CI-WATER
A Utah-Wyoming Cyberinfrastructure
Water Modeling Collaboration

EPSCoR Wyoming

NSF

Objective 3: Develop High-Resolution Large Watershed Hydrologic Model

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UNIVERSITY OF WYOMING
New Thinking

In cooperation with:

BYU
BRIGHAM YOUNG UNIVERSITY

UtahStateUniversity
COLLEGE OF ENGINEERING

THE UNIVERSITY OF UTAH

Petascale??

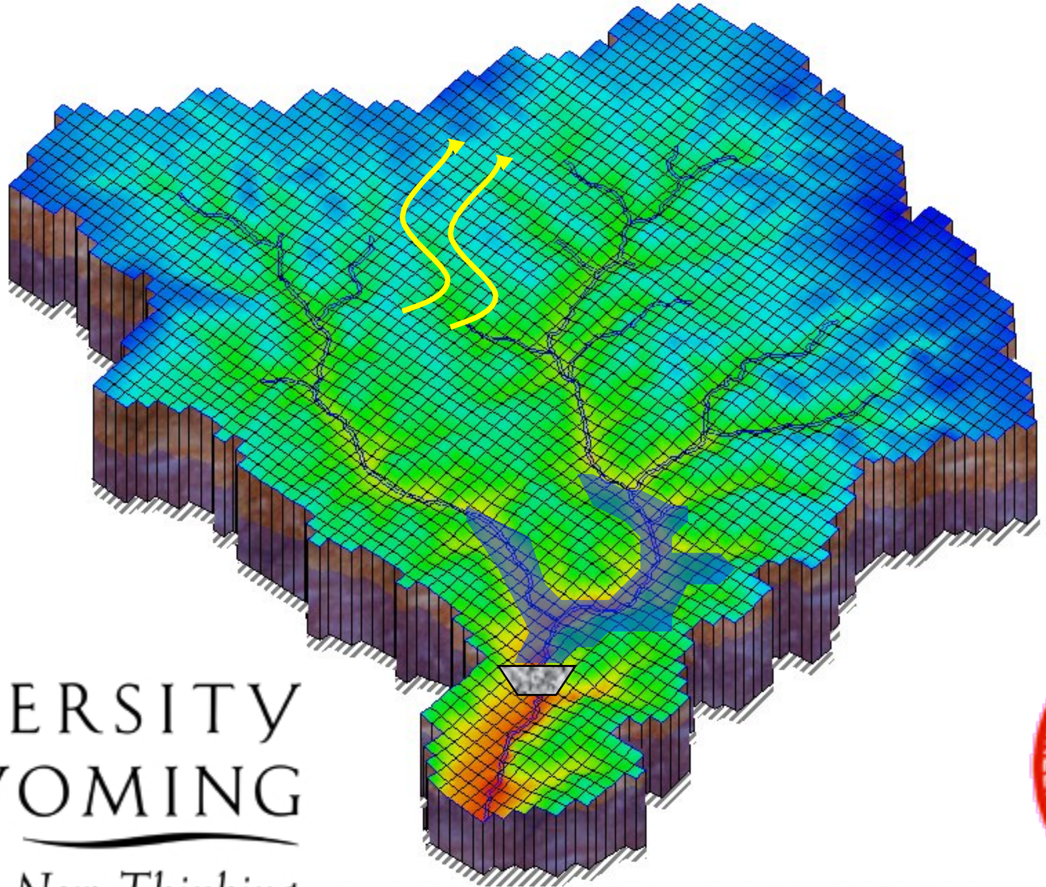
- HPC hydrologic modeling is in its infancy.
- We seldom do terascale modeling!
- We often do single CPU gigascale modeling.
- High Performance Computing is a new frontier for watershed modeling.

To consider the petascale in hydrology, one must think BIG.

Our Collaborators

- U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, Mississippi, Coastal & Hydraulics and Information Technology Laboratories
- National Center for Atmospheric Research, Research Applications Laboratory

Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model



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New Thinking

U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER
CERL GSL ITL TEC CRREL EL CHL

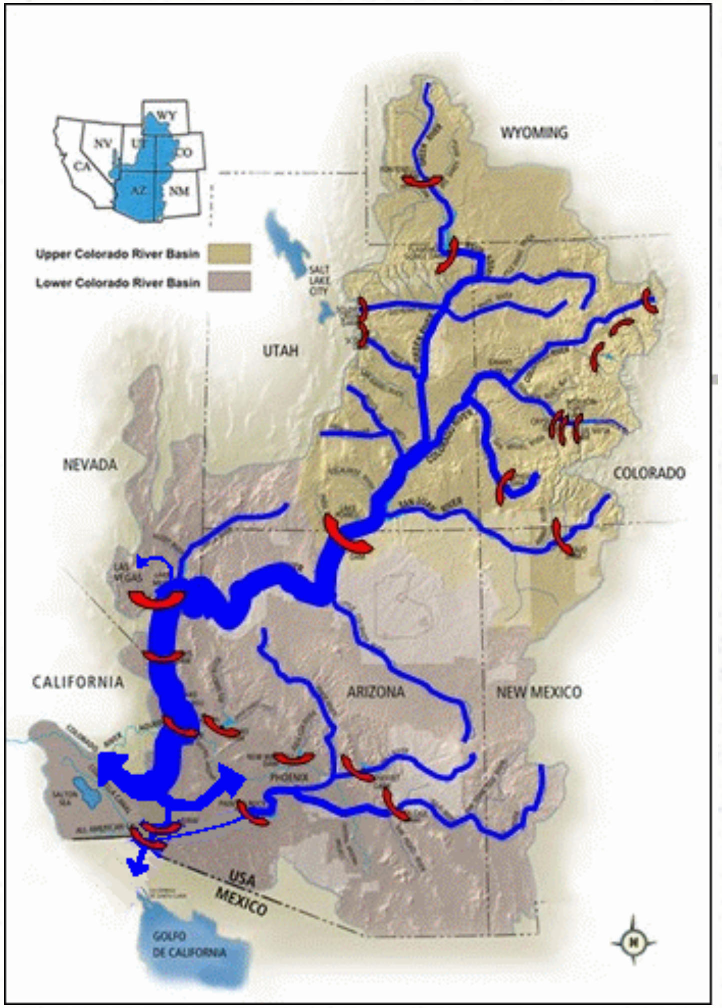
GSSHA

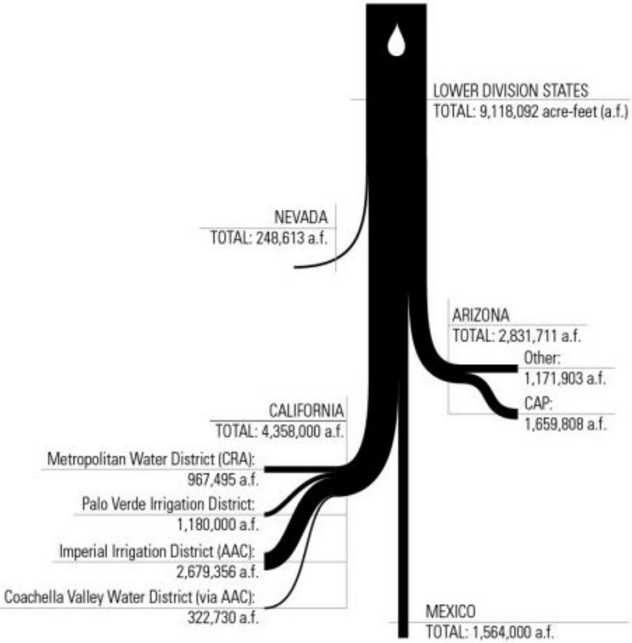
- Square grid (5 to 90 m typical)
- Multi-solver: different approximations of full PDE's, finite-difference and finite-volume.
- Multi-physics: different PDE's, or hybrid equations (mixed overland/groundwater)
- 2D overland flow and groundwater flow
- 1D channel routing with hydraulic structures
- Richards or Green-Ampt Redistribution coupling between overland flow and groundwater
- Sediment/contaminant/nutrient transport

A big watershed problem:

- Upper Colorado River Basin: 280,000 km^2
- High resolution important in mountains, where slope, aspect, vegetation, wind, drive snow redistribution, sublimation, and melt.
- Low resolution in broad and extensive basins, where runoff is infrequently produced.
- *Square grid model structure is very inefficient for large watersheds where process scales vary.*

Colorado River Basin





Numbers from the Colorado River Accounting and Water Use Report 2009.

CI-WATER Component 3 Objective

Develop a high-resolution, large-scale hydrologic model to answer three questions:

- What are the potential impacts of climate change on the long-term yield of water from the upper Colorado River basin?

- How will future land-use changes due to development and natural causes such as fire, pine bark beetle affect water supplies?

- What are the effects of trans-basin diversions and increases in water consumptive use on the water storage in Lake Powell in 30-50 years?

Research Goals

- Increase accessibility of high performance computing to water resources researchers, engineers, and managers.
- Produce a set of modeling tools that allow consideration of future conditions in a modeling and probabilistic framework.
- Engage the wider community by releasing the code developed for research, development, and testing.

Data Needs:

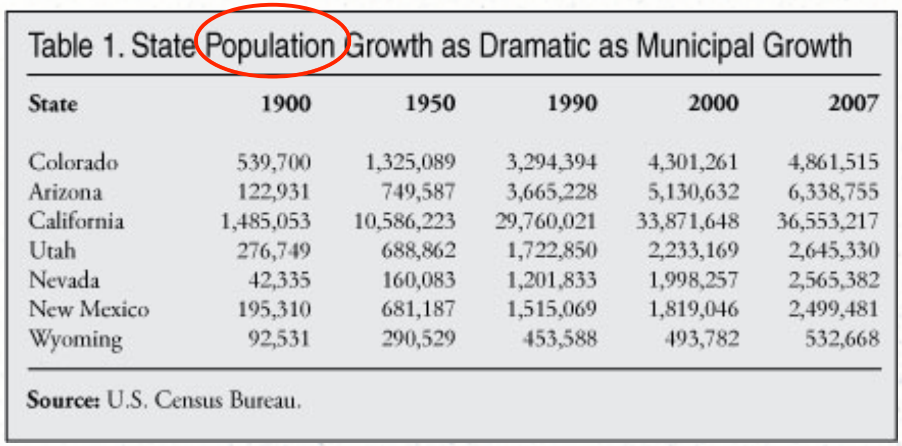


Table 1. State Population Growth as Dramatic as Municipal Growth

State	1900	1950	1990	2000	2007
Colorado	539,700	1,325,089	3,294,394	4,301,261	4,861,515
Arizona	122,931	749,587	3,665,228	5,130,632	6,338,755
California	1,485,053	10,586,223	29,760,021	33,871,648	36,553,217
Utah	276,749	688,862	1,722,850	2,233,169	2,645,330
Nevada	42,335	160,083	1,201,833	1,998,257	2,565,382
New Mexico	195,310	681,187	1,515,069	1,819,046	2,499,481
Wyoming	92,531	290,529	453,588	493,782	532,668

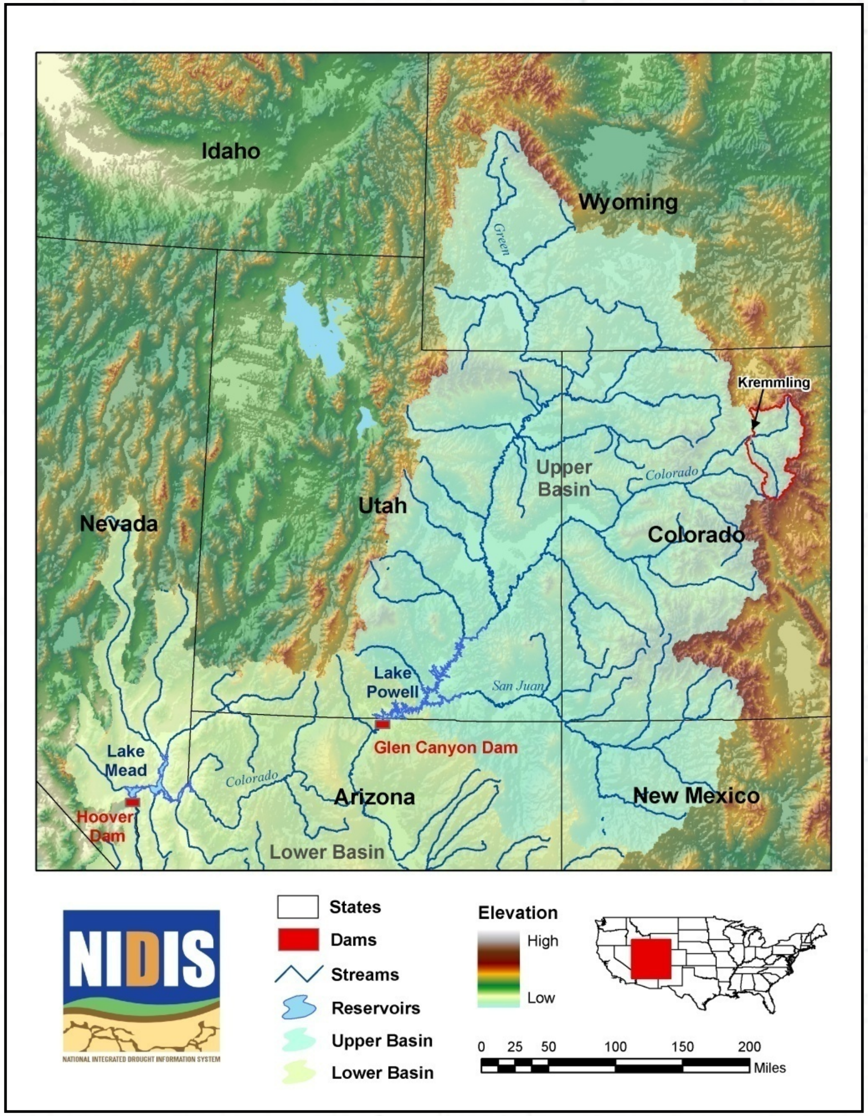
Source: U.S. Census Bureau.

Fire and
land use
changes:


Richard Armstrong, NSIDC

Snowfall and
redistribution:

Upper Colorado River Basin



Basin Area: 288,000 km^2

Streams: 467,000 km

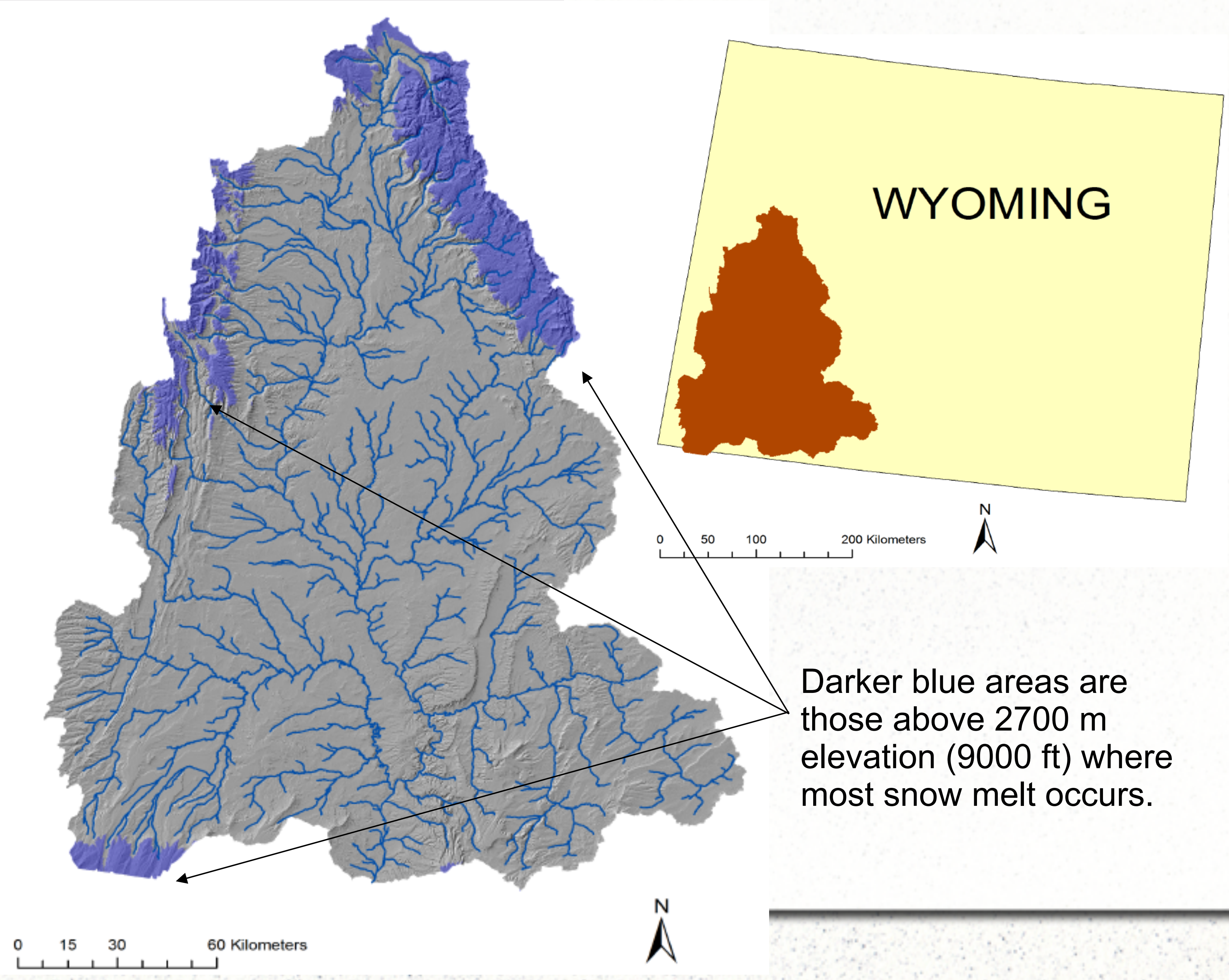
Population: 900,000 (USBR)

Area above 2700 m: 14.5% (9,000 ft)

Area above 3050 m: 3.2% (10,000 ft)

High Altitude Complexity

Test Area: Green River Basin in Wyoming



Darker blue areas are those above 2700 m elevation (9000 ft) where most snow melt occurs.

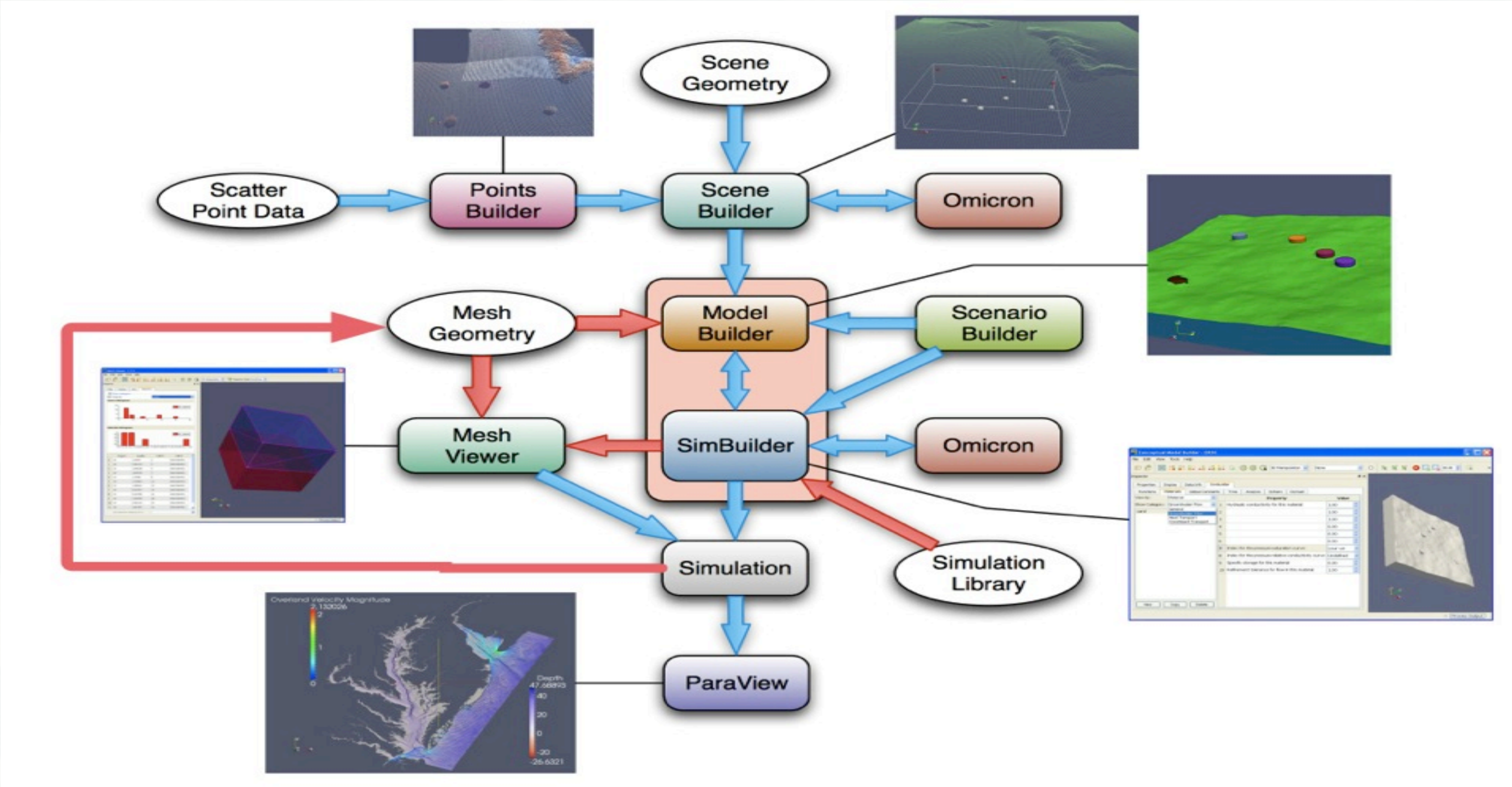
We are not starting from scratch (thanks to our collaborators)

- USACE-ERDC providing:
  - finite element computational kernel derived from the ADaptive Hydraulics (ADH) model
  - Computational model builder (CMB)
  - ezVIZ HPC vizualization tools
  - ezHPC user interface toolkit

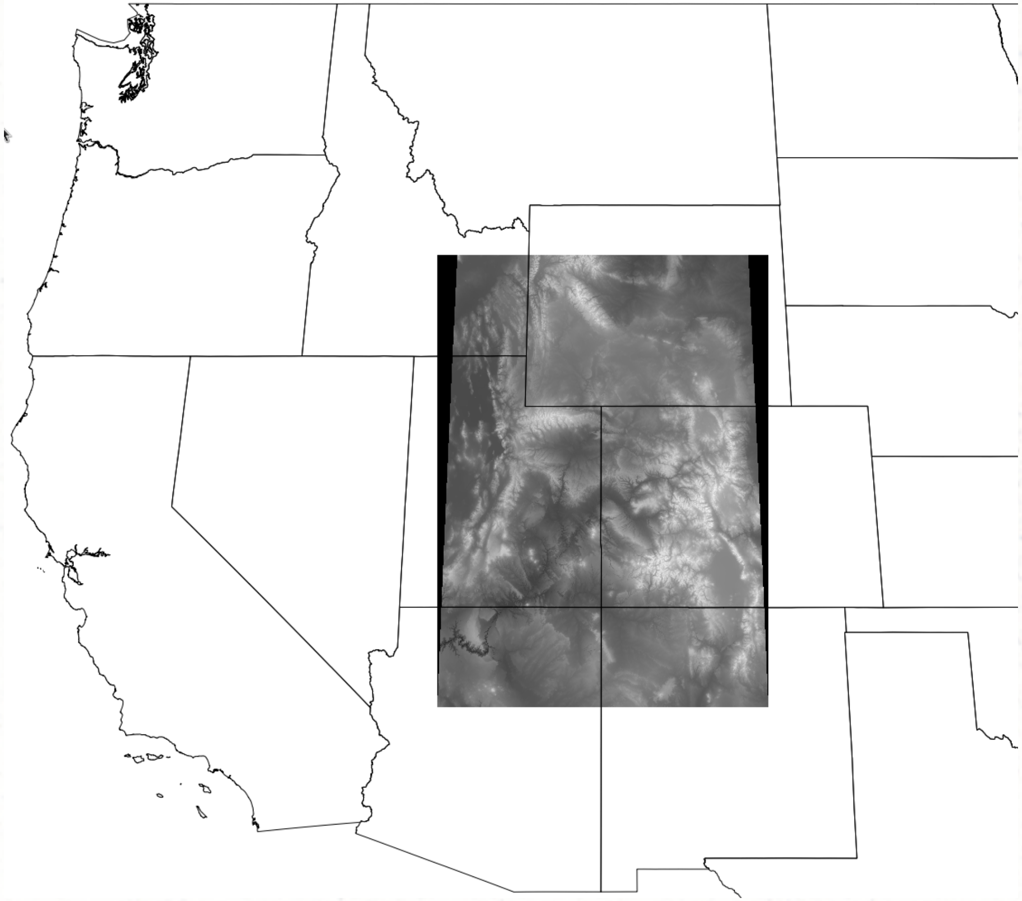
Computational Model Builder

- Designed for large complex domains & HPC
- No licensing fees
- Cross platform
- User-configurable
- Built as several complimentary, independent tools

Computational Model Builder Work Flow



Interrupted Sinusoidal Projection



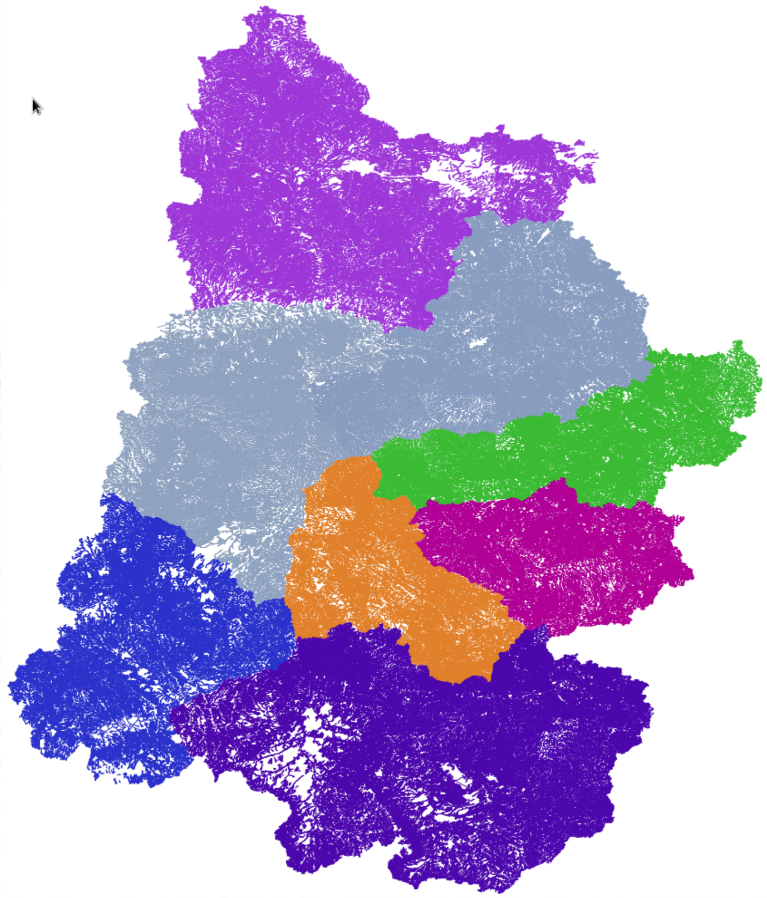
-Preserves area perfectly

- Lines of latitude are horizontal lines

- Longitudes converge towards the pole

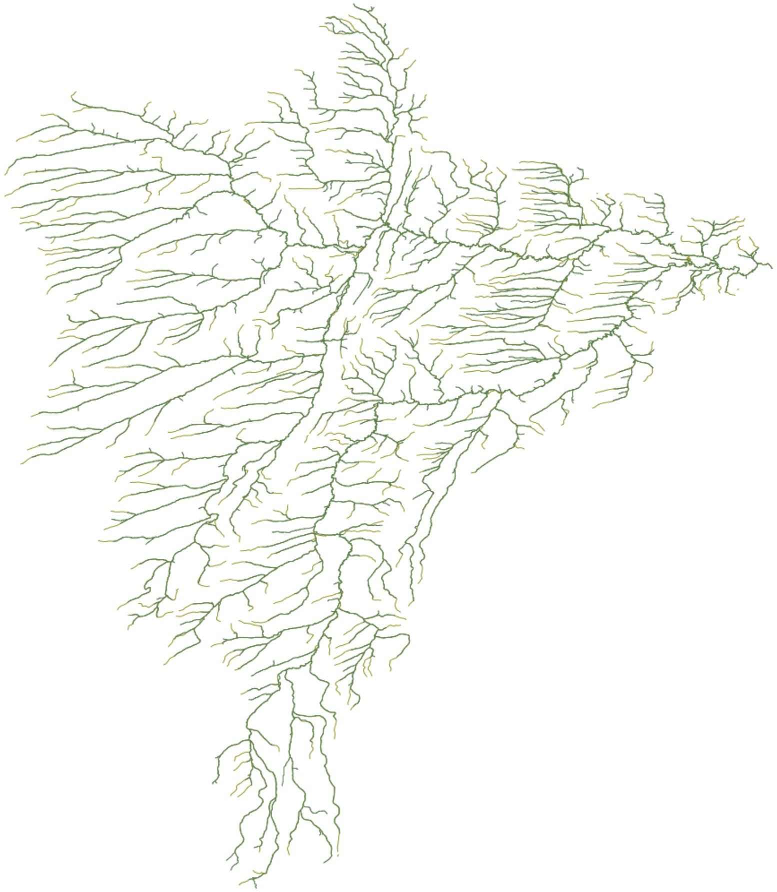
- Can describe Amazon basin with minimal distortion

Upper Colorado River Stream Network



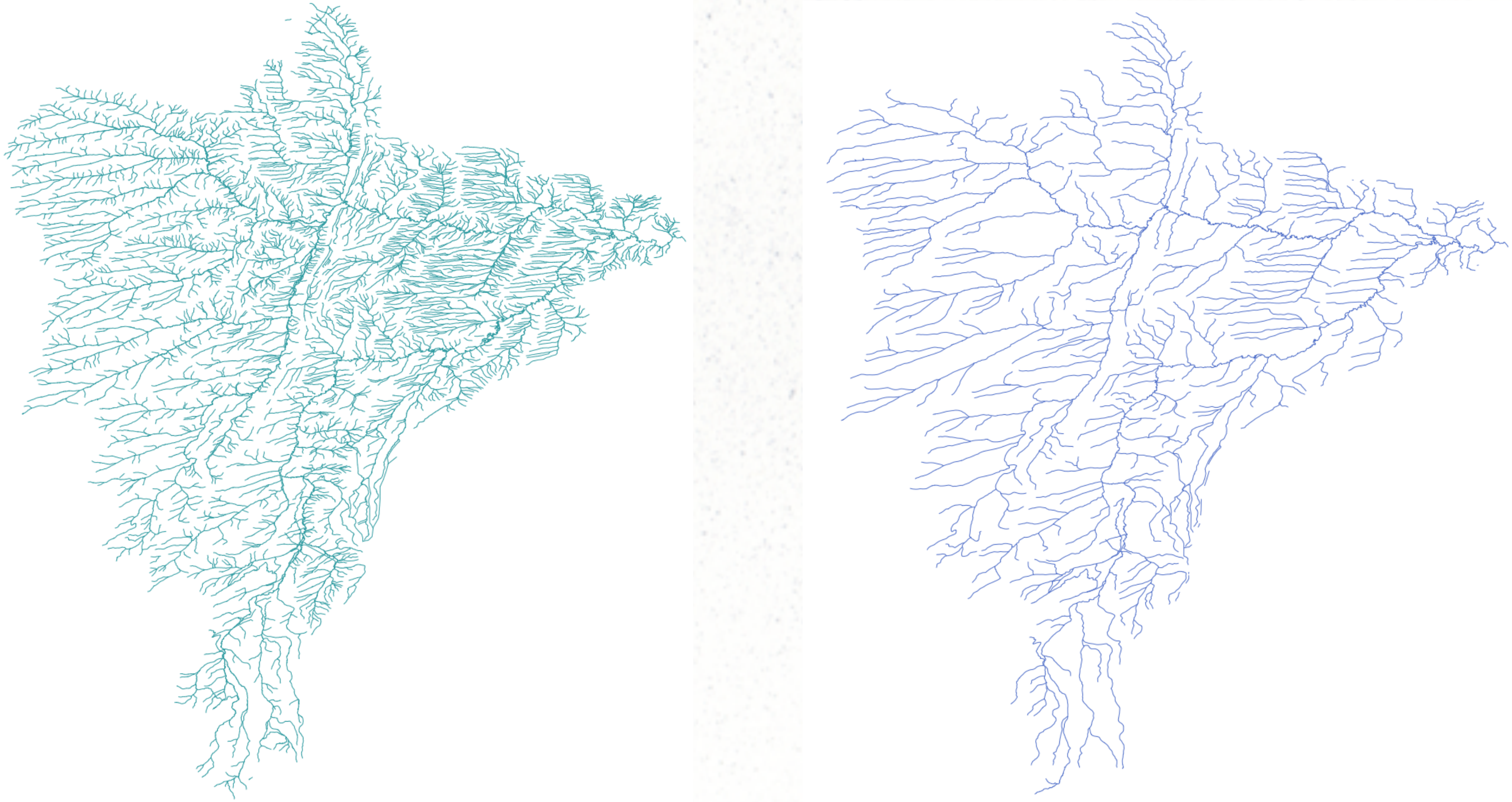
- National Hydrography Data Set
- Use geomorphological cross-section predictors
- Almost 500,000 km of streams
- River data set impossible to create manually

TauDEM vs. NHDPlus



TauDEM Accuracy Assessment

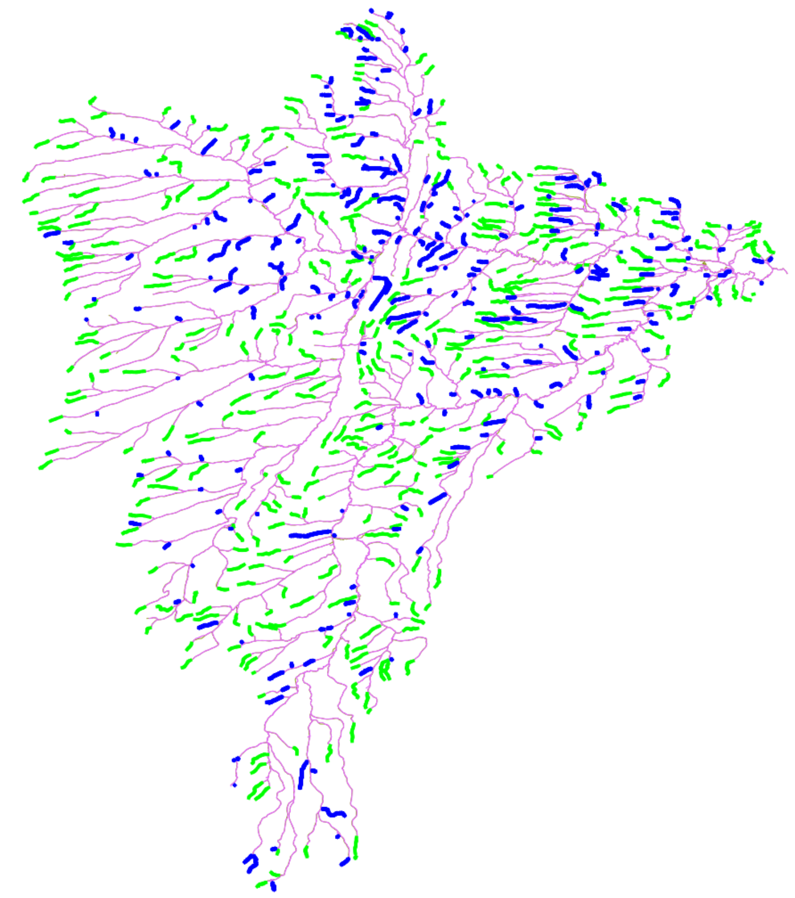
Compared TauDEM generated stream network to National Hydrography Data Set (NHD)



TauDEM vs. NHDPlus

Picked TauDEM threshold to match stream density of NHDPlus

Green and blue lines show where there is no match within 100 meters



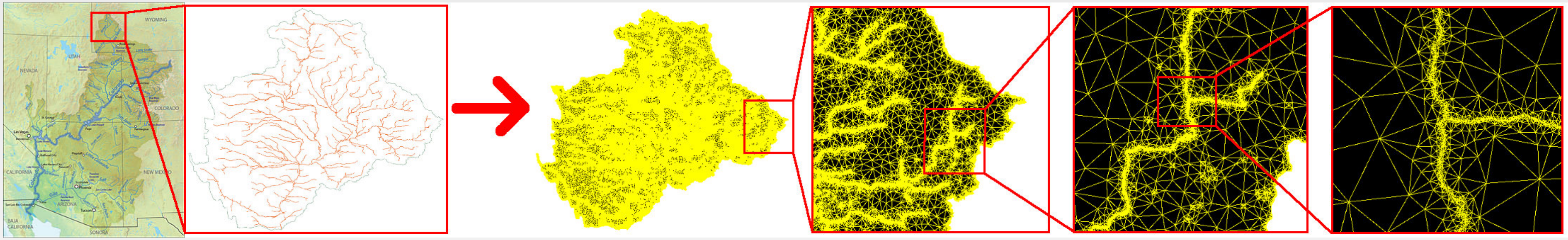
TauDEM vs. National Hydrography Dataset

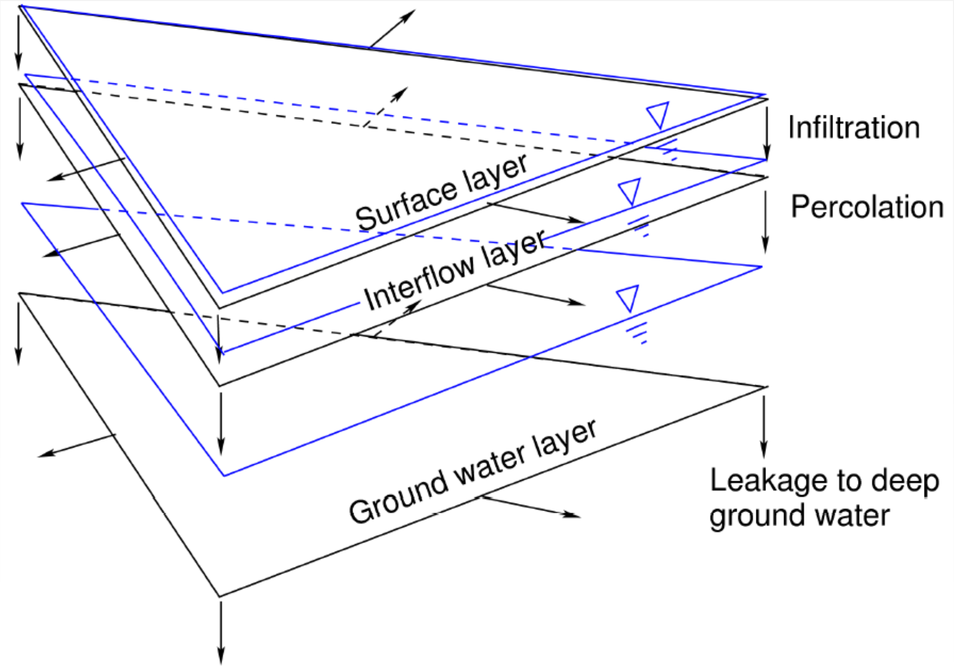
-Qualitatively, TauDEM performs well

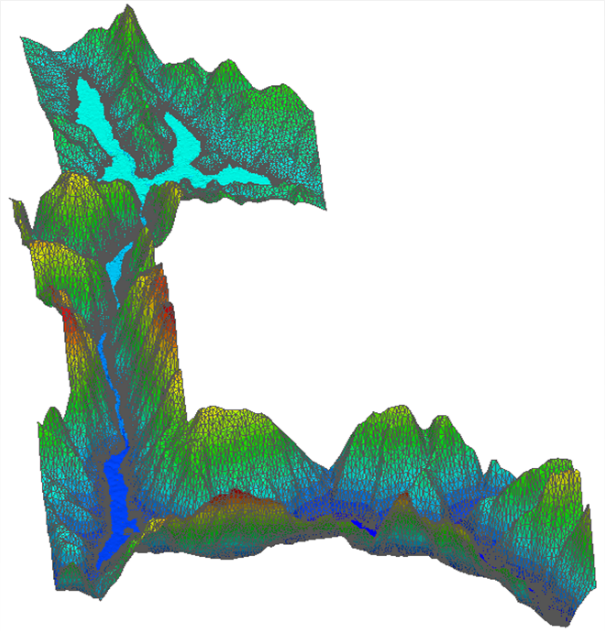
- We developed a quantitative algorithm to find points in one set of line segments far away from the closest point in another set of line segments

- We have submitted a paper describing the algorithm, which will become part of TauDEM

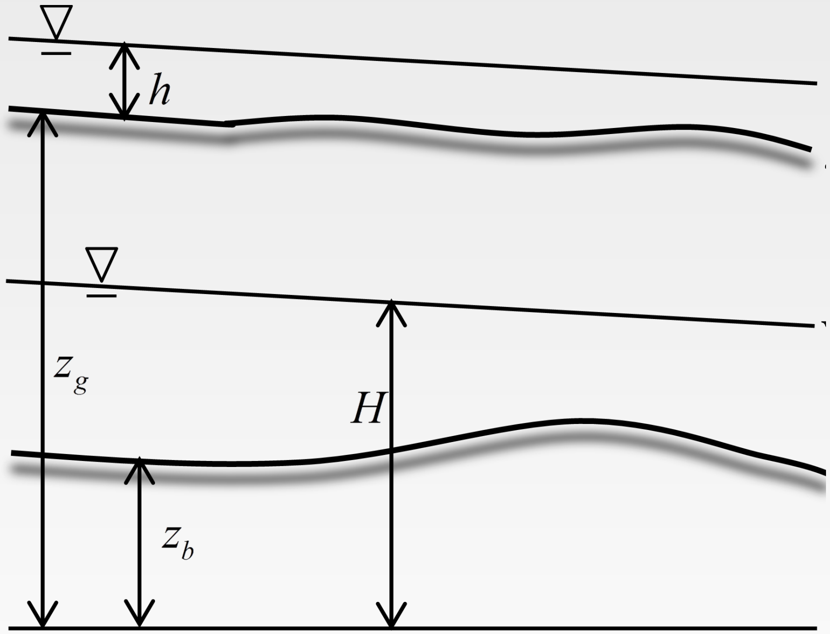
High Resolution Large Watershed Model







Mathematical model



surface water:

2D shallow water equations

- **dynamic wave**
- diffusive wave
- kinematic wave

subsurface water:

3D Richards' equation

1D vadose zone flow

2D saturated groundwater flow

Mathematical model

2D dynamic wave:

(hyperbolic convective)

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0$$

$$\frac{\partial hu}{\partial t}+\frac{\partial huu}{\partial x}+\frac{\partial huv}{\partial y}=-gh\frac{\partial z}{\partial x}-\frac{gn_x^2 u\sqrt{u^2+v^2}}{h^{1/3}}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hvv}{\partial y}=-gh\frac{\partial z}{\partial y}-\frac{gn_y^2 v\sqrt{u^2+v^2}}{h^{1/3}}$$

1D vadose zone flow

(ODE)

$$\frac{dZ}{dt}=\frac{1}{(\theta_o-\theta_i)}\left(\frac{K_s H_c}{Z}+K_s\right)$$

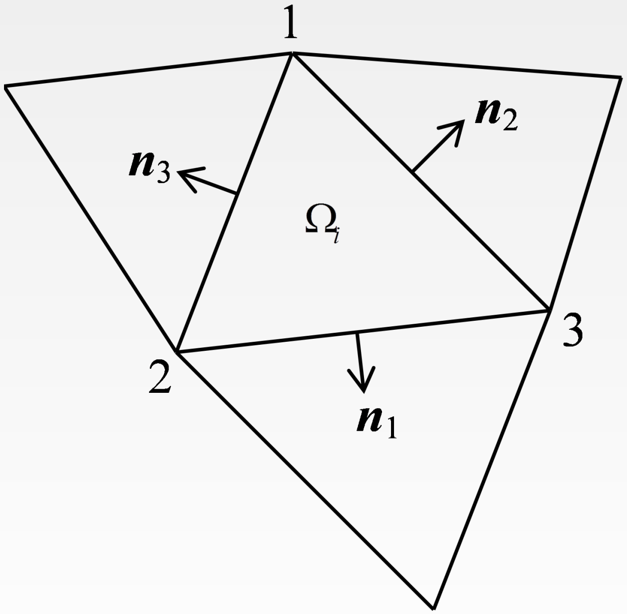
2D groundwater flow

(parabolic diffusive)

$$S_y\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(K_x(H-z_b)\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y(H-z_b)\frac{\partial H}{\partial y}\right)+R$$

Numerical model

2D unstructured finite volume method for overland flow and saturated groundwater flow



$$\frac{\partial U}{\partial t} + \nabla \cdot F = S$$

$$\int \frac{\partial U}{\partial t} d\Omega + \int \nabla \cdot F d\Omega = \int S d\Omega$$

$$\int \frac{\partial U}{\partial t} d\Omega + \oint F \cdot n \, d\Gamma = \int S d\Omega$$

$$\frac{U_i^{n+1} - U_i^n}{\Delta t} + \frac{1}{\Omega_i} \sum_{j=1}^{3} F_{ij} \cdot n_{ij} \Delta\Gamma_{ij} = S_i$$

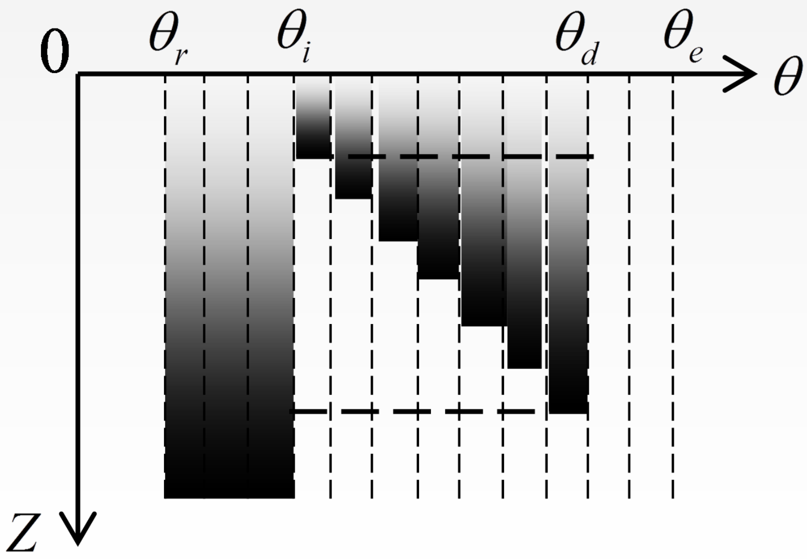
Upwind Riemann solver for convective flux in overland flow

Central difference for diffusion term in groundwater equation

1-D Unsaturated Flow model: T-O (Talbot and Ogden, 2008) infiltration and redistribution method

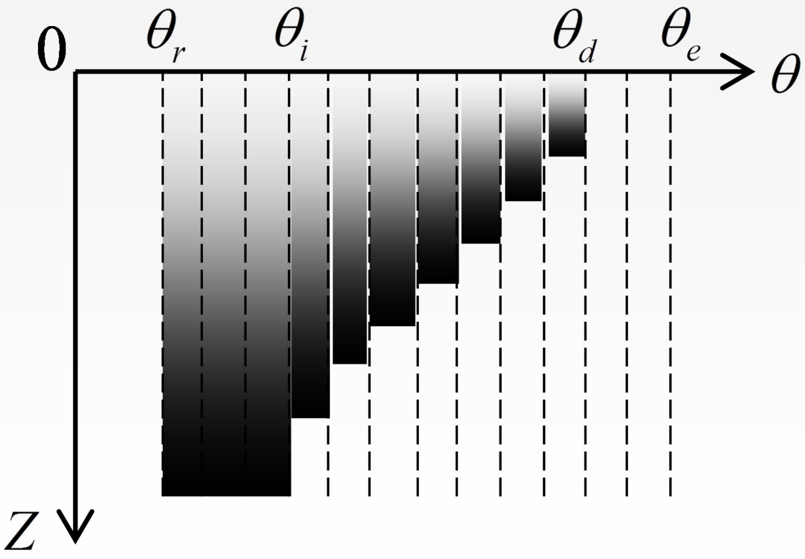
Infiltration:

$$\frac{dZ_k}{dt} = \frac{K(\theta_d)}{(\theta_d - \theta_i)}\left(\frac{(\Psi(\theta_d))}{Z_k} + 1\right)$$



Redistribution:

$$Z'_k = V\left(\frac{\Psi(\theta_k)}{\sum_j \Psi(\theta_j)}\right) + Z_k$$



Talbot and Ogden 1-D Infiltration (2008)

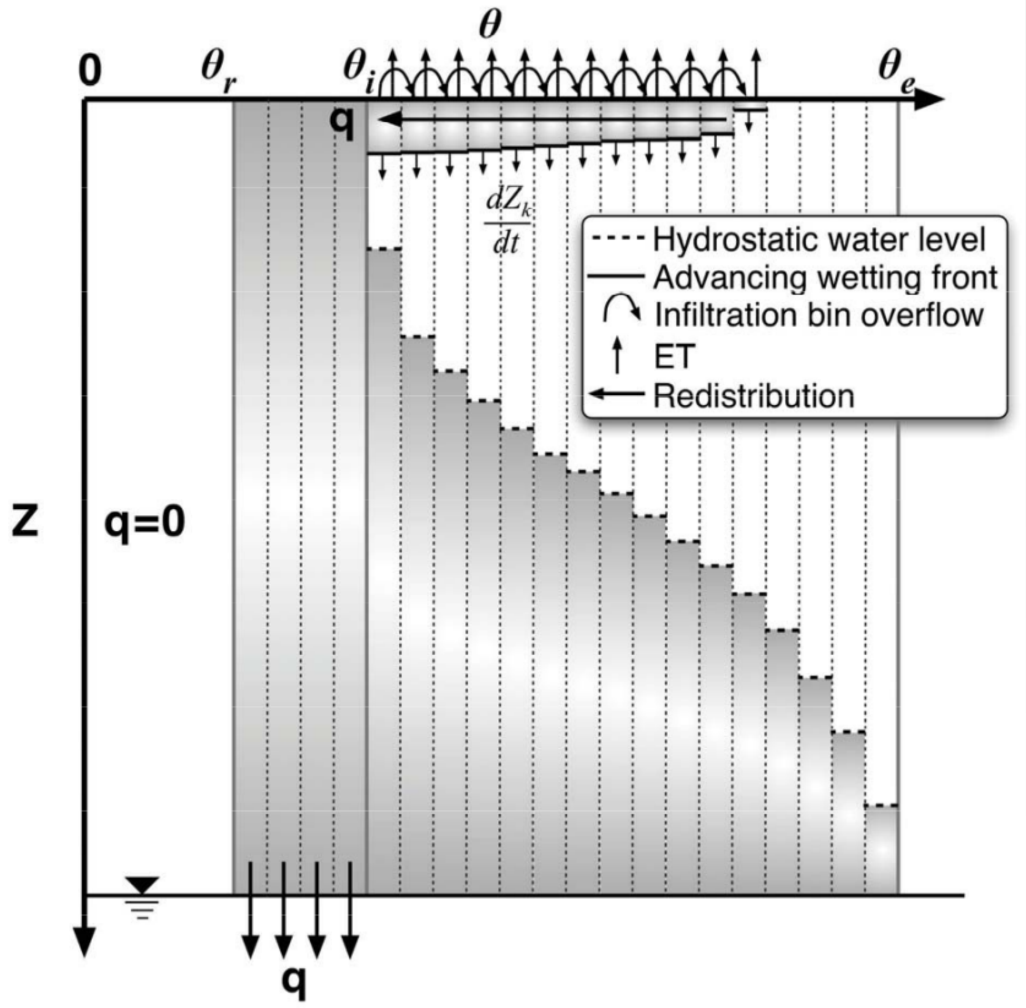
- Allows simulation of near surface ground water table without numerical solution of Richards (1931) equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \psi(\theta)}{\partial z} + 1\right)$$

with: $$\theta = \theta_r + \frac{\theta_e - \theta_r}{\left(1 + \left(\alpha \frac{\psi}{\rho_w g}\right)^n\right)^m}$$

$$K(\Theta) = \Theta^{1/2}\left(1 - \left(1 - \Theta^{1/m}\right)^m\right)$$

$$m = 1 - 1/n \qquad \Theta = \frac{\theta - \theta_r}{\theta_e - \theta_r}$$

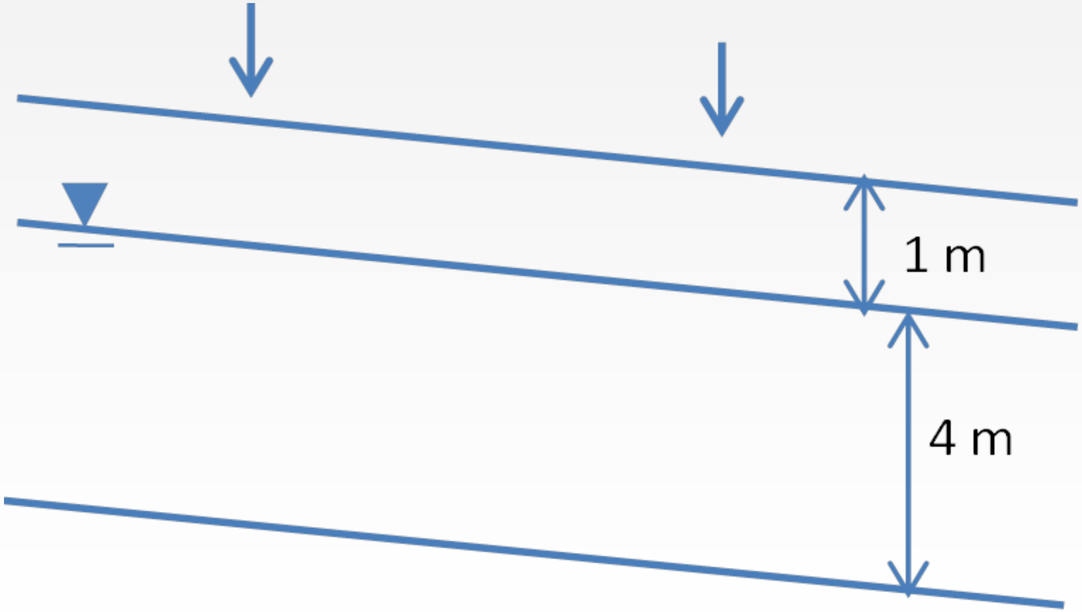


Numerical results: Hypothetical sloping plane (Sulis et al., 2010)

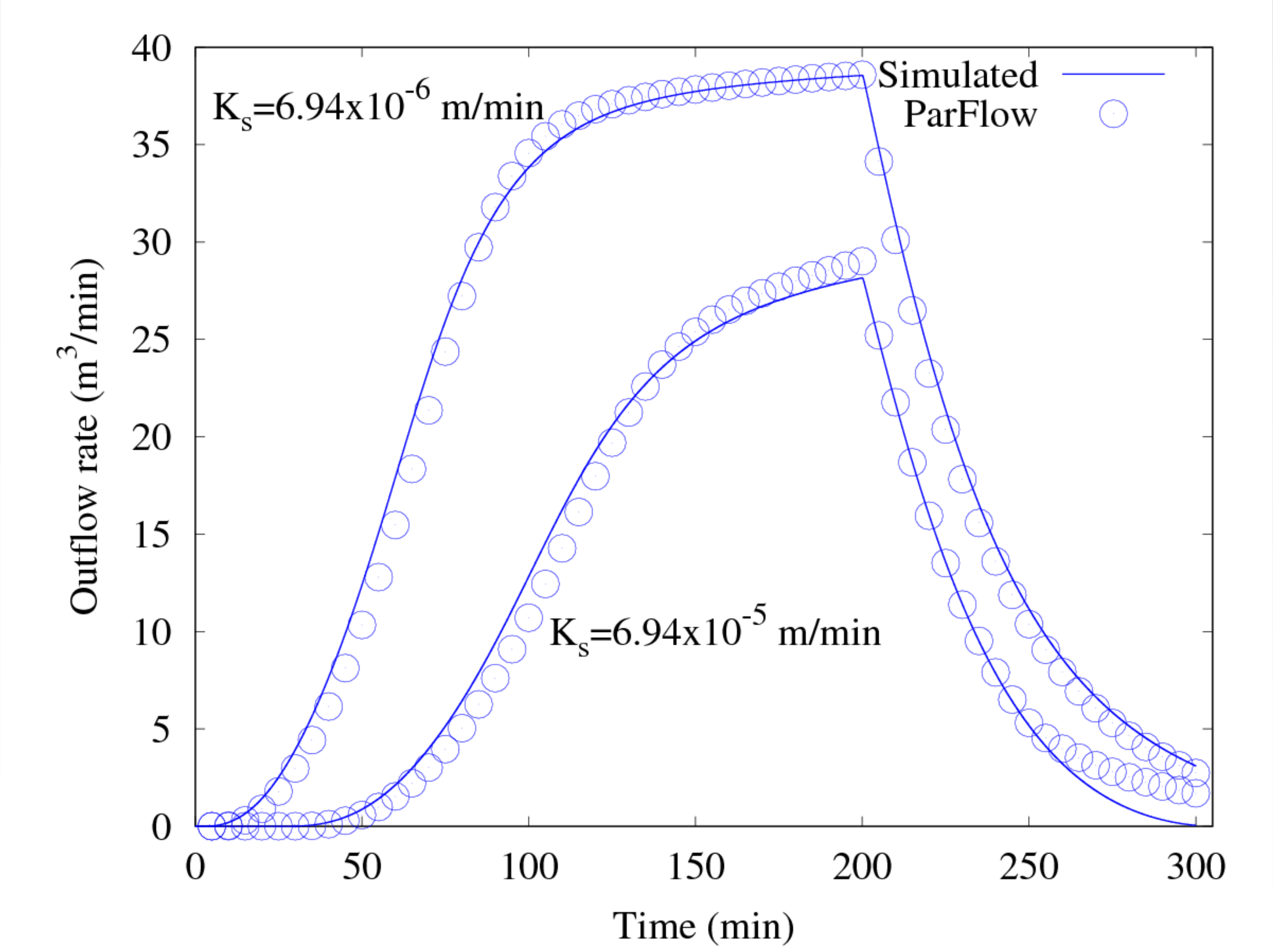
400 m X 320 M sloping plane;

5 m deep soil with water table 1 m below;

Uniform rainfall intensity of 33 mm/min for 200 minutes;



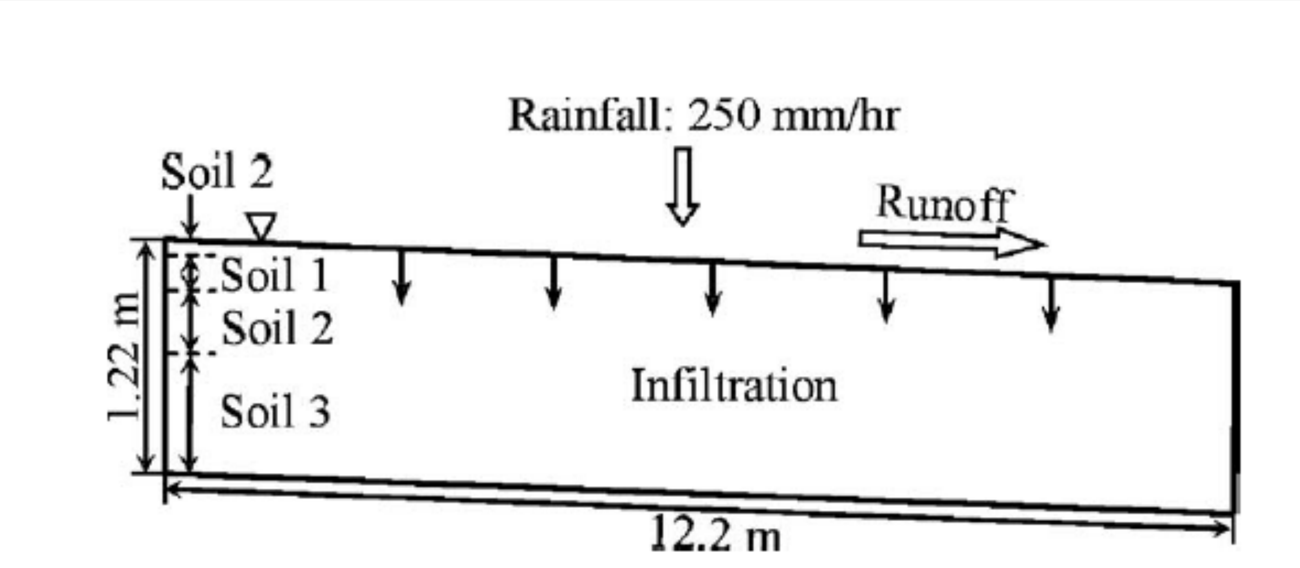
Numerical results: Hypothetical sloping plane (Sulis et al., 2010)



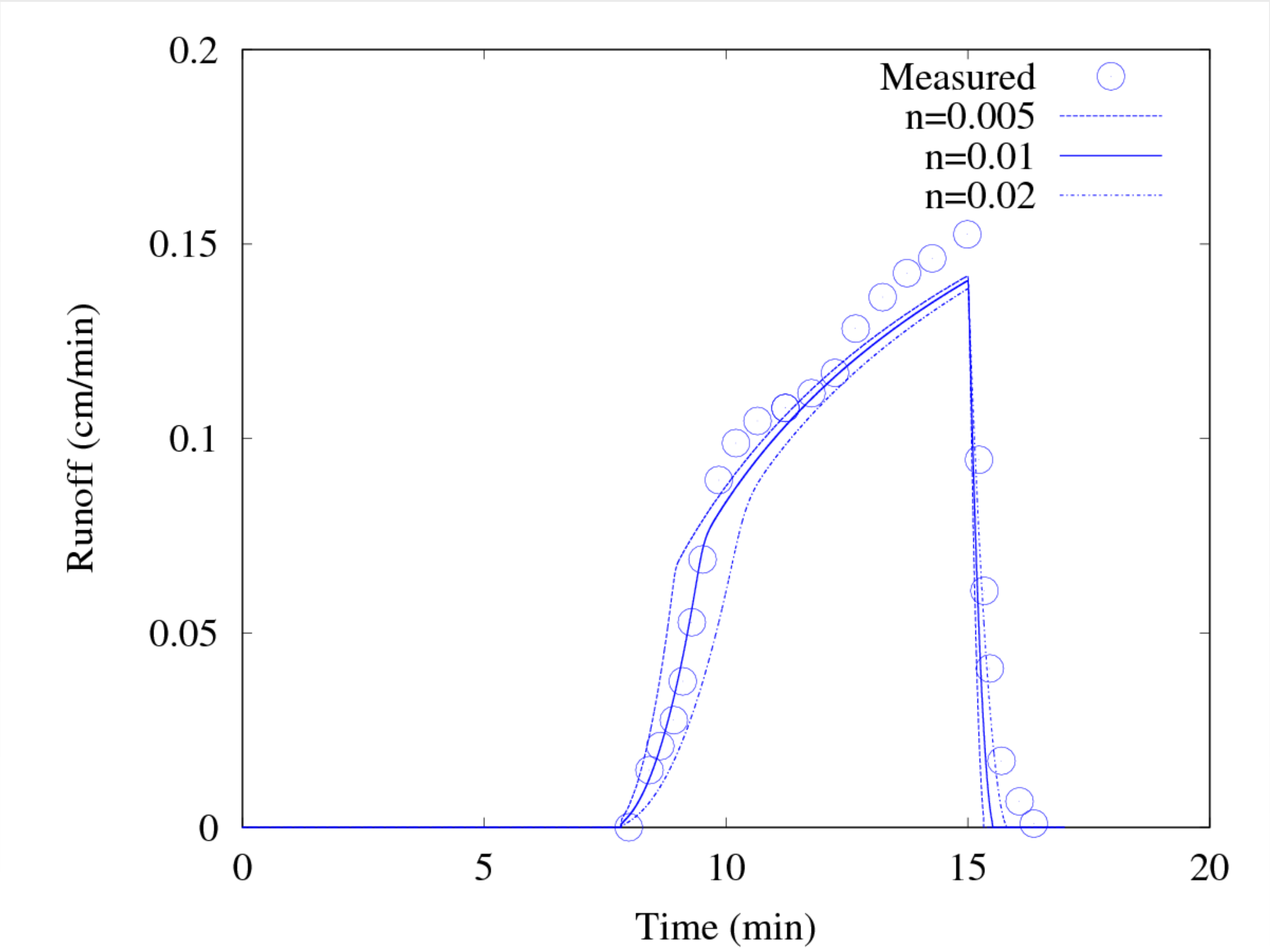
Published laboratory results: sloping plane (Smith and Woolhiser, 1971)

1.22 m deep soil with 3 layers of fine sand with different porosities

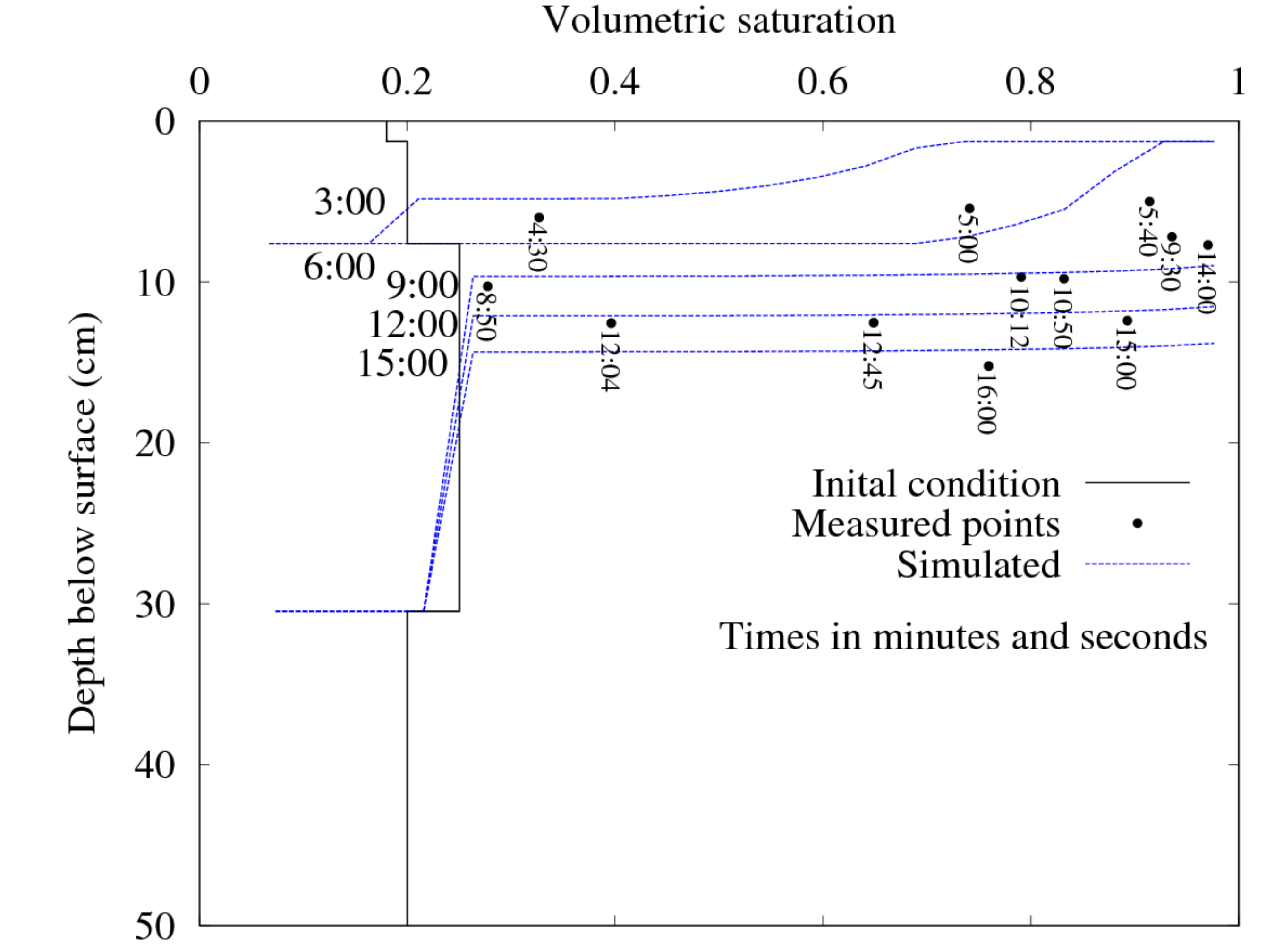
Uniform rainfall intensity of 250 mm/hr for 15 minutes;



Numerical results: Laboratory sloping plane (Smith and Woolhiser, 1971)



Numerical results: Laboratory sloping plane (Smith and Woolhiser, 1971)



Objectives for next 12 months

- Incorporate lakes, reservoirs, bathymetry in channel network
- Develop comparison simulations using ADH, PARFLOW, GSSHA
- Add evapotranspiration to ADHydro
- Add channel routing to ADHydro
- Incorporate Utah Energy Balance snowmelt model in ADHydro
- Run ADHydro in Green River headwaters catchment (May, 2013)
- Communicate data needs/input structures/work flow to Utah
- Add needed solvers to ADH parallel code, and set up partitioner
- Run ADHydro in Parallel on entire Green River in Wyoming, November, 2013.
- Release code and establish user community, December, 2013.
- Collaborate with USBR and upper Basin water managers in developing reservoir simulation model.
- Incorporate irrigated areas, begin developing irrigation simulator, early 2014

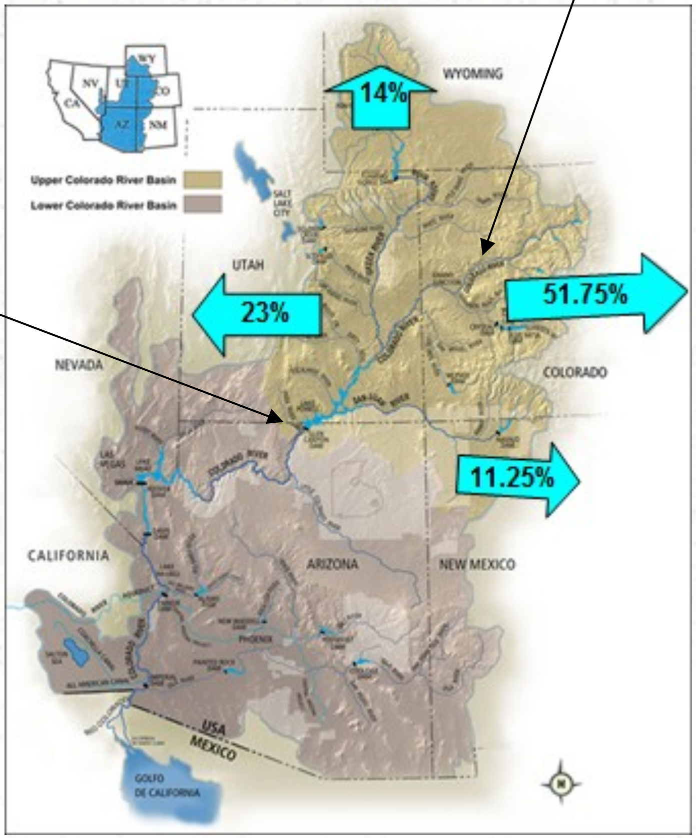
Thank you

Establishing a Petascale Collaboratory for the Geosciences: Scientific Frontiers

- “A PCG will enable the simulation of the full spectrum of interactions among physical, chemical, and biological processes in coupled Earth system models.
- Land-atmosphere property fluxes are forced by surface ecosystem heterogeneity on scales of 1 m or less. The forcing is the result of a huge array of interacting biological, chemical, and geological processes
- Understanding the integrated effects of these processes is necessary for predicting ecosystem change and water availability.”

A Report to the Geosciences Community.
UCAR/JOSS. 80 pp., 2005

Law of the River, Colorado River Compact, 1922



Upper Basin (CO, UT, WY, NM),

Lees Ferry, AZ, is the legal dividing point between Upper and Lower Basin

Lower Basin (CA, AZ, NV) guaranteed 7.5 MAF/y

International: Mexico- 1.5 MAF/y

Note: 1 AF = 1.233 Ml

Glen Canyon Dam:
The Upper States' bank account

- Pre-1963 average 12,963,000 AF
- Post-1963 average 10,701,000 AF


© Ron Niebrugge

The NCAR-Wyoming Supercomputing Center (NWSC) provides dedicated *petascale* capabilities for geosciences.


For more information visit, www.nwsc.ucar.edu

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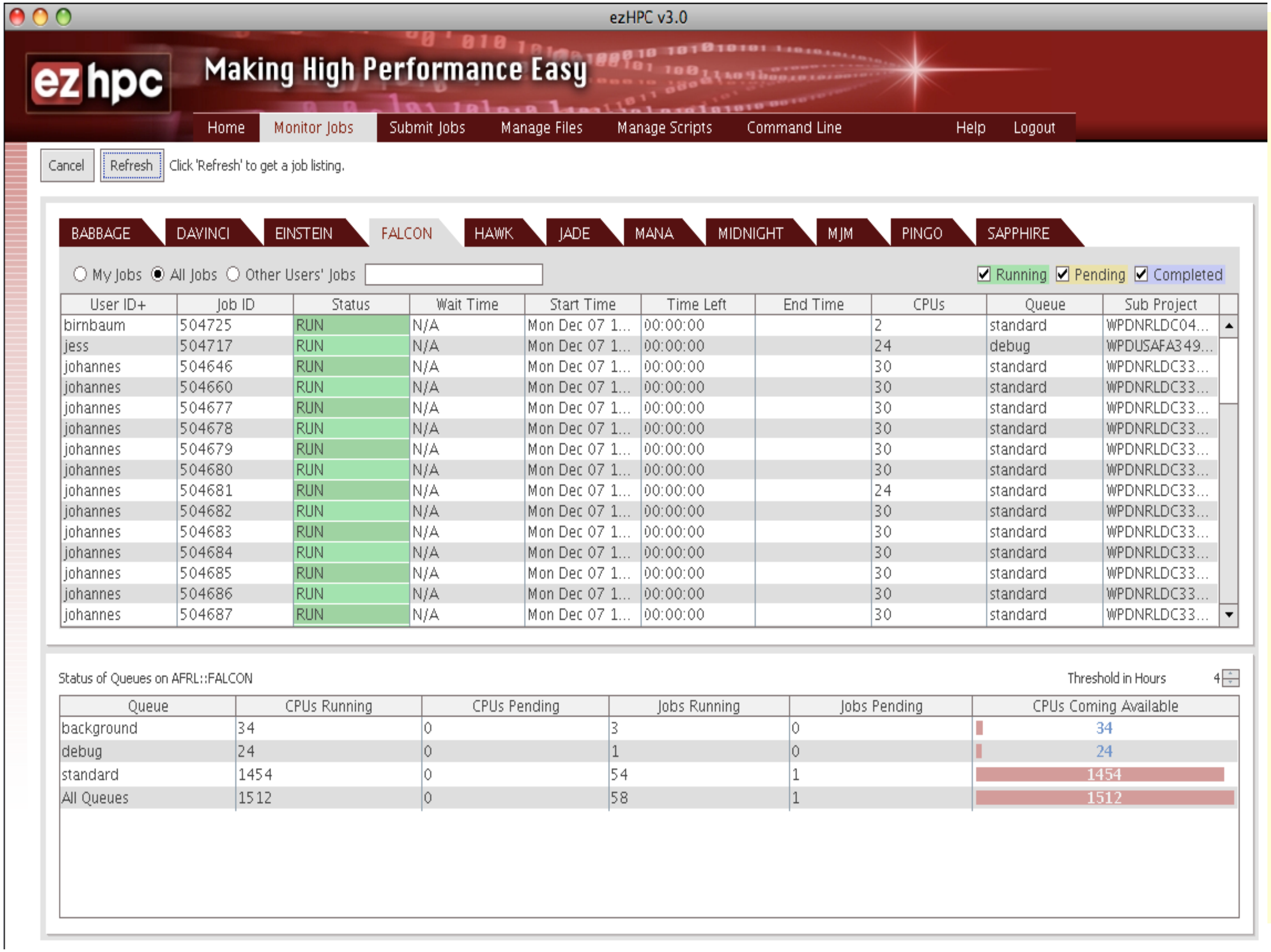
Martin & Martin Consulting Engineers | Rider Levett Bucknall | Reliable Resources | E Cube, Inc.

Wyoming's 20% Share of NWSC's 72,300 cores represents a huge increase in EPSCoR HPC capabilities…

- On the latest (6/11) Top500 list of fastest supercomputers, Wyoming's share on NWSC-1 alone is estimated to be…
  - The 28th fastest computer in the world
  - The 14th largest supercomputer in the US
  - The largest system in an EPSCoR state outside of Department of Energy facilities
  - The largest resource controlled by a university in the US

Reference: http://www.top500.org

User Interface Toolkit – ezHPC



Click 'Refresh' to get a job listing.

○ My Jobs ● All Jobs ○ Other Users' Jobs

☑ Running ☑ Pending ☑ Completed

User ID+	Job ID	Status	Wait Time	Start Time	Time Left	End Time	CPUs	Queue	Sub Project
birnbaum	504725	RUN	N/A	Mon Dec 07 1...	00:00:00		2	standard	WPDNRLDC04...
jess	504717	RUN	N/A	Mon Dec 07 1...	00:00:00		24	debug	WPDUSAFA349...
johannes	504646	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504660	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504677	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504678	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504679	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504680	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504681	RUN	N/A	Mon Dec 07 1...	00:00:00		24	standard	WPDNRLDC33...
johannes	504682	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504683	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504684	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504685	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504686	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...
johannes	504687	RUN	N/A	Mon Dec 07 1...	00:00:00		30	standard	WPDNRLDC33...

Status of Queues on AFRL::FALCON

Threshold in Hours 4

Queue	CPUs Running	CPUs Pending	Jobs Running	Jobs Pending	CPUs Coming Available
background	34	0	3	0	34
debug	24	0	1	0	24
standard	1454	0	54	1	1454
All Queues	1512	0	58	1	1512

Tabbed Functions

- **MOTD and system news @ HOME Tab**
- **Monitor Jobs & Queue Status on all machines**
- Job Management
  - Script generator & editor
  - Allocation and Utilization viewer
  - **Fast large file transfers**
  - **Easy access to custom scripts**

Monitor Kerberos Ticket Session Time

Easy Access to on-line documentation

MB Revised: 7/9/2009

HPC Data Issues

- Data assimilation
    - How do we collect enough data to keep a Petascale computer busy? Just inventing data through interpolation is not acceptable.
    - We need a tsunami of data from inexpensive sensors or high-resolution simulations.
    - Satellite images 1-2 times per day in composite (incomplete) JPEG files. This is not necessarily high enough resolution and cloud cover is a problem.
    - *We need a massive number of remote, on ground sensors, not just a massive quantity of data from a relatively few sensors*.
    - We need a symbiotic relationship between smart sensors and computational models, e.g., a dynamic data-driven application system, so that we get the right amount of data for the right scales while computing.
    - Finally, how do we afford massive data collection?

HPC Numerical Algorithms

- Multiscale methods
  - We use a base resolution with an average or median mesh size.
  - We can *upscale* to compute on a coarser mesh much quicker than on the base mesh.
  - We can *downscale* to compute on a finer mesh in a subregion of the entire domain to pick up features that are not visible on the base mesh. If the subregion is small enough, this is both computationally feasible and scientifically useful.
  - Dynamic steering of a computation is essential to make this work and can be done as postprocessing.
- Load balancing
  - This is a preprocessing step in the major computations.
  - First generate base meshes of interest and store them.
  - Generate a series of domain decompositions for different representative numbers of cores and store them.
  - Similar to the ocean modeling community meshes.

HPC Time Stepping

- Implicit methods
  - Implicit time stepping allows larger time steps while maintaining stability.
  - With massively parallel computers, an implicit method requires using massively parallel solvers from one time step to the next, while many common algorithms today just do not scale to O(100K) cores, unfortunately.

- Explicit methods
  - Time steps usually limited by stability conditions to $\Delta t < C(\Delta x)^2$, where C is a positive real constant.
  - A new set of algorithms has recently been developed that are stable on given time steps, but use intermediate time steps (where stability may be violated) so that the stability condition is $\Delta t < C\Delta x$ instead (different C). Hence, vastly larger time steps are possible.
  - Massively parallel computations are straightforward with explicit methods.

HPC Time Stepping

- Hybrid explicit-implicit methods
  - On the boundaries of the subregions use an explicit method to approximate the solution on the next time step.
  - Use an implicit method in each subregion, where the size of the subregions is small enough so that the algorithm used to get to the next time step scales well.
  - Possibly iterate on the boundary points to improve accuracy.

- Hybrid implicit-explicit methods
  - Downscale the problem to only the boundaries of the subregions and use an implicit method to approximate the solution on the next time step. This can be done in parallel based on subregions.
  - Use an explicit method in each subregion.
  - Possibly iterate on the boundary points to improve accuracy.
- Implications for Petascale computing
  - Both hybrid methods should scale and be fast.
  - Need to analyze which hybrid method works best for CI-WATER.