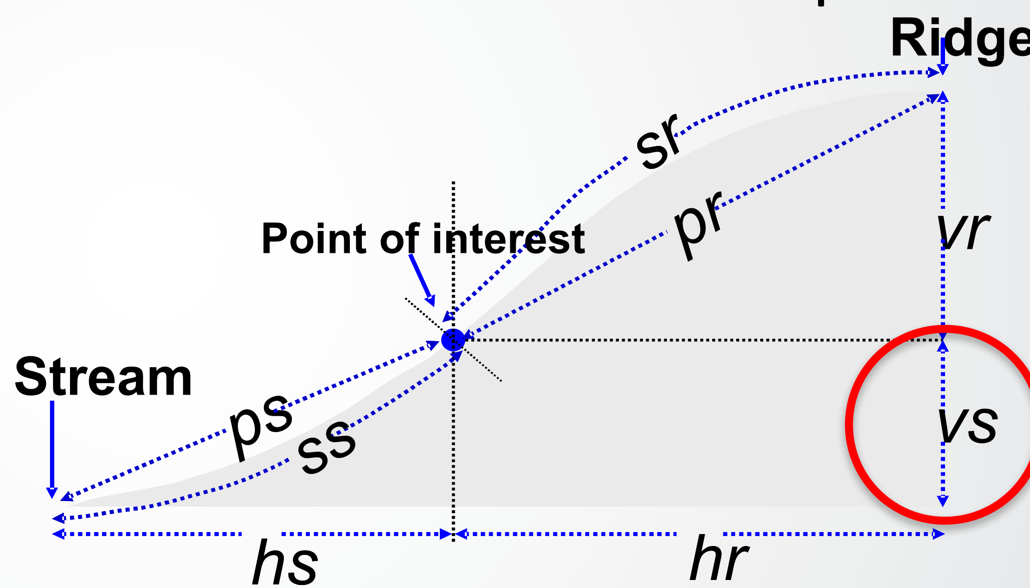
DEM derived stream network is consistent with the DEM but at the scale (drainage density) of NHD Plus.

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

6. HAND evaluated using TauDEM Dinfinity Vertical Distance Down function



TauDEM Distance Down and Distance Up



Vertical distance to stream evaluated as weighted average over multiple flow paths. This results in a “smooth” height above nearest stream layer

Tesfa, T. K., D. G. Tarboton, D. W. Watson, K. A. T. Schreuders, M. E. Baker and R. M. Wallace, (2011), "Extraction of hydrological proximity measures from DEMs using parallel processing," Environmental Modelling & Software, 26(12): 1696-1709, http://dx.doi.org/10.1016/j.envsoft.2011.07.018.

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

7. Mapping from height above nearest drainage to flood extent

Reach and Watershed id

$h_w(1) = 3.5$

			1						
		1	1	1	1				
	1	1	1	1	1	1			
	2	2	2	3	3	3	3		
2	2	2	2	3	3	3	3	3	
2	2	2	2	3	3	3	3	3	
2	2	2	2	3	3	3	3	3	
2	2	2	2	3	3	3	3	3	3
2	2	2	2	3	3	3	3	3	3
	2				3	3	3	3	

Height above nearest drainage raster h_{HAND}

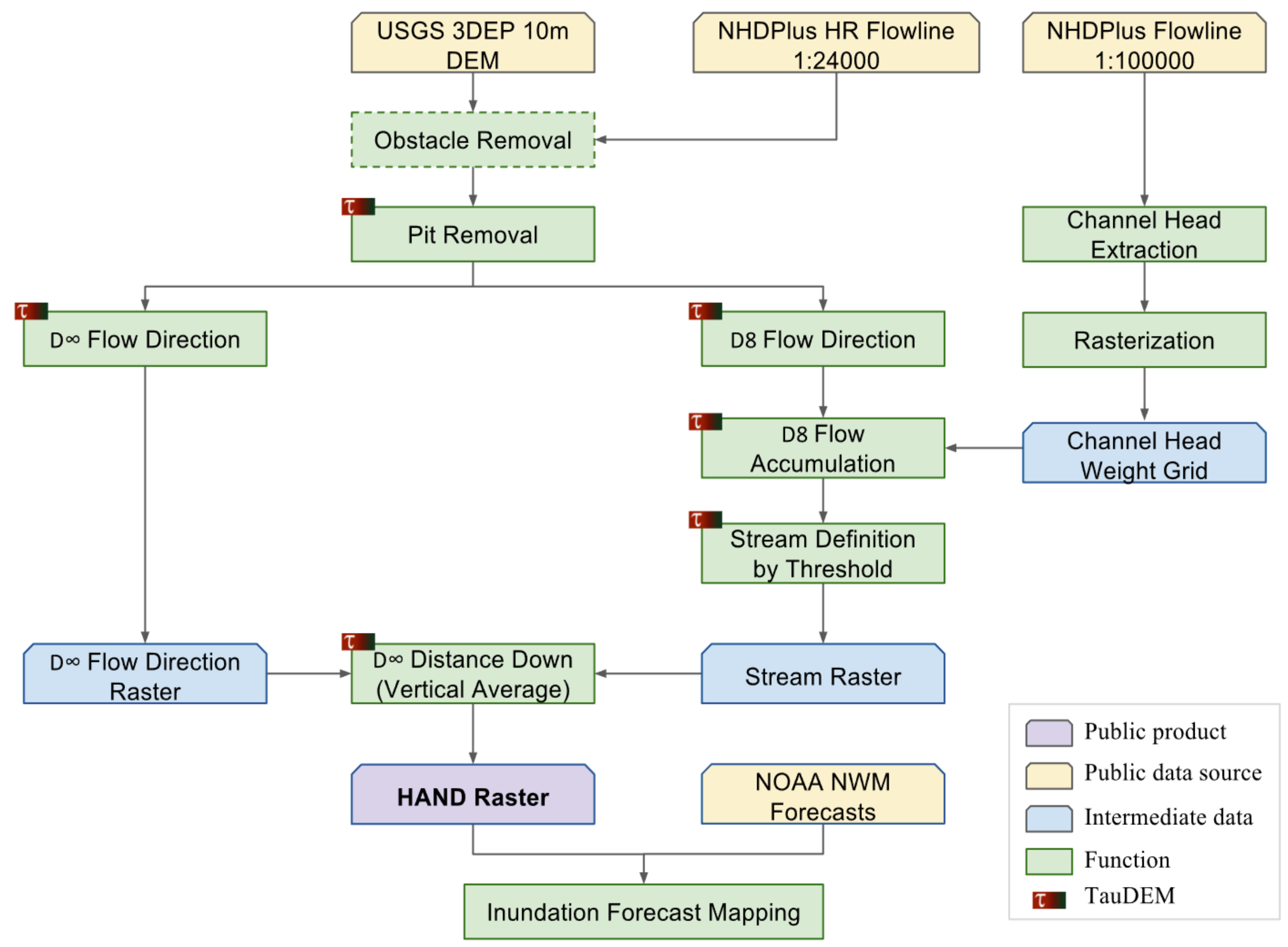
			0						
		2	0	2	4				
	4	3	0	3	4	5			
	3	2	0	0	1	2	4		
3	1	0	1	1	0	1	2	5	
2	1	0	1	1	1	0	1	5	
2	0	1	2	2	1	0	1	4	
2	0	1	3	3	2	1	0	1	4
2	2	2	3	4	3	2	1	1	4
	3				3	2	3	4	

$h_w(2) = 2.5$

$h_w(3) = 1.5$

Source: Maidment *et. al*, USGS leadership team briefing. 07/18/2016

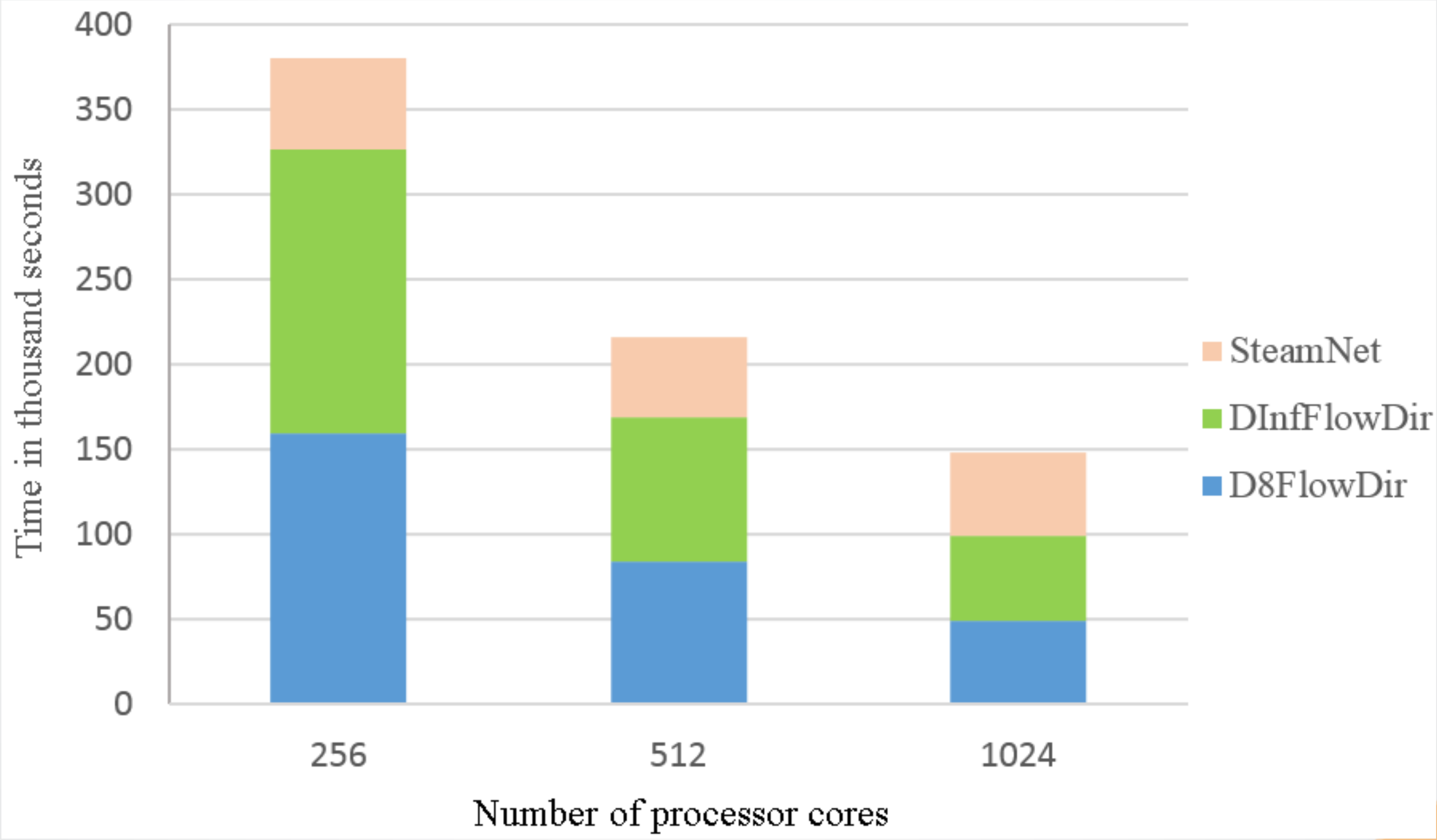
HAND Workflow



TauDEM Acceleration

- TauDEM - a Parallel Computing Solution to DEM-based Hydrological Information Analysis
  - Open source software
  - A suite of DEM tools for the extraction and analysis of hydrologic information from topographic data
  - A growing user community
- Parallel Computing in TauDEM
  - Parallel programming model: Message Passing Interface (MPI)
  - Spatial data decomposition
    - Each process reads a sub-region for processing
    - MPI communication for exchanging runtime hydrological information at border cells
    - Each process writes a sub-region defined by output data decomposition
    - Row-wise and block-wise decomposition
  - Input/output (IO)
    - MPI IO for DEM read and write – old version
    - GDAL IO

Three Costly TauDEM Functions

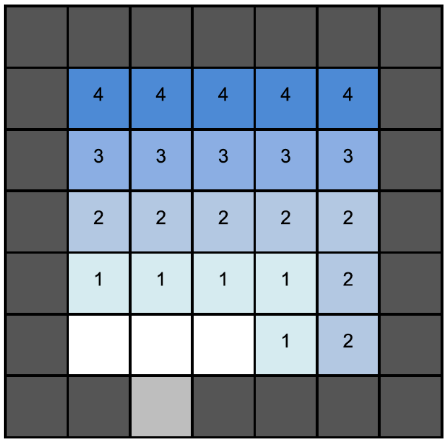


Execution time of the three most costly TauDEM functions on a 36GB DEM dataset. (*Fan et al. 2014*)

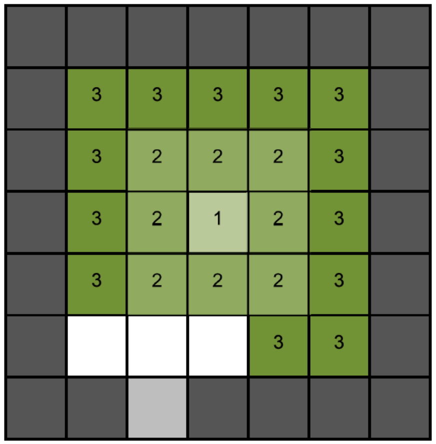
TauDEM Flow Direction Algorithm Acceleration

- Performance issues
  - 10m NED tile (1° x 1°) – 400MB
    - 3 hours with 1 processor
    - 1 hour with 4 processors
  - 5 NED tiles combined – 2.2GB
    - 1 hour with 100 (faster) processors
  - Most of the time is spent resolving flat regions
- Algorithm issues (Garbrecht & Martz 1997)
  - Pixel by pixel approach
  - No knowledge about the flat regions
    - Yet flat regions are independent
  - Every cell re-checked every iteration
    - …even if the cell shouldn't change
    - …even if the whole region is complete
    - Communication after every iteration

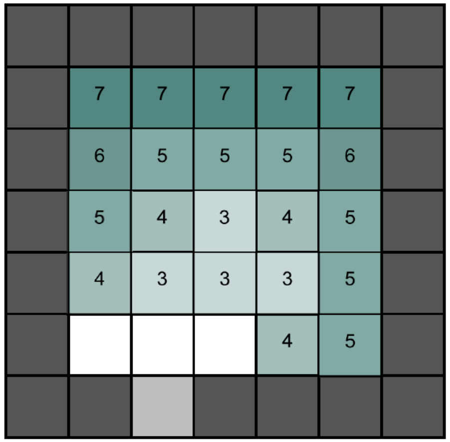
Flat Resolving Algorithm



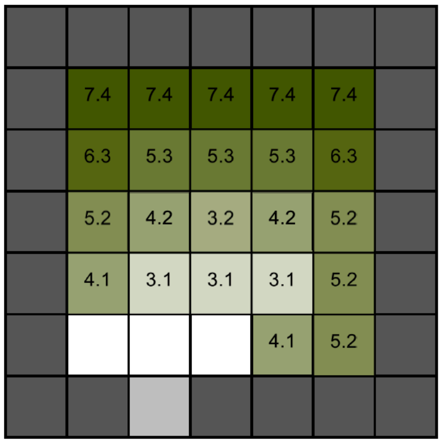
(a) Step 1



(b) Step 2



(c) Step 3



(d) Step 4

Step1. Gradient toward lower;
Step 2. Gradient away from higher;
Step 3. Combination;
Step 4. Recursive resolving if new flats appear

- Dark gray cells have higher elevation
- Light gray cells have lower elevation

New Parallel Algorithm

Algorithm 1 Parallel D8 flow algorithm

Require: Input elevation DEM D_p of the processor p
Ensure: Flow direction grid F_p of the processor p

```
F_p ← CalculateSlope(D_p)
if there exist cells with FLAT value in F_p then
    IS ← findIslands(F_p)
    while there exists shared flat regions do
        F_p ← resolveSharedFlats(IS)
    end while
    F_p ← resolveLocalFlats(IS)
end if
```

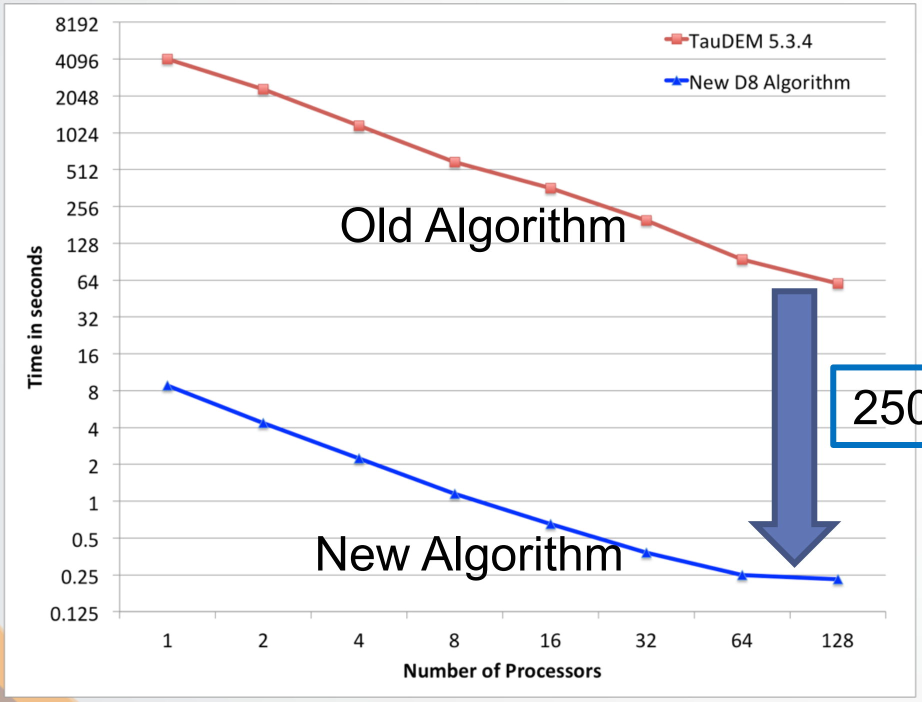
Survila, K., Yildirim, A.A., Li, T., Liu, Y., Tarboton, D. and Wang, S. 2016. "A Scalable High-performance Topographic Flow Direction Algorithm for Hydrological Information Analysis". *Proceedings of the 2016 Annual Conference on Extreme Science and Engineering Discovery Environment (XSEDE'16)*. July 17-21. Miami, Florida, USA

Sequential Algorithm Improvements

- Rewrite of the sequential algorithm
  - Identification of flat regions
  - Every flat cell is visited only once in flat resolving
- Worst case complexity reduced from $O(n^2)$ to $O(n)$
- Results
  - 10m NED tile (1º x 1º) – 400MB
  - Before:
    - 3 hours with 1 processor
    - 1 hour with 4 processors
  - After: 15 seconds with 1 processor

Performance

New D8 (100 million cells)



250 times faster

Table 1: Performance on large watershed DEMs (Time in seconds).

Region (HUC2)	Size	Num Flats	Time
Arkansas-White-Red (11)	170919x114734	433,807,730	39.57
Missouri (10)	227191x177787	1,225,082,919	91.43

Github repository: https://github.com/cybergis/cybergis-toolkit/tree/master/taudem

TauDEM HUC6 Experiment

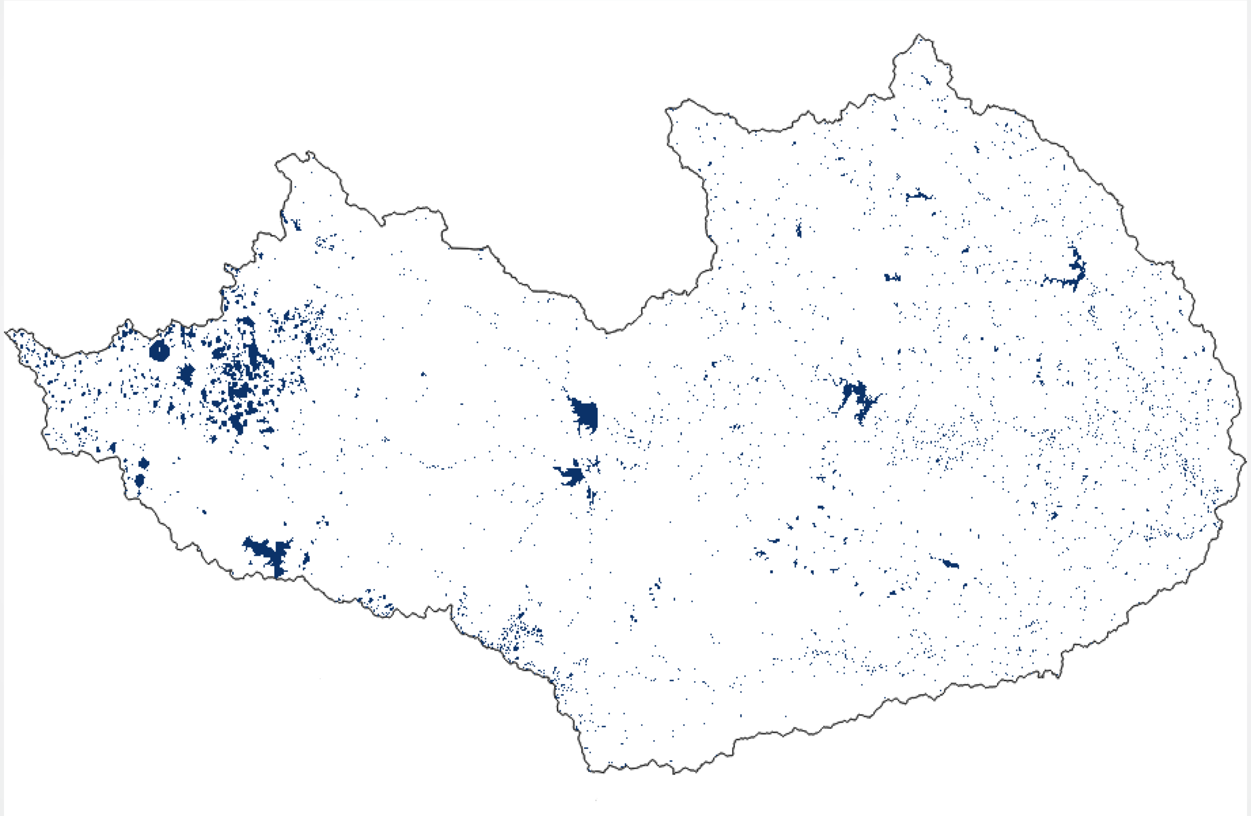


FIGURE 7. Illustration of the map of flats for HUC6 unit 120901, Middle Colorado-Concho. Flats in hydrologically conditioned DEM may include natural flats, flat surfaces in DEM (such as water surface where elevation information on the water channel beneath the water is not available), and filled pits.

Performance

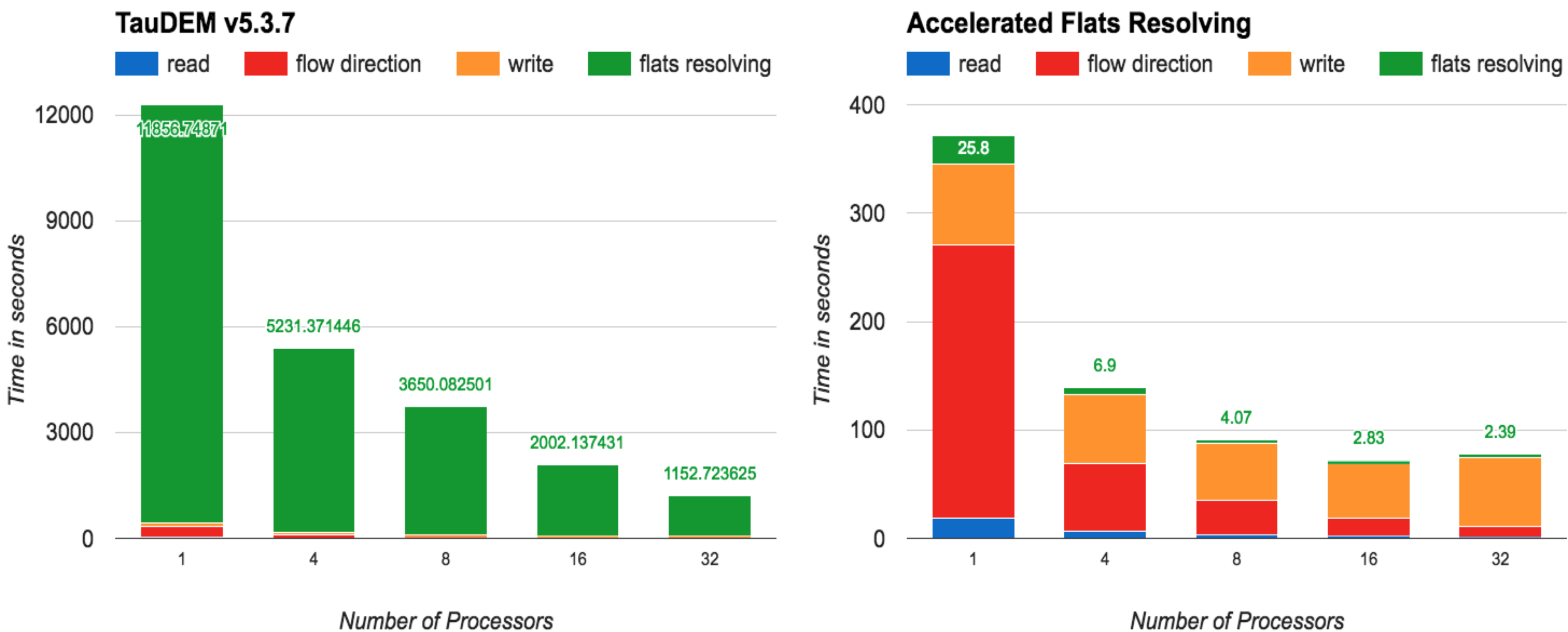


FIGURE 8. Performance of the *D8* flow direction algorithm before and after the acceleration on flats resolving. HUC6 unit: 120901. DEM size: 42877 x 21711, 2.18GB. For visual purpose, the range on Y-axis is plotted based on actual maximal values obtained in the two tests, respectively.

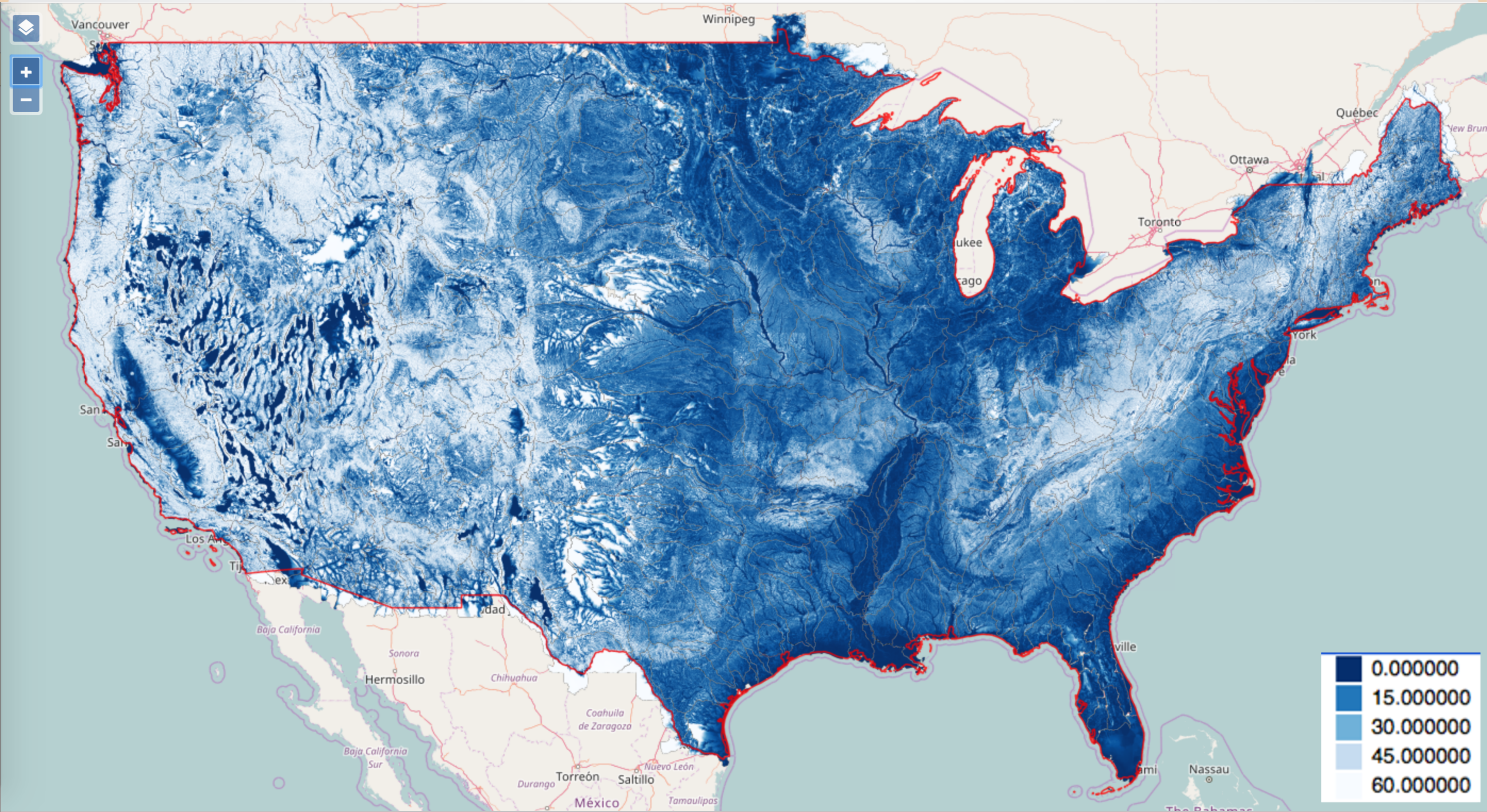
Inner Join Acceleration on NHDPlus HR Query

```
ogr2ogr -mapFieldType Real=String -sql "SELECT NHDPlusBurnLineEvent.NHDPlusID AS
NHDPlusID, NHDPlusBurnLineEvent.ReachCode AS ReachCode, NHDPlusFlowlineVAA.FromNode
AS FromNode, NHDPlusFlowlineVAA.ToNode AS ToNode FROM NHDPlusBurnLineEvent LEFT JOIN
NHDPlusFlowlineVAA ON NHDPlusBurnLineEvent.NHDPlusID=NHDPlusFlowlineVAA.NHDPlusID
WHERE NHDPlusBurnLineEvent.ReachCode LIKE '120902%'" 120902-flows.shp
HRNHDPlus1209.gdb
```

Soft Burn-in Workflow

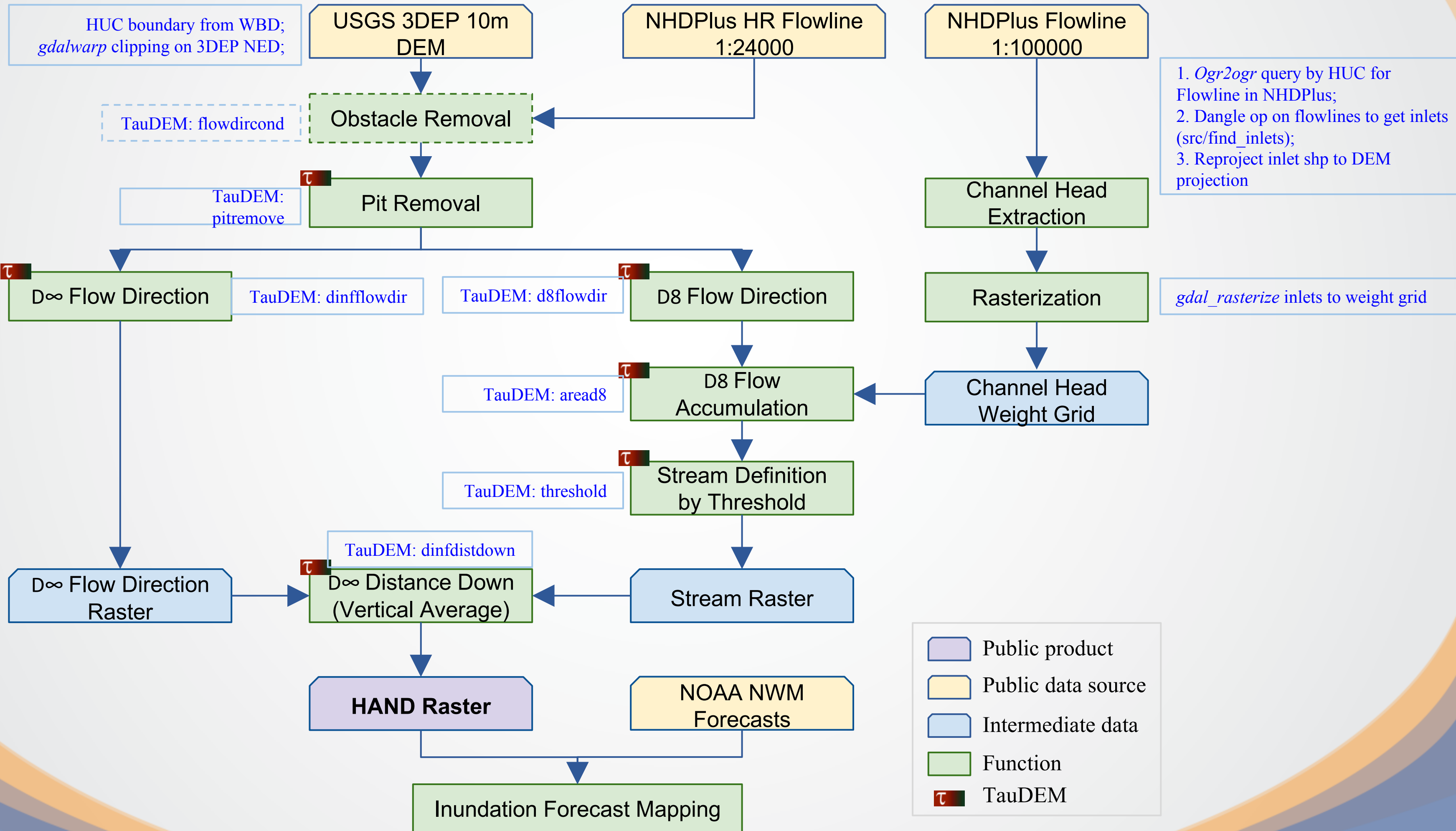
1. Rasterize NHDPlus HR flowline;
2. Lower the elevation of stream cells on DEM by 100m;
3. Remove pits on the burned DEM;
4. Derive D8 flow direction on the pit-removed DEM;
5. Keep D8 flow direction on stream cells only;
6. Call TauDEM:flowdircond to burn the original DEM
   1. Identify ‘top cells’ which are on NHDPlus HR streams, have D8 direction, and are not downstream cells. Put them in a queue;
   2. For each cell in the queue:
      1. If the elevation is higher than its neighbors, level the elevation with neighbors;
      2. If above step makes any of the neighboring cell a non-downstream cell, add the neighboring cell to the queue. This step propagates the burn-in until the upstream connects to the downstream.

HAND 10m for CONUS



HAND Workflow-Code References

HAND Workflow for CONUS https://github.com/cybergis/nfie-floodmap/blob/master/test/handbyhuc.sh



June 18, 2017. Derived from the original version by Xing Zheng

HAND Output

- Intermediate + final results: 4.9TB
- HAND raster
  - 363GB compressed GeoTIFF as VRT (virtual raster format)
  - Online map (zoom level 5-10) through Tile Map Service (TMS)
    - http://nfie.roger.ncsa.illinois.edu/nfiedata/maps/maps.html#source=..%2Fyanliu%2Fviz%2Fhuc6-mercator-new-singlelayer.json&extent=-14392000_2436200_-7279500_6594375

Data Name	**Description**
${HUCID}-wbd.shp	HUC unit boundary shape file, extracted from USGS WBD
${HUCID}-wbdbuf.shp	HUC unit boundary shape file, extracted from USGS WBD (buffered)
${HUCID}-flows.shp	Flowline shape file, extracted from NHDPlus V21
${HUCID}-inlets0.shp	Inlets point shape file in the HUC unit. Native projection
${HUCID}-inlets.shp	Inlets point shape file in the HUC unit. EPSG:4269
${HUCID}-weights.tif	Weight grid of the rasterized inlet points
${HUCID}.tif	Clipped HUC unit DEM from USGS 3DEP elevation dataset (buffered)
${HUCID}fel.tif	Pit-removed DEM; output of TauDEM *pitremove*
${HUCID}p.tif	*D8* flow direction raster; output of TauDEM *d8flowdir*
${HUCID}sd8.tif	*D8* slope raster; output of TauDEM *d8flowdir*
${HUCID}ang.tif	$D\infty$ flow direction raster; output of TauDEM *dinfflowdir*
${HUCID}slp.tif	$D\infty$ slope raster; output of TauDEM *dinfflowdir*
${HUCID}ssa.tif	Contributing area raster; output of TauDEM *aread8*
${HUCID}src.tif	Stream grid; output of TauDEM *threshold* (threshold=1)
${HUCID}dd.tif	Bufferred HAND raster; output of TauDEM *dinfdistdown*
${HUCID}hand.tif	HAND raster, buffer removed, final result

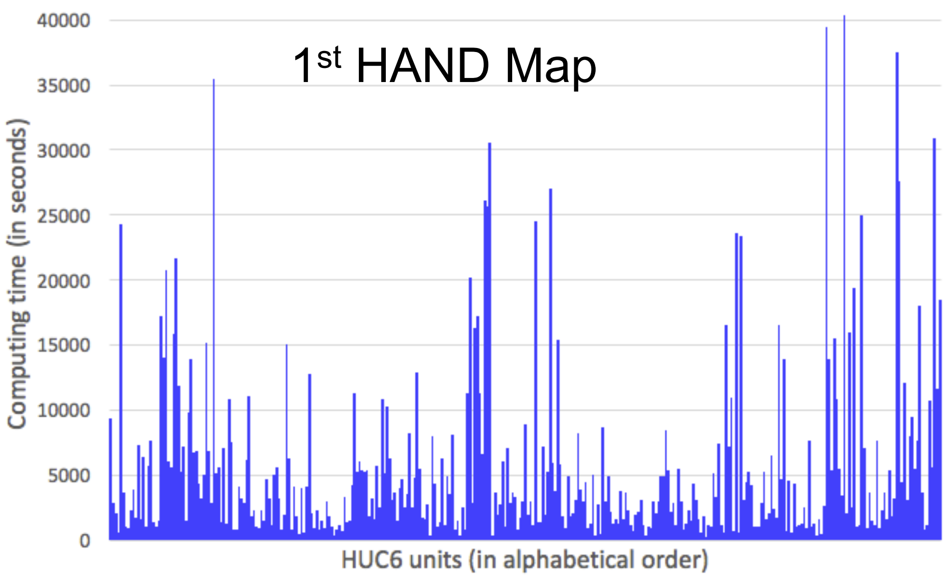
Metadata for each HUC6 HAND output

Computation Summary

- *36 hours in total for 331 HUC6 units*
- 1.34 CPU years
- On average, each job used 65.26 cores and took 0.54 hours to compute
- The two flow direction algorithms only took 12.65% computing time, on average
- The rest of the time was spent on transformation and pre- & post-processing of geospatial data

Computing Time Comparison

Old flow direction algorithms

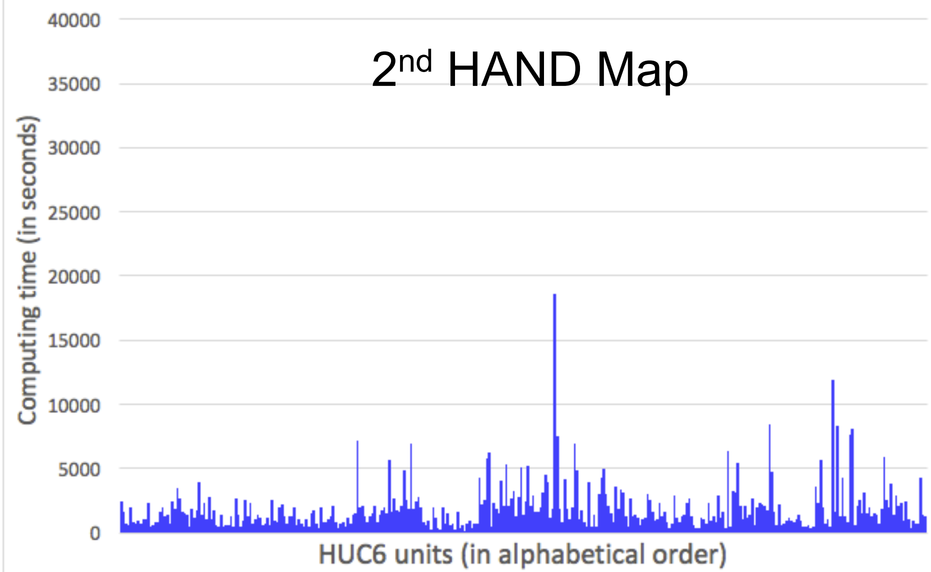


(a) 1st run

5.76 CPU Years

8 days of elapsed time

New flow direction algorithms

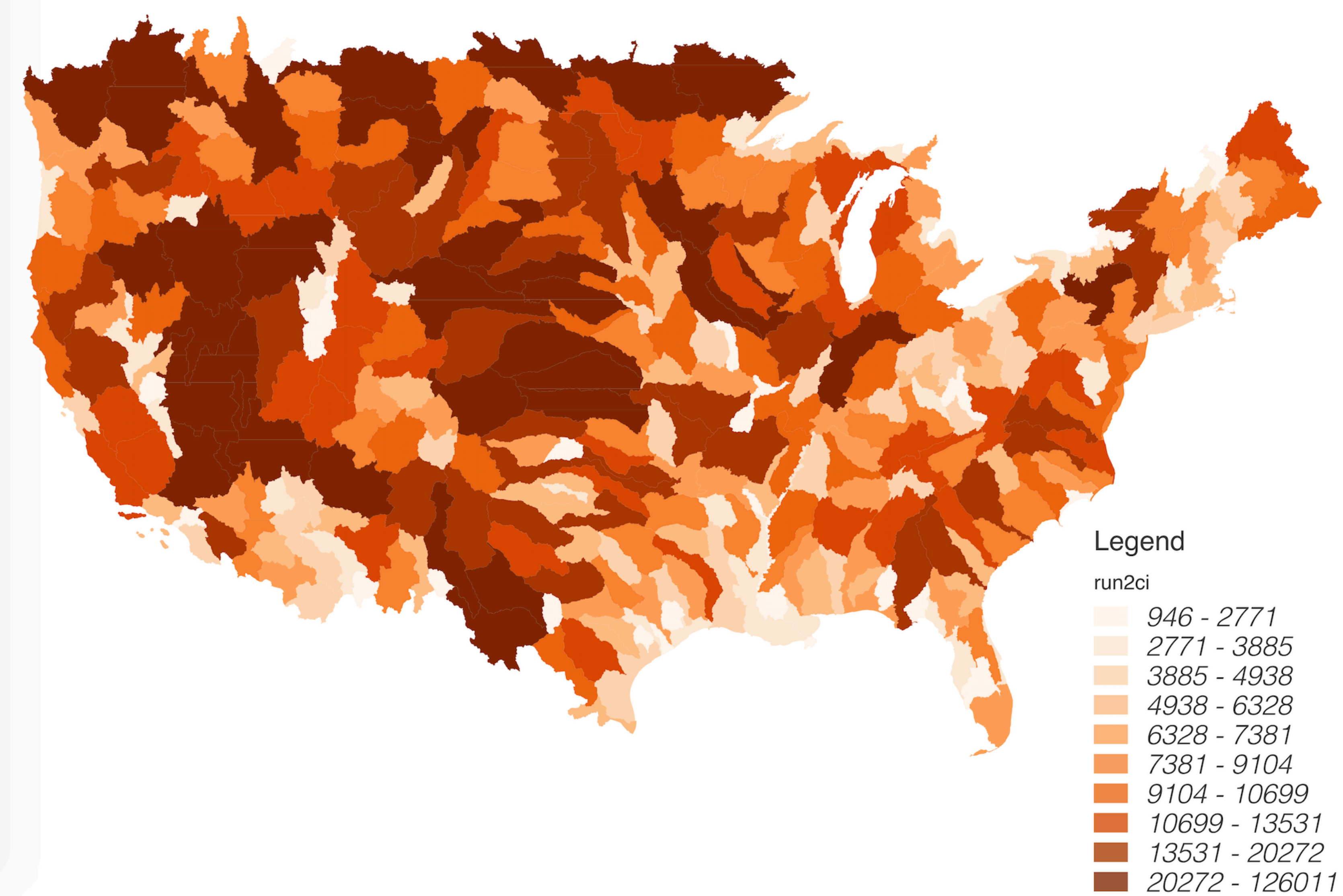


(b) 2nd run

1.34 CPU Years

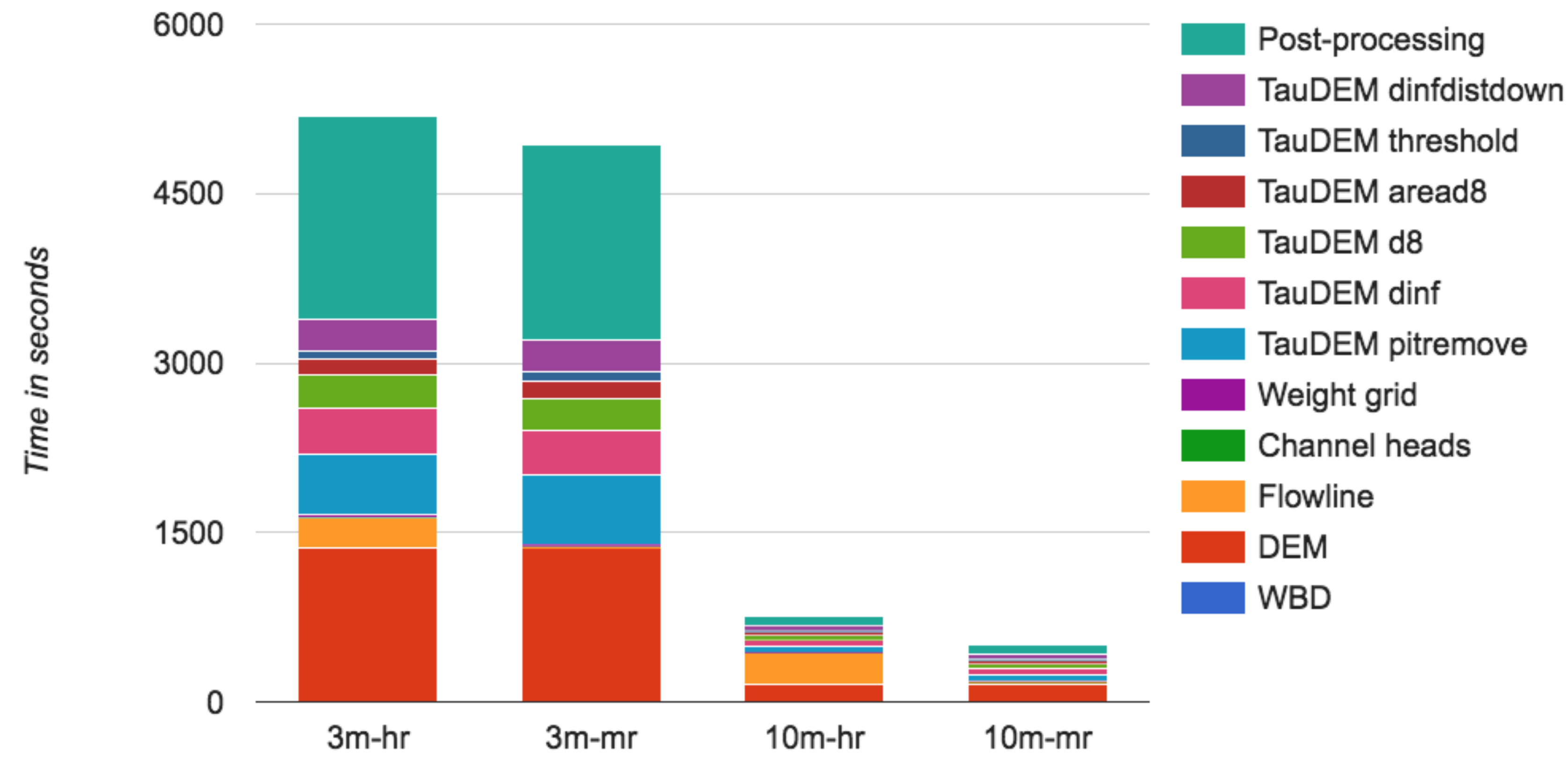
1.5 days of elapsed time

Computation Map for the 2nd Run



Scalability to Higher Resolution

- Experiment on HUC6 unit 120402
  - 6 nodes, 120 cores
- 3m *vs.* 10m DEM
  - 5.4GB *vs.* 595MB
- NHDPlus MR *vs.* NHDPlus HR

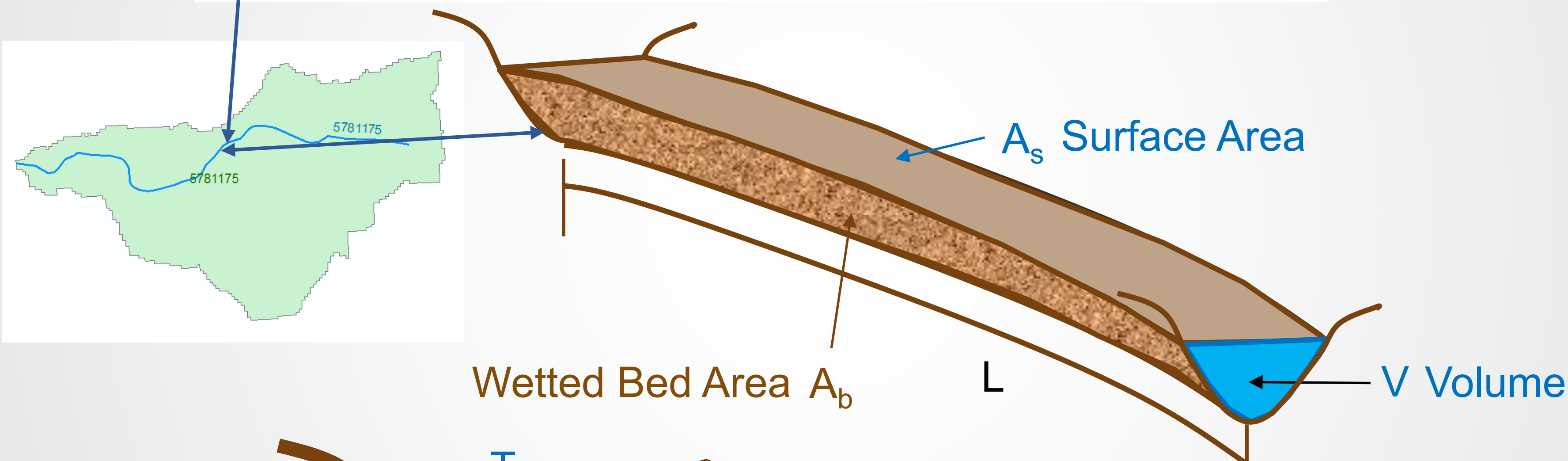


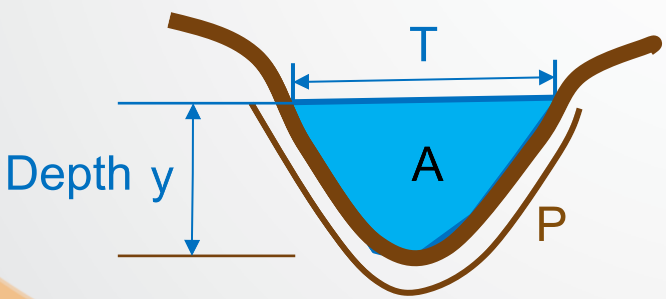
Inundation Mapping

- Create hydraulic property table for CONUS
  - 2.7m river reaches
  - 82 water depth stages
- Inundation forecast mapping
  - Inundation forecast table for CONUS
  - Inundation map for each HUC6 unit
  - Inundation map for CONUS
  - Visualization

Reach Hydraulic Parameters

Comid	y	A	R	P	T	V	Ab	As
5781175	3							
5781175	4							





$A = \frac{V}{L}$ Cross Section Area

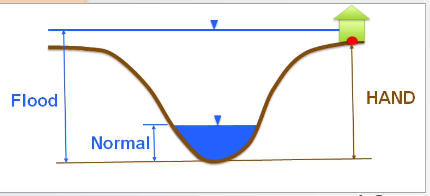
$P = \frac{A_b}{L}$ Wetted Perimeter

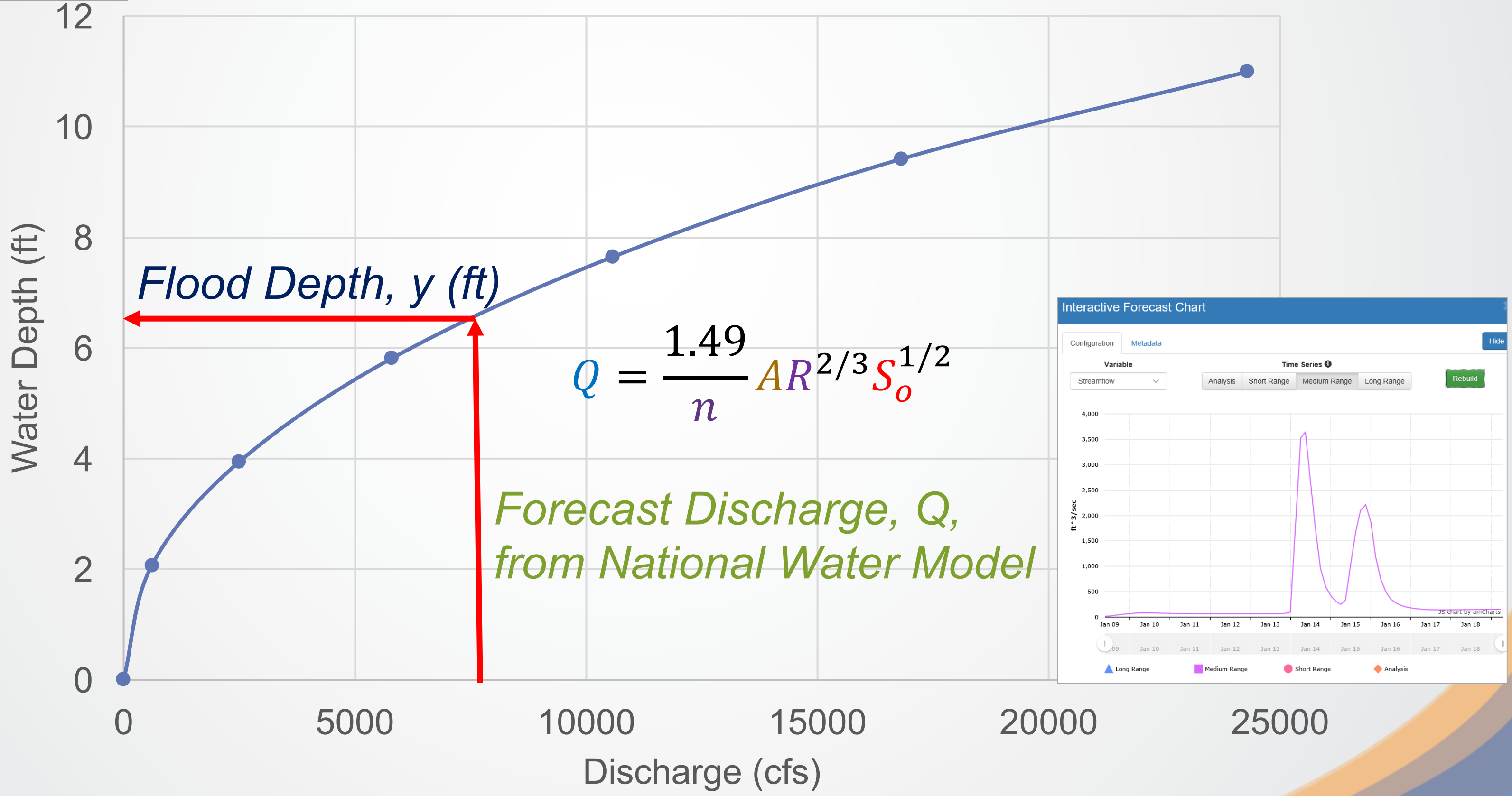
$T = \frac{A_s}{L}$ Top Width

$R = \frac{A}{P}$ Hydraulic Radius

Source: Maidment, NOAA NWS leadership team briefing. 01/09/2017

Rating Curve – Connects Discharge with Depth

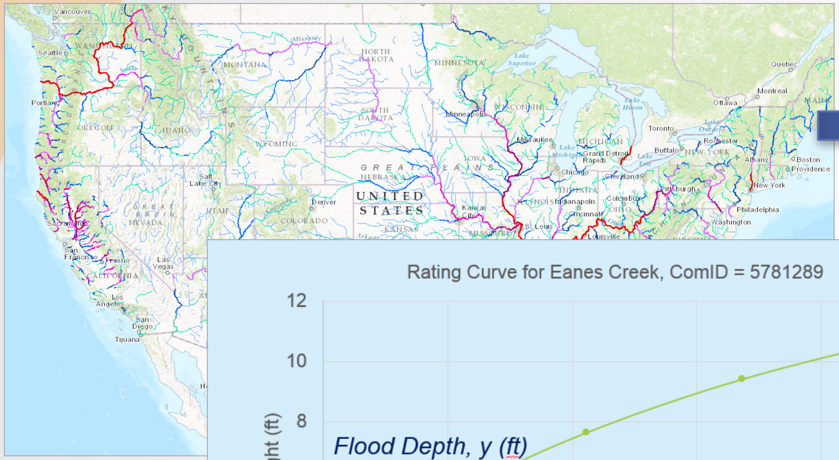


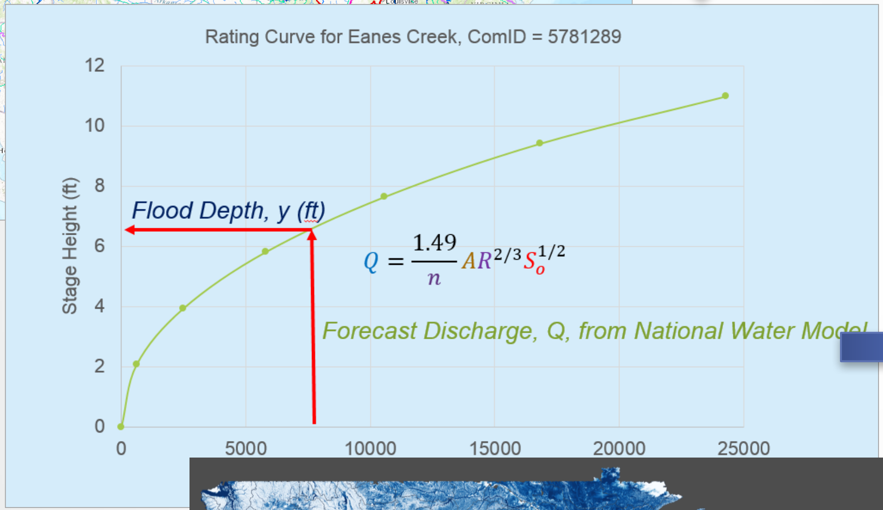


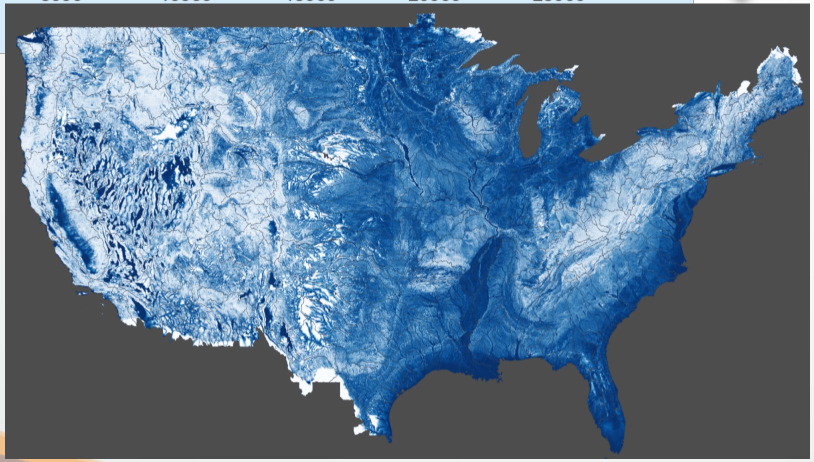
$$Q = \frac{1.49}{n} A R^{2/3} S_o^{1/2}$$

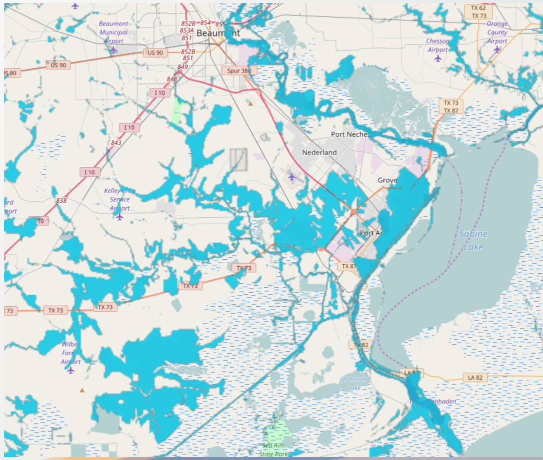
Source: Maidment, NOAA NWS leadership team briefing. 01/09/2017

Continental-Scale Flood Inundation Mapping









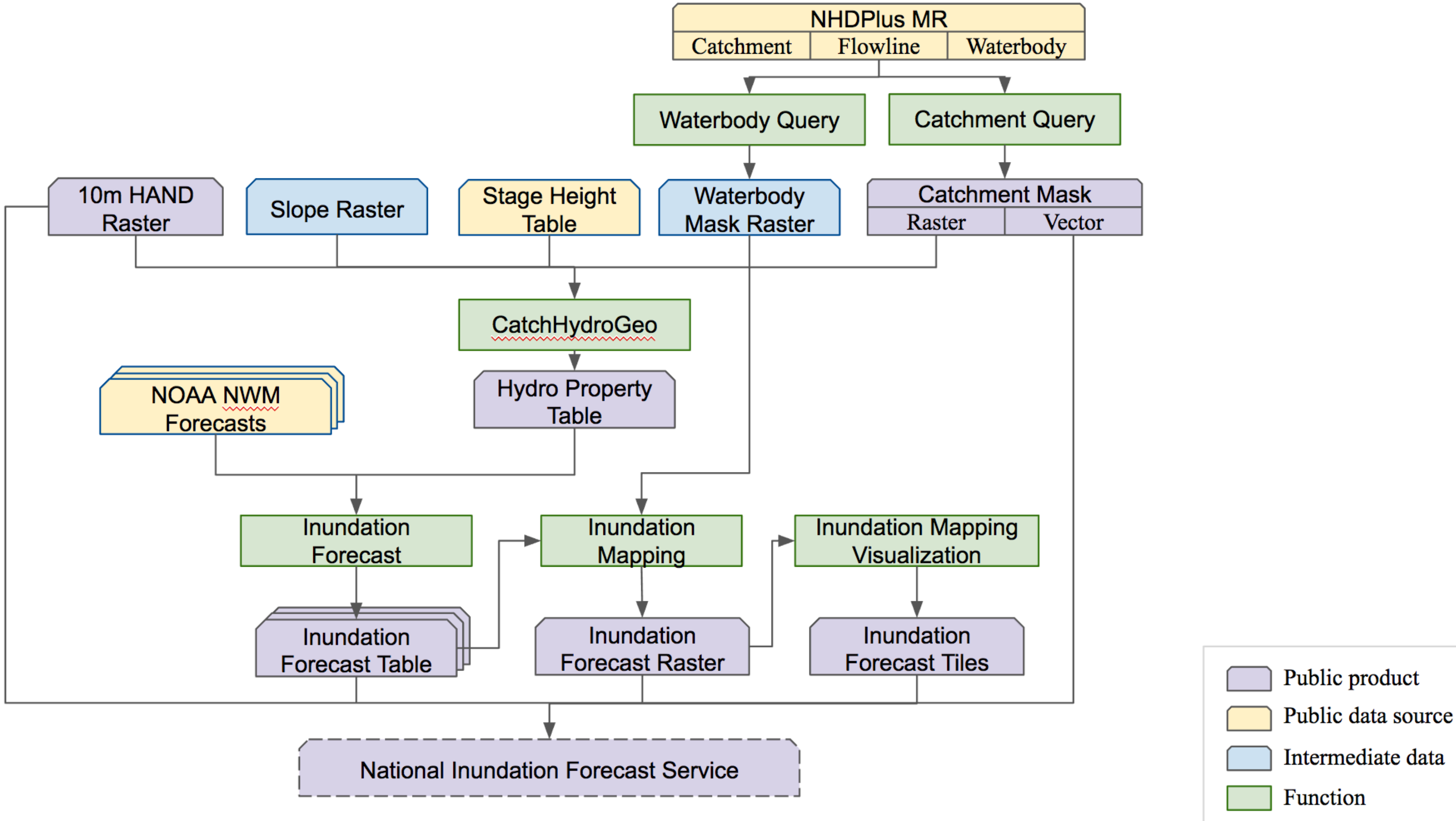
1. Forecast **discharge** with National Water Model

2. Convert discharge to **depth** using rating curve

3. Convert depth to **inundation** using HAND

Source: Maidment, NOAA NWS leadership team briefing. 01/09/2017

Inundation Forecast for CONUS



NWM Operational Configuration

Running Continuously on WCOSS since May 9th

	Analysis & Assimilation	Short-Range	Medium-Range	Long-Range
Cycling Frequency	Hourly	Hourly	Daily at 06Z	Daily Ens (16 mem)
Forecast Duration	- 3 hrs	0-15 hours	0-10 days	0-30 days
Forecast Latency (latency of external forcing data accounts for most of delay)	1 hour	1 hour 45 mins	6 hours	19 hours
Meteorological Forcing	MRMS blend/ HRRR/RAP bkgnd.	Downscaled HRRR/RAP blend	Downscaled GFS	Downscaled & bias-corrected CFS
Spatial Discretization & Routing	1km/250m/NHDPlus Reach	1km/250m/NHDPlus Reach	1km/250m/NHDPlus Reach	1 km/NHDPlus Reach

Assimilation of USGS Obs

Reservoirs (1260 water bodies parameterized with level pool scheme)

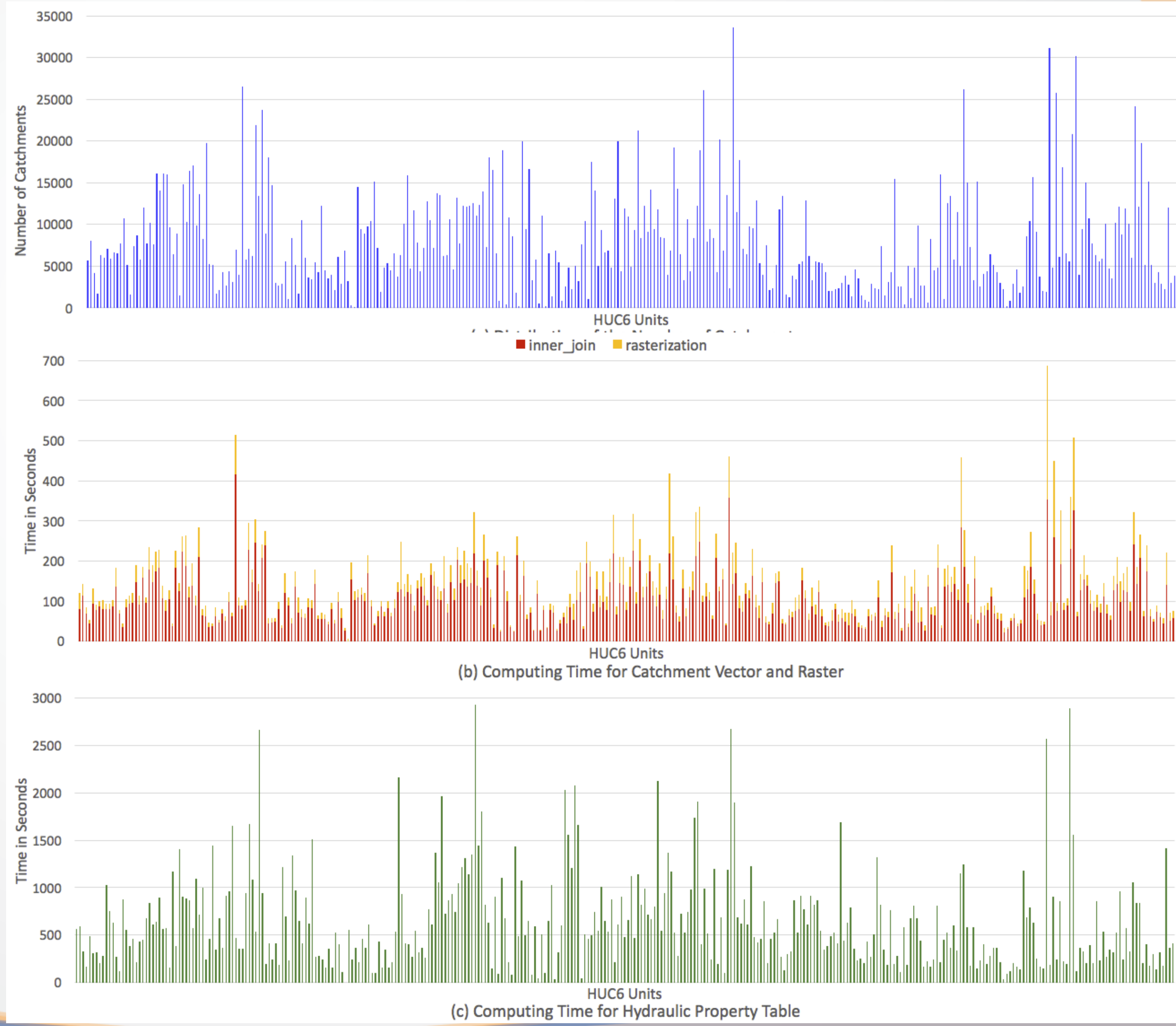
Source: http://www.nws.noaa.gov/com/weatherreadynation/files/NationalWaterModel.pdf

Derived Hydraulic Properties

- Lookup keys
  - COMID
  - Stage (83 stages, 0-25m at 1-foot interval)
- Hydraulic properties
  - Number of Cells
  - SurfaceArea (m2)
  - BedArea (m2)
  - Volume (m3),
  - SLOPE
  - LENGTHKM of the flowline
  - AREASQKM of the catchment
  - Roughness = 0.05
  - TopWidth (m)
  - WettedPerimeter (m)
  - WetArea (m2)
  - HydraulicRadius (m)
  - Discharge (m3s-1)

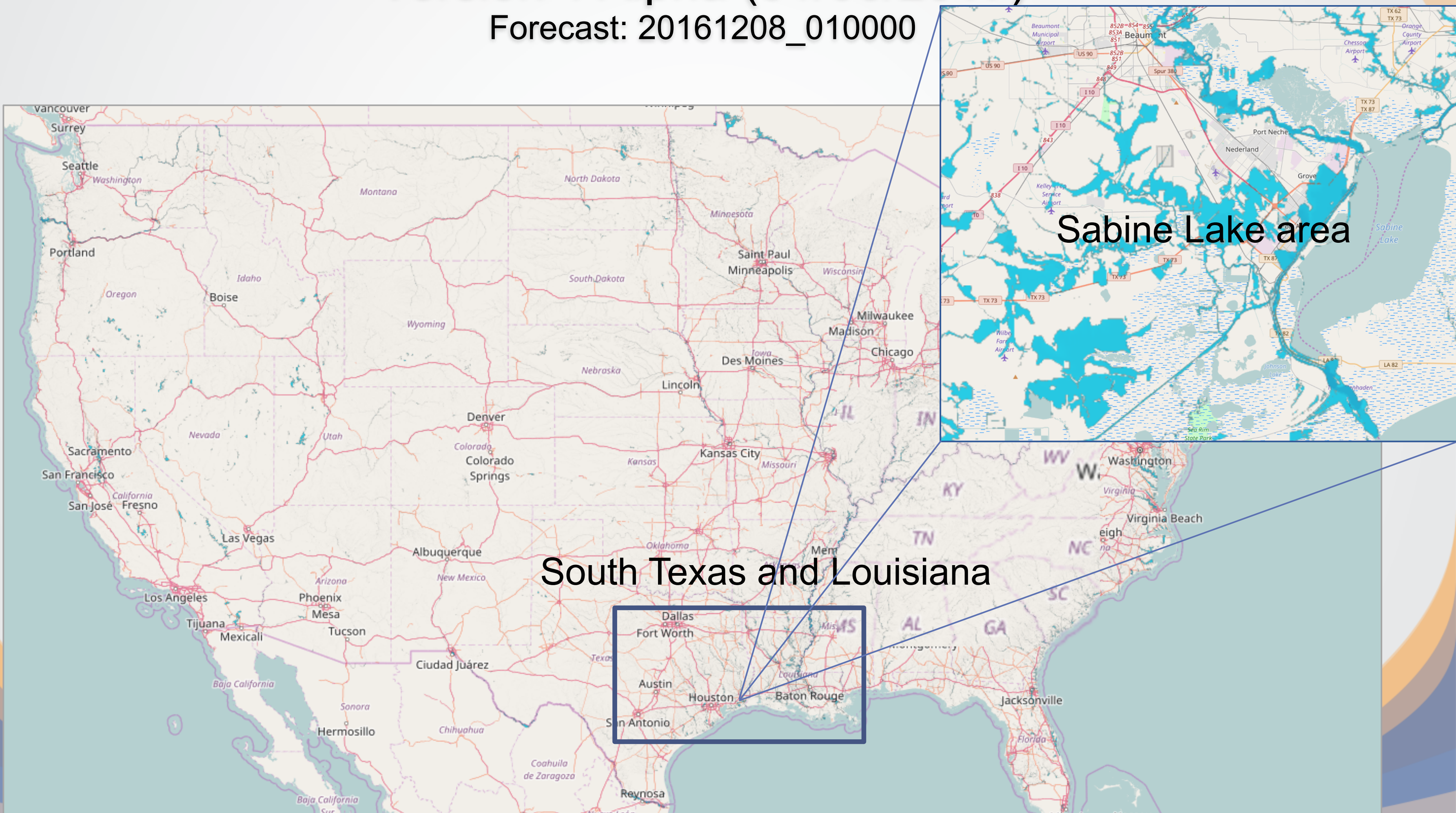
Performance: Hydraulic Property Table

FIGURE 12. Computational performance of hydraulic property table calculation. (a) is the count of catchments in each HUC6 unit, used as coarse estimation of computational intensity; (b) is the computing time for preparing the catchment vector and raster; and (c) is the computing time of *CatchHydroGeo* using one processor.



Continental-Scale Flood Inundation Mapping Process, Version 1 Alpha (01/06/2017)

Forecast: 20161208_010000



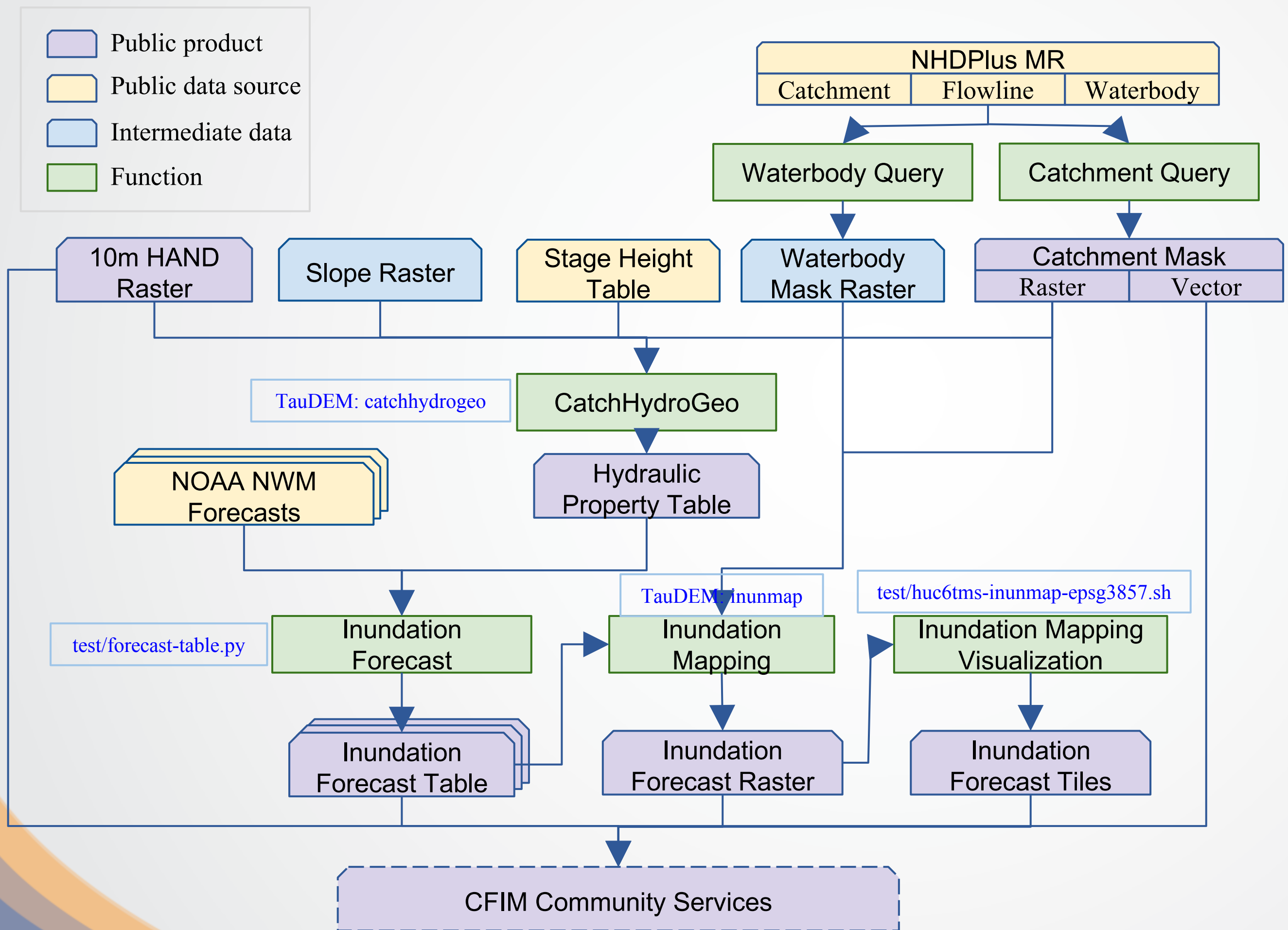
Source: Maidment, NOAA NWS leadership team briefing. 01/09/2017

Performance: Inundation Mapping Visualization

TABLE 3. Execution time of the inundation map generation process, in seconds.

	NWM Download	Forecast Table	Forecast Map	HUC6 TMS	CONUS TMS
Time	49	603	1779	27,845	13,892
Data size	780MB unzipped (52MB x 15 forecasts)	889MB (60MB x 15 forecasts)	223GB (4901 maps for 331 HUC6 units)	45GB (4,140,833 tiles; 8 zoom levels)	35GB (2,405,624 tiles; 8 zoom levels)

Inundation Mapping Workflow-Code References



Inundation Mapping Workflow

June 18, 2017

test/catchmentmaskbyhuc.sh

1. *test/catchShapeByHUC.py*: query catchment polygons;
2. *gdal_rasterize* catchment;
3. TauDEM:catchhydrogeo: create basic hydraulic properties as csv;
4. *test/hydraulic_property_postprocess.py*: calc all hydraulic properties as csv.

test/csv2netcdf-hydroprop-fulltable.py

Convert csv property files of all HUCs to NetCDF.

test/oneforecast.sh

1. *wget* NWM forecast from NWM/HS;
2. *test/forecast-nwm-worst.py*: calc worst scenario forecast;
3. *test/forecast-table.sh*: create inundation forecast table as NetCDF;
4. *test/forecast-map-batch.sh*: call *test/forecast-map.sh*, which calls TauDEM:inunmap, to create inundation map geotiff files for all HUC6 units;
5. *test/huc6tms-inunmap-epsg3857.sh*: use *gdaldem* and *gdal2tiles.py* to create TMS pyramids
6. *test/tmsmerge-inunmaptest.sh*: call *test/tmsmerge.py*, which uses ImageMagick, to merge all HUC6-level tiles into CONUS single map layer.

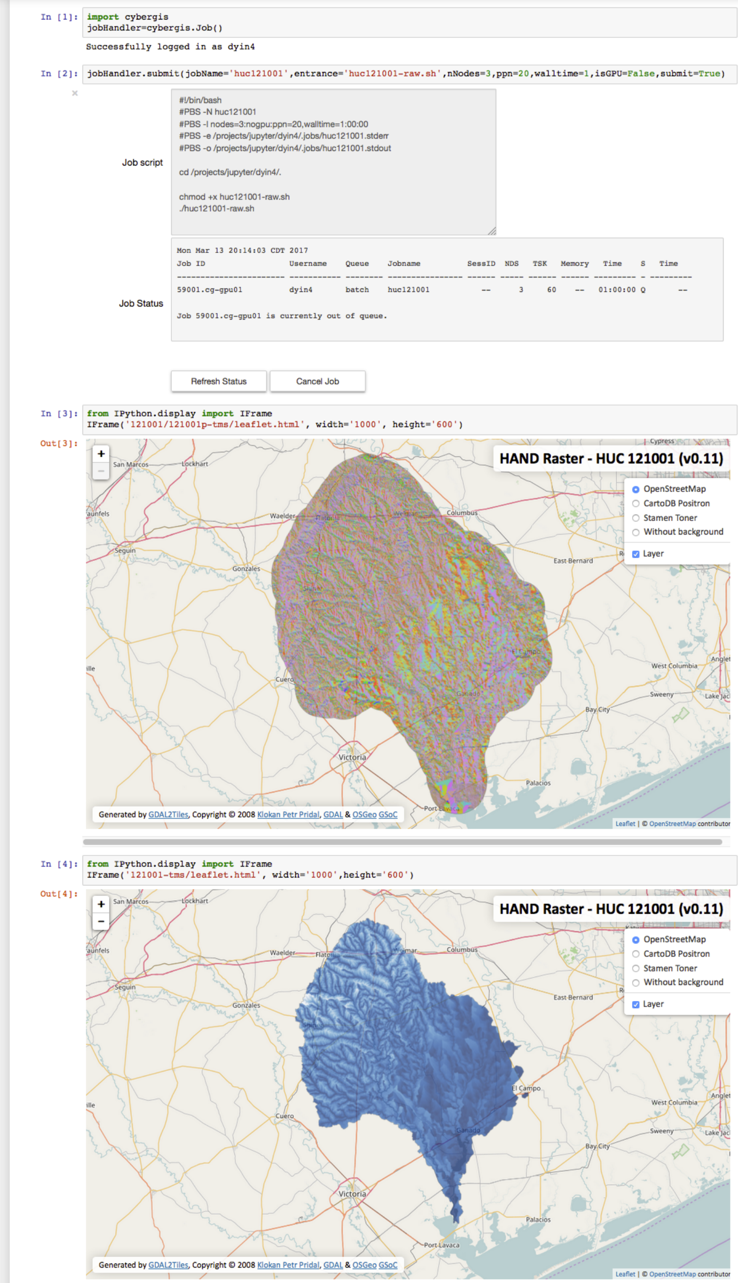
Computation Summary of CFIM

- HAND: 1.5 days
- Hydraulic Property Table: 2.5 hours
- Inundation tables and maps: 45 minutes
    - Excluding the TMS tile pyramiding step

Ongoing Work

- Methodology improvements
  - Soft burnin
  - River channel geometry
  - Flat and coastal area handling (non-DEM approaches)
  - High-resolution LiDAR-derived DEM
- A big data visualization challenge
  - Exploring industrial and open source solutions
  - Big raster+vector visualization
    - Animation
    - Data partitioning, indexing, querying, and online streaming
- Online co-development and EOT environment
  - CyberGIS Jupyter
- Software code polishing and release
- EOT
  - UCGIS summer school (May 2017)
  - NWC summer institute (June 2017)

CyberGIS Jupyter HAND Notebook



hydroroger.ncsa.illinois.edu/user/yanliu/notebooks/notebooks/help/taudem.ipynb

jupyter taudem Last Checkpoint: Yesterday at 4:15 PM (autosaved)

Welcome yanliu | Control Panel | Logout

File | Edit | View | Insert | Cell | Kernel | Widgets | Help | Python 2

Markdown | CellToolbar

TauDEM Raster Processing Notebook

This notebook demonstrates basic watershed processing using the TauDEM GIS library. For more information about TauDEM, see http://hydrology.usu.edu/taudem/taudem5/. This tutorial is divided into the following three categories:

- Setup and Preparation
- GIS Processing using TauDEM
- New Resource Creation using HydroShare

....

2. Remove DEM Pits

In [ ]:

```
# Fill the DEM Pits

# set the output paths
fill = os.path.join(data_directory, 'loganfel.tif')
cmd = 'pitremove -z %s -fel %s' % (raw_dem_path, fill)
taudem.run_cmd(cmd, processors=4)
```

3. Calculate Flow Directions

In [ ]:

```
#####################
# D8 Flow Direction #
#####################

# set the output paths
fdr = os.path.join(data_directory, 'fdr.tif')  # flowdir
sd8 = os.path.join(data_directory, 'sd8.tif')  # slope

cmd = 'd8flowdir -fel %s -sd8 %s -p %s' % (fill, sd8, fdr)
taudem.run_cmd(cmd, processors=4)
```

Conclusion

- Built all the technical pieces for continental inundation mapping
- Produced the 1st 10m HAND map for CONUS
  - May 29, 2016
- TauDEM accelerated to handle high-resolution DEMs for CONUS
- Produced the 1st real-time inundation map for CONUS at 10m raster resolution and 1km NHDPlus vector resolution
  - Jan 06, 2017
- Community feedback
  - USGS and NOAA NWS leadership team briefings, 07/18/2016 and 01/09/2017
  - Conference presentations
    - AWRA'16 summer, CyberGIS'16
  - EOT
    - NWC summer institute'16
    - Online class Fa'16

Resources

- Code:
  - https://github.com/dtarb/TauDEM
  - https://github.com/cybergis/nfie-floodmap
- Data: http://nfie.roger.ncsa.illinois.edu/nfiedata/
- Maps:
  - HAND raster: http://nfie.roger.ncsa.illinois.edu/nfiedata/maps/maps.html#source=..%2Fyanliu%2Fviz%2Fhuc6-mercator-new-singlelayer.json&extent=-14392000_2436200_-7279500_6594375
  - Inundation map – 20161208_010000: http://nfie.roger.ncsa.illinois.edu/nfiedata/maps/maps.html#source=..%2Fyanliu%2Fviz%2Finunmap-mercator-singlelayer-1color.json&extent=-14392000_2436200_-7279500_6594375

Acknowledgments

- **Federal Agencies**
  - **National Science Foundation**
    - ACI-1443080
    - ACI-1429699
    - ACI-1047916
    - 1343785
    - 1148453
    - XSEDE
  - **US Geological Survey**
    - G14AC00244
- **Government Agencies**
  - **NOAA NWS**
  - **USGS**
  - **City of Austin**
  - **Texas Division of Emergency Management**
- **Industry**
  - **Environmental Systems Research Institute (Esri)**