CI-WATER
A Utah-Wyoming Cyberinfrastructure
Water Modeling Collaboration

EPSCoR Wyoming

NSF

Component 3:
Advance High-Resolution Hydrological Modeling

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CENTER FOR COMPUTATIONAL
HYDROLOGY AND HYDROSCIENCES

UNIVERSITY
OF WYOMING
New Thinking

AAAS Review Nov. 17, 2014

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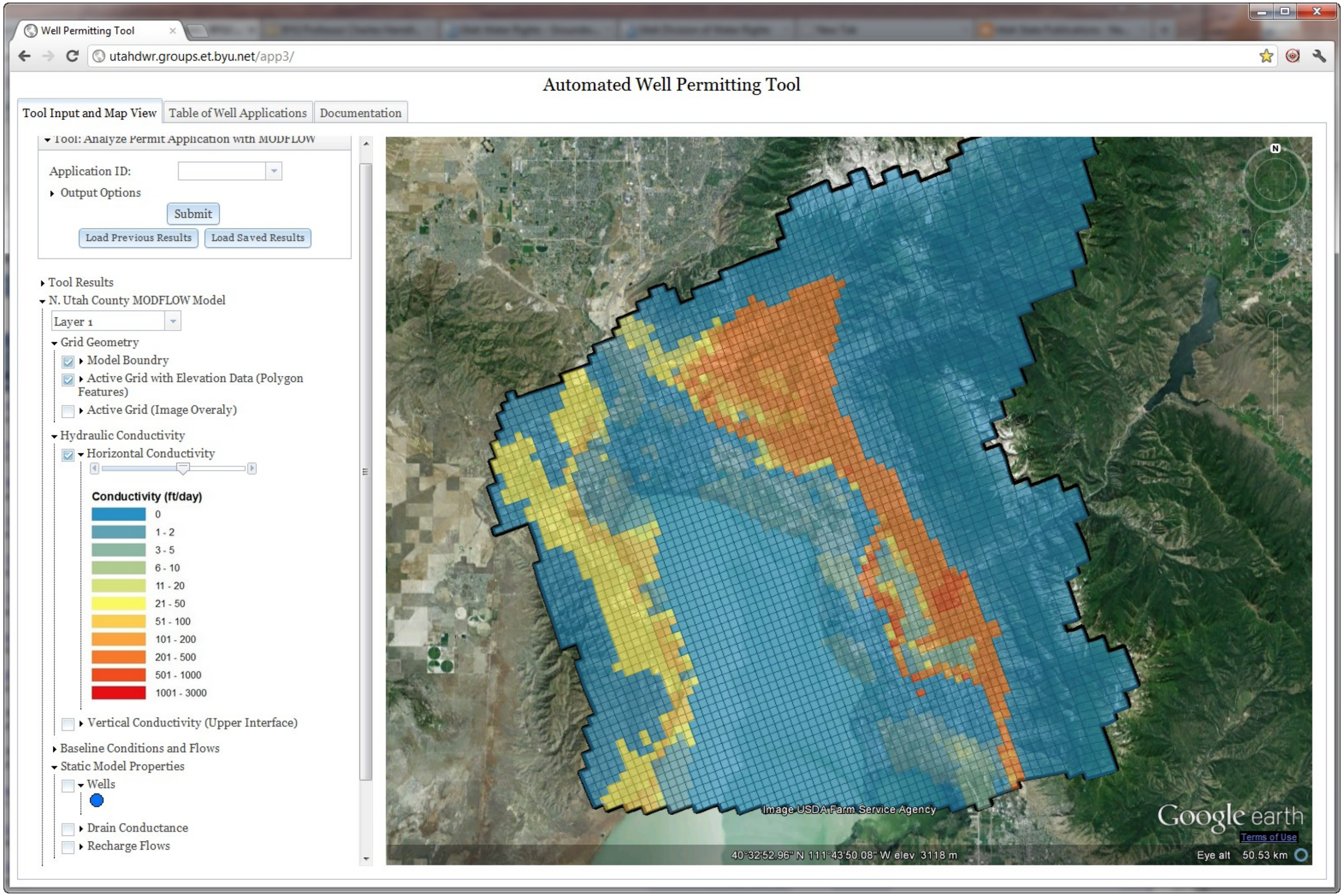
Project Components:

1. Enhance cyberinfrastructure facilities at collaborating universities.
2. Enhance access to data- and computationally- intensive modeling
3. Advance high-resolution multi-physics watershed modeling
4. Promote STEM learning and water science engagement across diverse groups

A Utah-Wyoming Cyberinfrastructure Water Modeling Collaboration

Motivating Example: Utah DWR Web-Based Groundwater Simulation Tool



Conductivity (ft/day)

🟦	0
🟦	1 - 2
🟩	3 - 5
🟩	6 - 10
🟨	11 - 20
🟨	21 - 50
🟧	51 - 100
🟧	101 - 200
🟧	201 - 500
🟥	501 - 1000
🟥	1001 - 3000

Norm Jones, BYU

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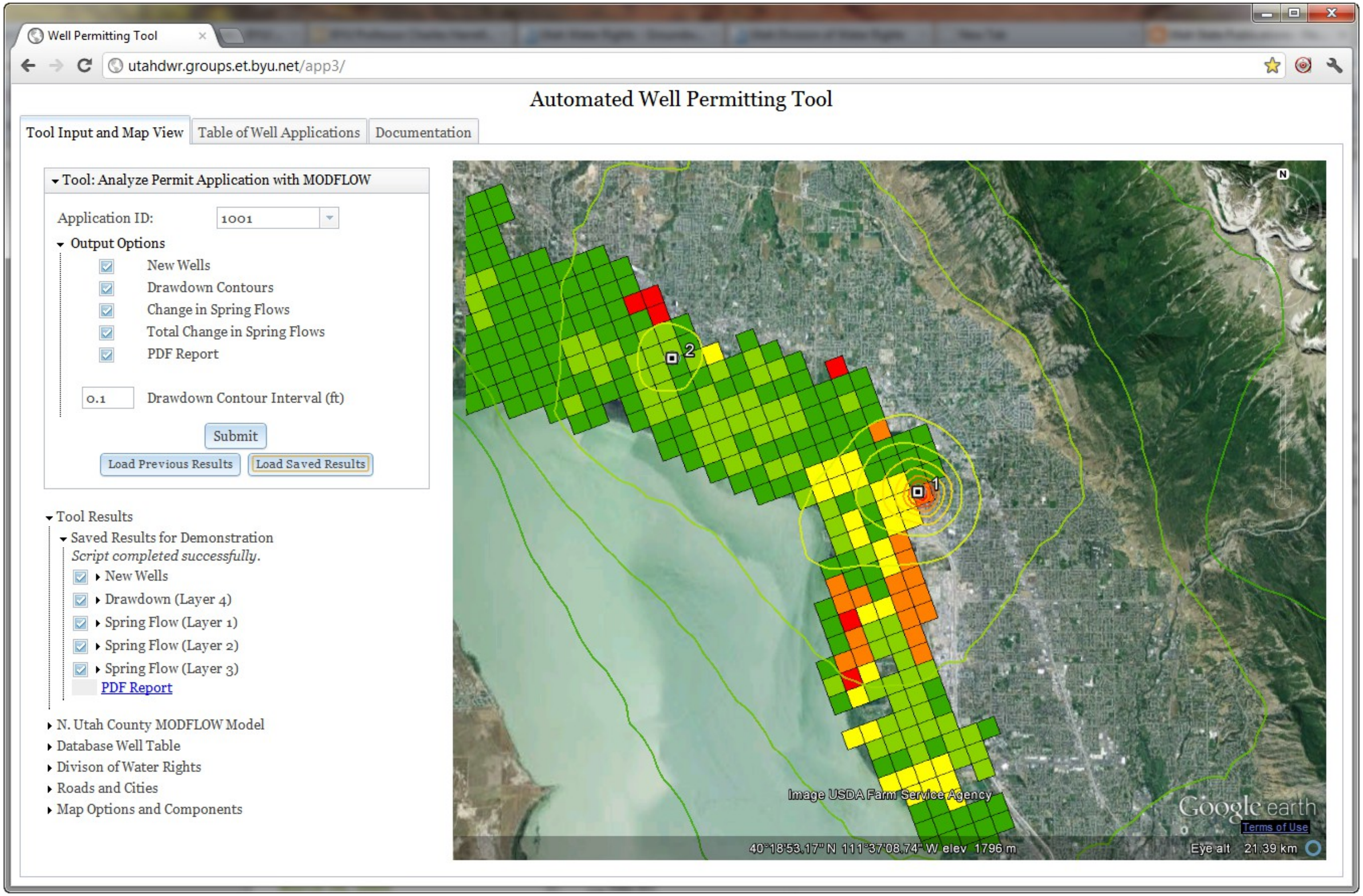
Model Output Visualization



Automated Well Permitting Tool

Tool Input and Map View | Table of Well Applications | Documentation

▾ Tool: Analyze Permit Application with MODFLOW

Application ID: 1001

▾ Output Options
- ☑ New Wells
- ☑ Drawdown Contours
- ☑ Change in Spring Flows
- ☑ Total Change in Spring Flows
- ☑ PDF Report

0.1 Drawdown Contour Interval (ft)

Submit

Load Previous Results | Load Saved Results

▾ Tool Results
- ▾ Saved Results for Demonstration
  - *Script completed successfully.*
  - ☑ ▸ New Wells
  - ☑ ▸ Drawdown (Layer 4)
  - ☑ ▸ Spring Flow (Layer 1)
  - ☑ ▸ Spring Flow (Layer 2)
  - ☑ ▸ Spring Flow (Layer 3)
  - PDF Report

- ▸ N. Utah County MODFLOW Model
- ▸ Database Well Table
- ▸ Divison of Water Rights
- ▸ Roads and Cities
- ▸ Map Options and Components

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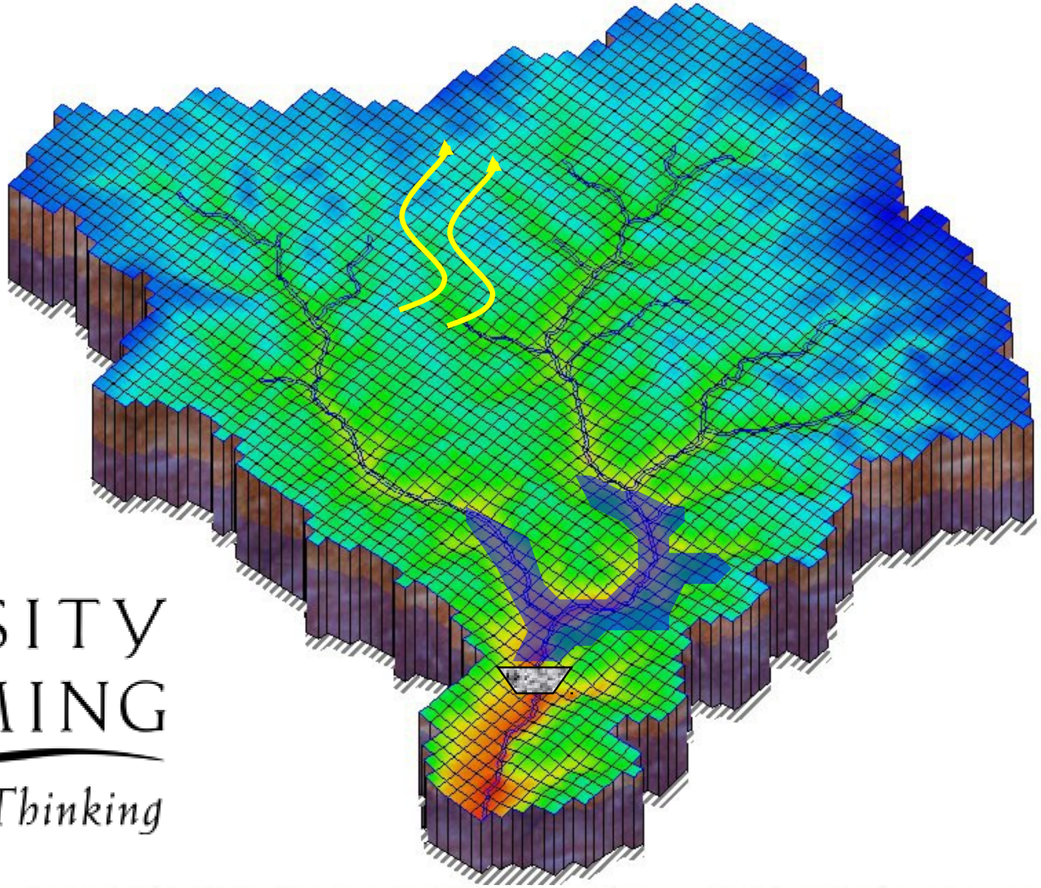
Gridded Surface/Subsurface Hydrologic Analysis (*GSSHA*) model



Downer and Ogden, *GSSHA* User's Manual (2003), *J. Hydrologic Engineering* (2004)
http://www.gsshawiki.com

GSSHA

- Square grid (5 to 90 m typical grid size)
- 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, wetland and groundwater flow
- 1D channel routing with hydraulic structures, lakes, wetlands, detention basins, rule curves, rating curves.
- Richards or Green-Ampt Redistribution coupling between overland flow and groundwater
- Erosion/deposition, sediment transport, nutrients

GSSHA Applications

The GSSHA model is supported by the DoD Watershed Modeling System (WMS) interface

- Flood forecasting in civil and military contexts
- Soil moisture/trafficability predictions
- Urban flood hydrology/storm drainage/land use change
- Flood inundation mapping/post event analysis
- Hurricane storm surge predictions in coastal areas
- Channel improvements and levee design
- FEMA Certified for use in flood insurance studies, 2013

GSSHA Model Simulations

We have published numerous papers showing:

- Runoff generation mechanism is important
- Where things are located in the watershed is important
- We need more detailed soil infiltration parameters

- We can teach junior-level engineering students to run GSSHA using the Watershed Modeling System (WMS) software in less than one week.

A big watershed problem:

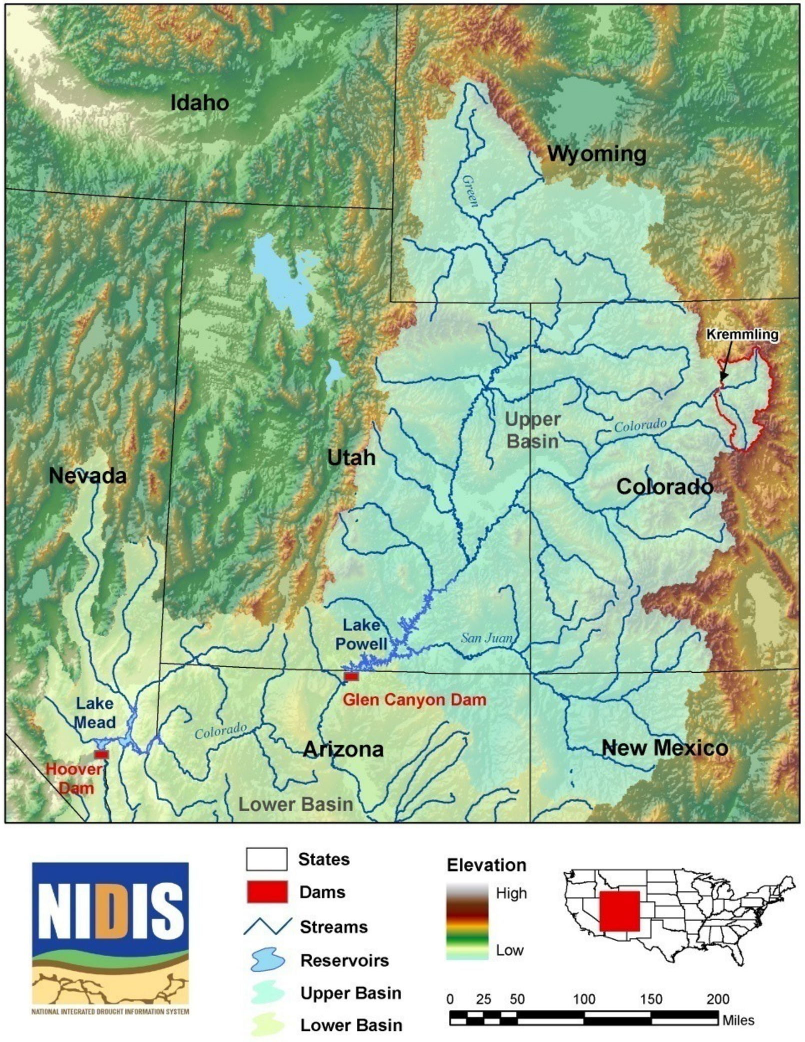
- Upper Colorado River Basin: 280,000 km^2 =3.1x10^8 grids at 30 m square grid size.
- High resolution important in mountains, where slope, aspect, vegetation, wind, drive snow redistribution, sublimation, and melt.
- Low resolution in broad and extensive basins, where runoff is infrequently produced.

Glen Canyon Dam: the Upper Basin States' bank account

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

© Ron Niebrugge

Upper Colorado River Basin



Basin Area: 288,000 km^2

Streams: 467,000 km

Population: 900,000 (USBR)

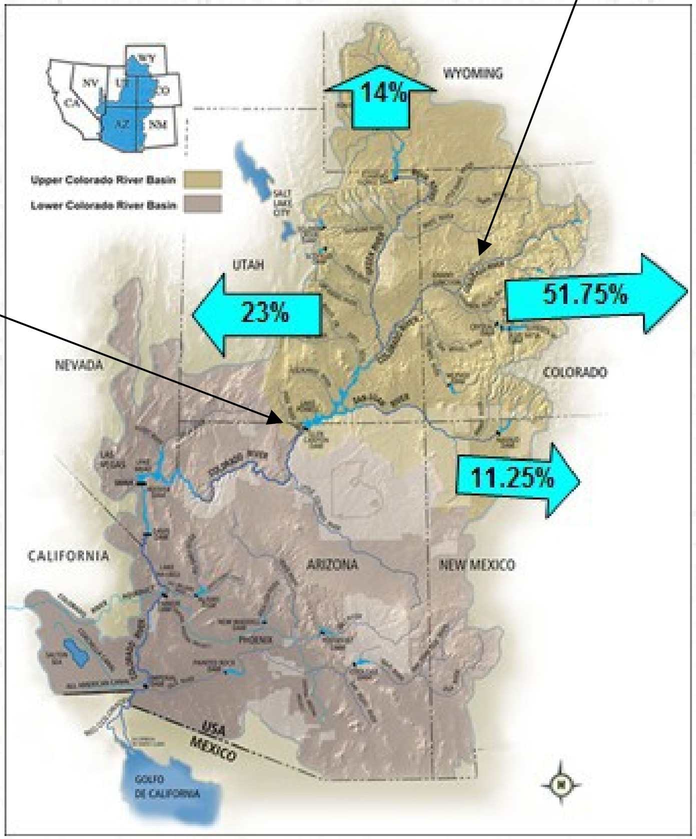
Area above 2700 m: 14.5% (9,000 ft)

Area above 3050 m: 3.2% (10,000 ft) produces most snow-melt runoff

Law of the River, Colorado River Compact, 1922

Lee's Ferry, AZ, is the legal dividing point between Upper and Lower Basin

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



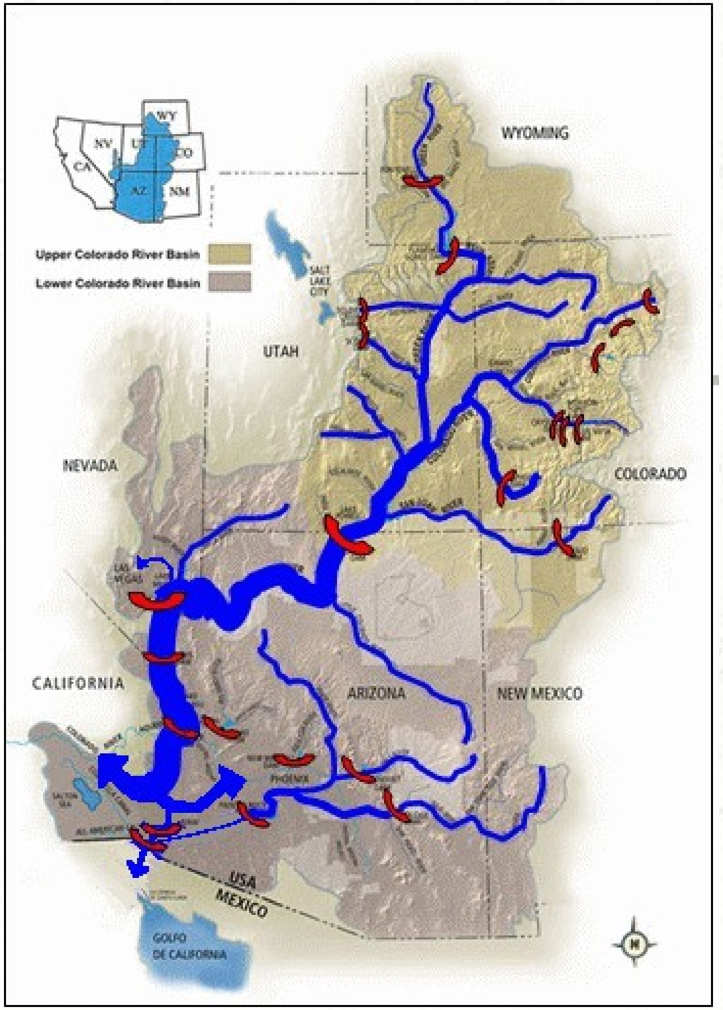
Lower Basin (CA, AZ, NV)
<u>guaranteed</u> 7.5 MAF/y

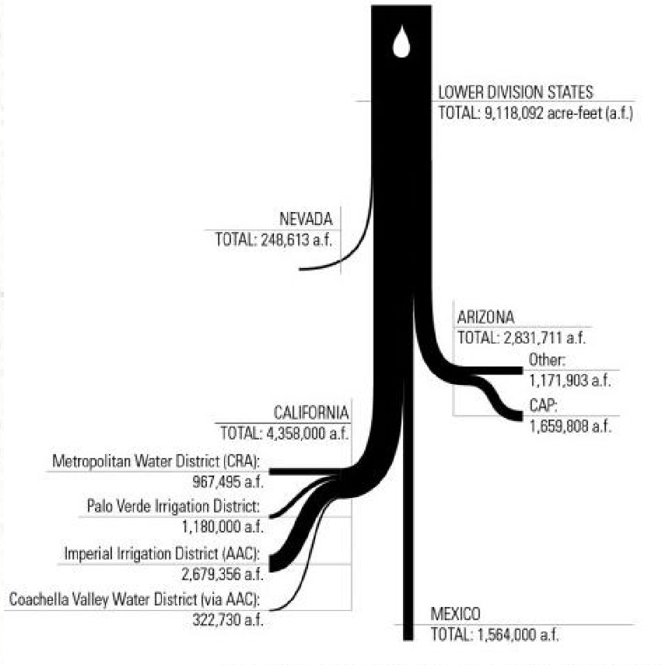
<u>plus</u>

Mexico- 1.5 MAF/y

Note: 1 AF = 1.233 Ml

Water Use in the Colorado River Basin





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

High Altitude Complexity

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Compelling socioeconomic issues

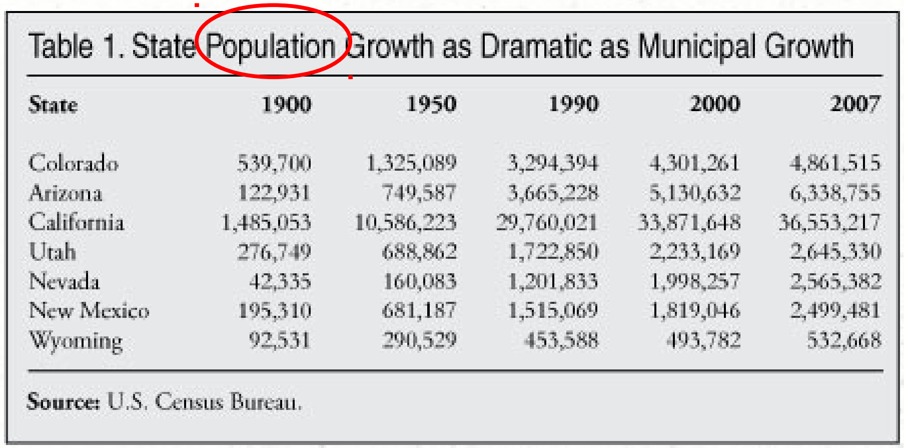


Table 1. State Population Growth as Dramatic as Municipal Growth

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:

Planned diversions:


Richard Armstrong, NSIDC

Snowfall and redistribution:

CI-WATER Component 3 Objective

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

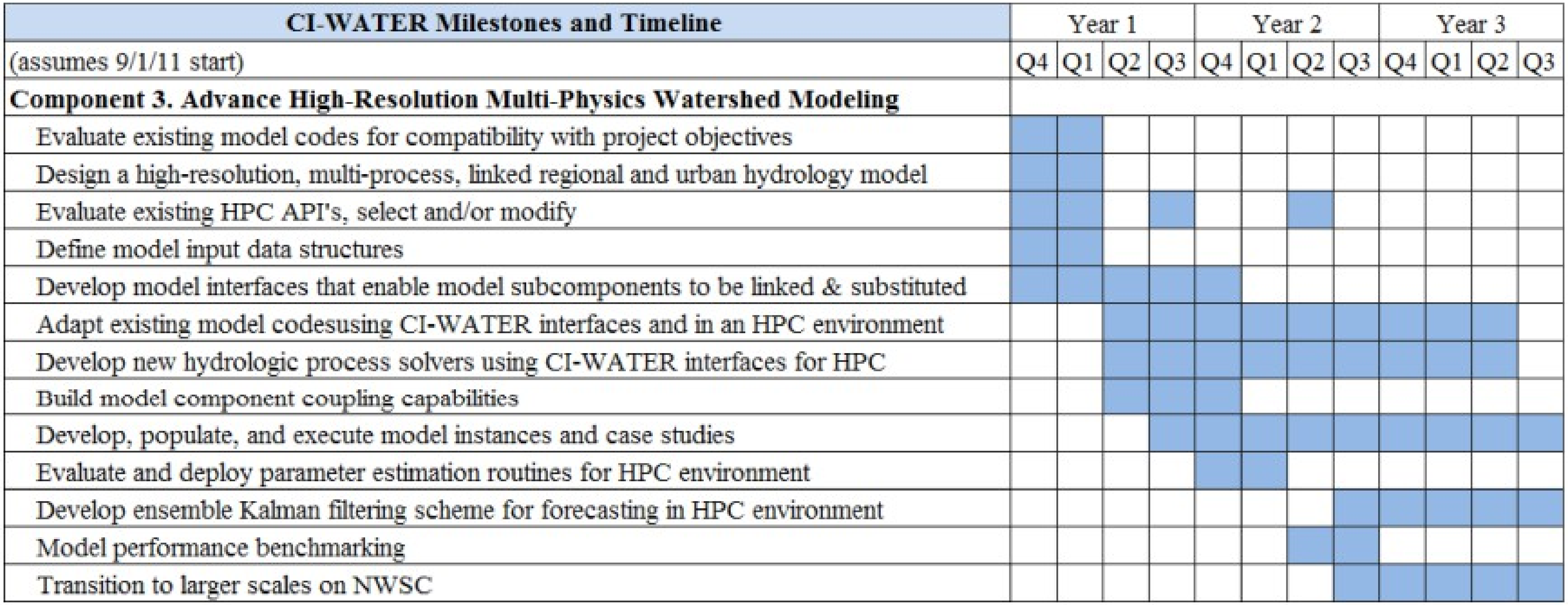
- What are the potential impacts of climate change on the long-term yield of water from the upper Colorado River basin?

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

CI-WATER Component 3

Milestones from proposal:



CI-WATER Milestones and Timeline	Year 1				Year 2				Year 3			
(assumes 9/1/11 start)	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Component 3. Advance High-Resolution Multi-Physics Watershed Modeling												
Evaluate existing model codes for compatibility with project objectives	■	■										
Design a high-resolution, multi-process, linked regional and urban hydrology model	■	■										
Evaluate existing HPC API's, select and/or modify	■	■		■			■					
Define model input data structures	■	■										
Develop model interfaces that enable model subcomponents to be linked & substituted	■	■	■	■	■							
Adapt existing model codesusing CI-WATER interfaces and in an HPC environment			■	■	■	■	■	■	■	■	■	
Develop new hydrologic process solvers using CI-WATER interfaces for HPC			■	■	■	■	■	■	■	■	■	
Build model component coupling capabilities			■	■	■							
Develop, populate, and execute model instances and case studies				■	■	■	■	■	■	■	■	■
Evaluate and deploy parameter estimation routines for HPC environment					■	■						
Develop ensemble Kalman filtering scheme for forecasting in HPC environment								■	■	■	■	■
Model performance benchmarking							■	■				
Transition to larger scales on NWSC								■	■	■	■	■

CI-WATER Component 3

Premise: Large-scale high-resolution hydrological modeling must simulate diverse runoff generation mechanisms from infiltration excess to saturation excess.

We evaluated two existing 3D Richards Eqn. codes:

ADH – US Army Corps of Engineers

Parflow – LLNL

CI-WATER Component 3

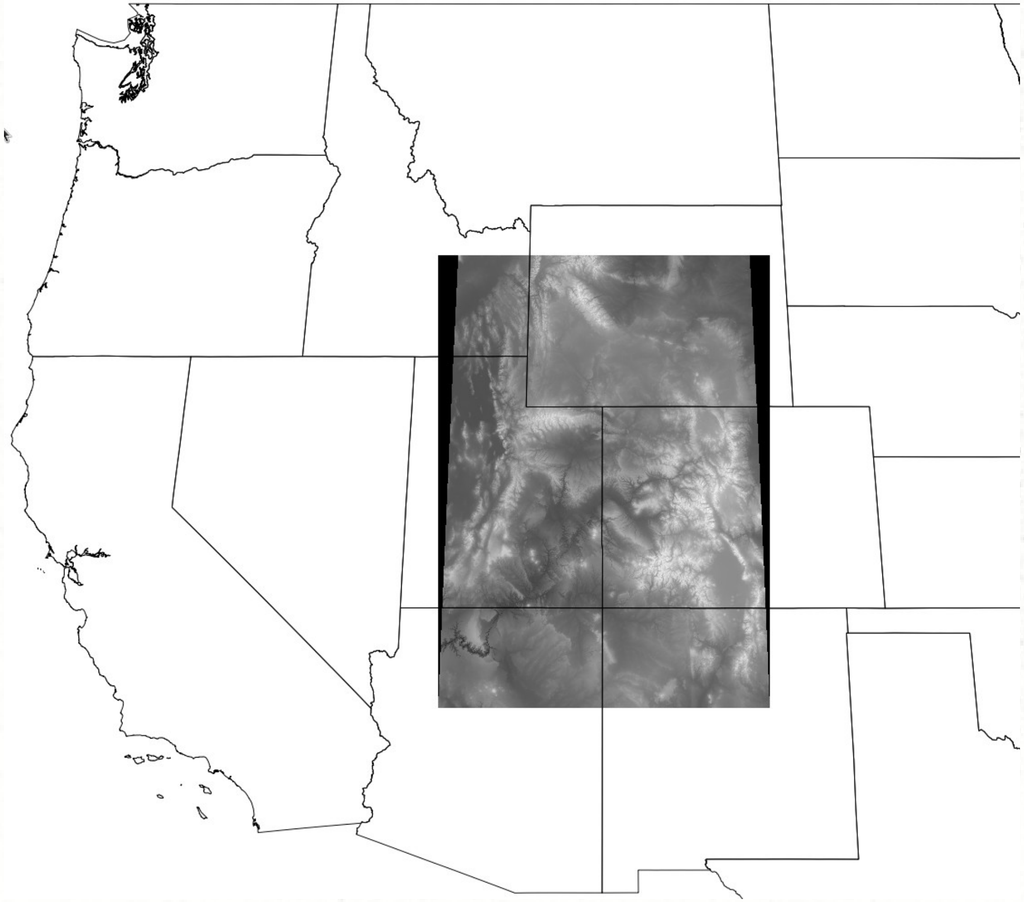
Results of that evaluation:

- 3D Richard's solvers have aspect ratio limitations that impede their use in simulating large watersheds.
- Converting 3D solvers to quasi-3D solvers is more complex than starting from scratch.

Petascale??

- HPC hydrologic modeling is in its infancy
- We seldom do terascale modeling!
- We sometimes do single CPU gigascale modeling
- Conceptual models remain in widespread use because of regulatory requirements, familiarity, relative ease of parameter estimation, and negligible run time.

Interrupted Sinusoidal Projection

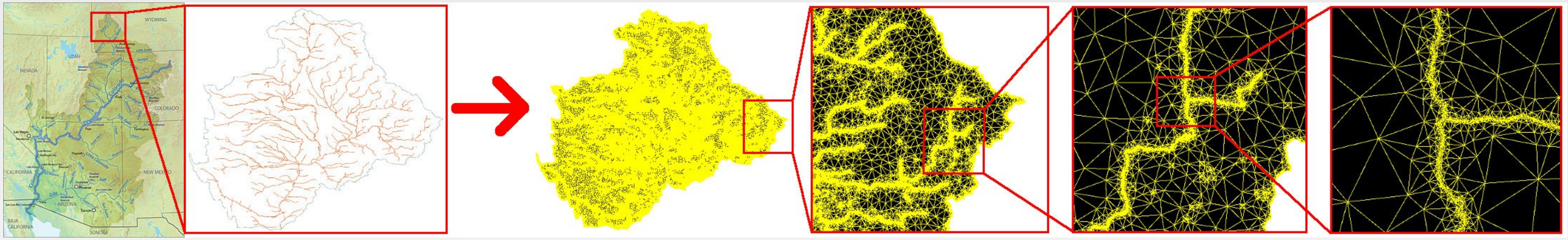


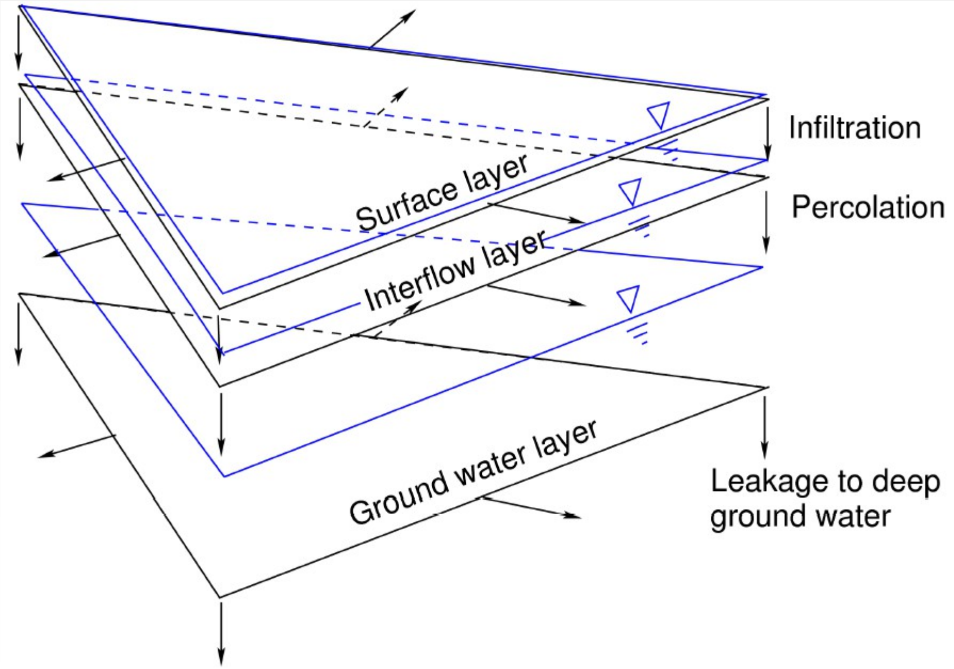
$x=R(\lambda-\lambda_o)\cos\varphi \quad y=R\varphi$

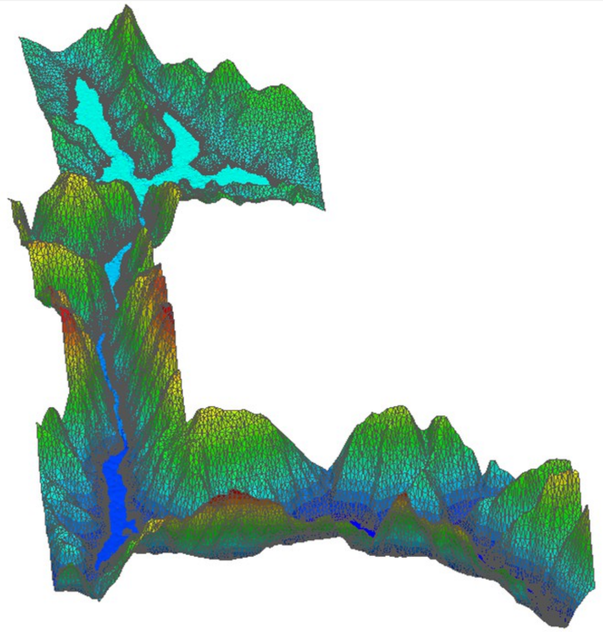
-Preserves area perfectly

- Lines of latitude are horizontal lines
- Longitudes converge towards the pole
- Can describe the Mississippi or Amazon basin with minimal distortion
- Inset shows 10 m Digital Elevation Model (32 GB)

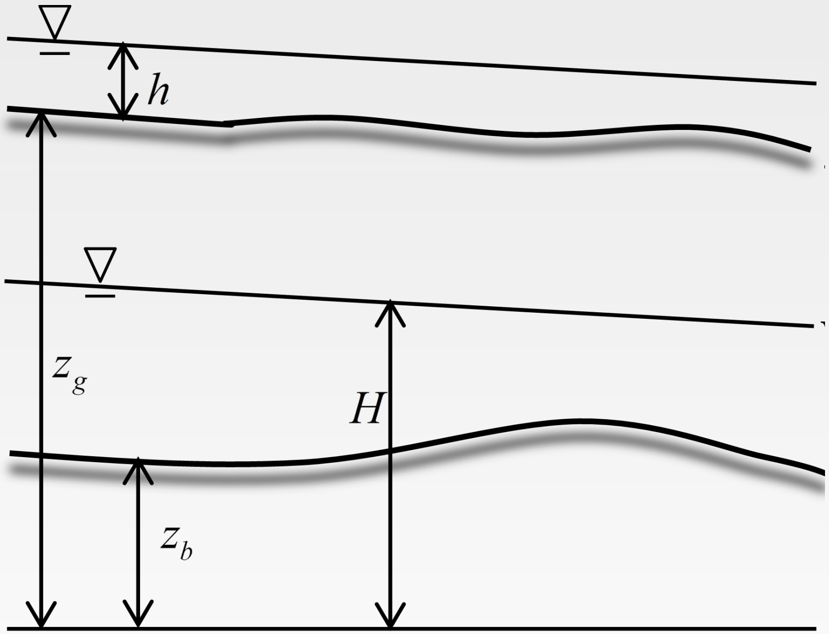
Variable Resolution Large Watershed Model on an unstructured grid







Mathematical model



surface water:
2D shallow water equations
- dynamic wave
- **diffusive wave**
- kinematic wave

1D vadose zone coupling

2D saturated groundwater flow
two layers that represent perched and unconfined aquifers.

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)

$$\frac{dZ_j}{dt}=\frac{K(\theta_d)-K(\theta_i)}{(\theta_d-\theta_i)}\left(\frac{\psi(\theta_d)}{Z_j}+1\right)$$

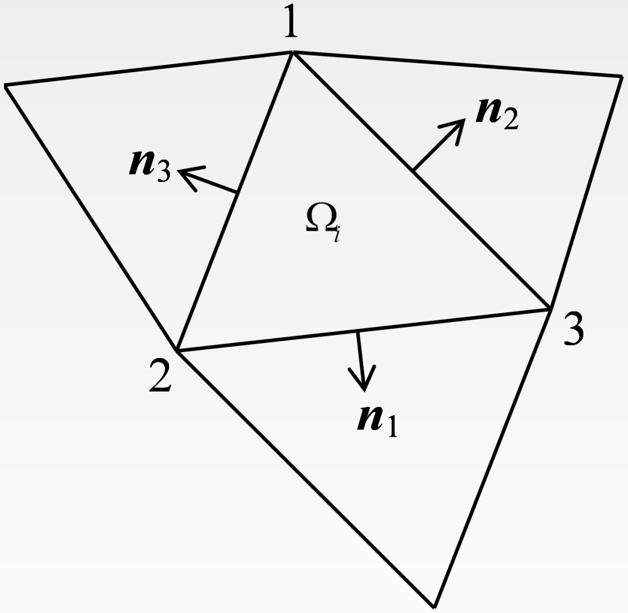
2D groundwater flow

(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



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

$$\int \frac{\partial U}{\partial t}d\Omega+\int \nabla\cdot Fd\Omega=\int Sd\Omega$$

$$\int \frac{\partial U}{\partial t}d\Omega+\oint F\cdot nd\Gamma=\int Sd\Omega$$

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

Upwind Riemann solver for convective flux in overland flow

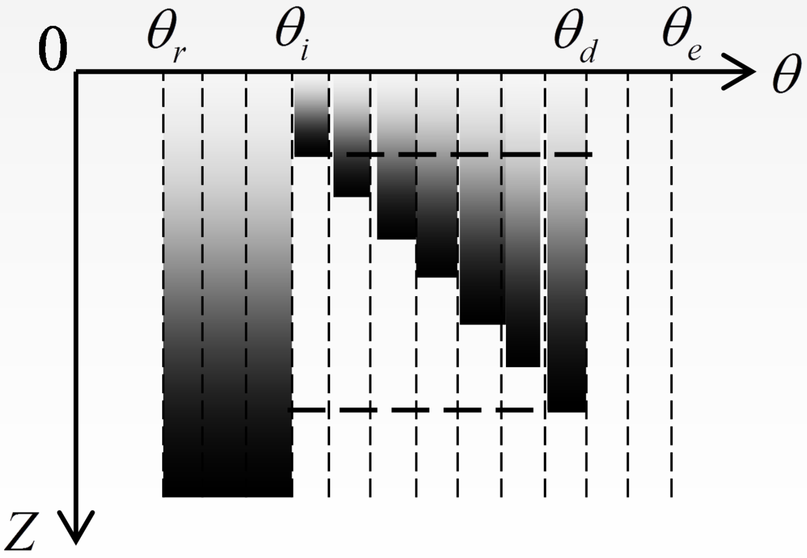
Central difference for diffusion term in groundwater equation

- We have developed new groundwater-surface water interaction methodologies that are *transformative* in terms of simulating large areas.
- Our vadose zone simulation methods are:
    - computationally simple
    - robust
    - numerically efficient and computationally fast
    - guaranteed to conserve mass
    - guaranteed to converge
    - as accurate as the numerical solution of Richards equation in many instances.
    - the most innovative feature of the quasi-3D ADHydro model.

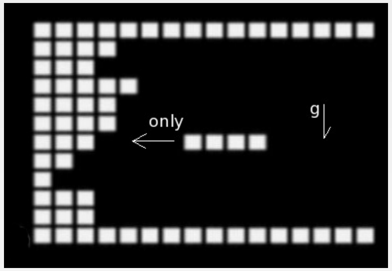
1-D Unsaturated Flow model: T-O (Talbot and Ogden, 2008) infiltration and redistribution method

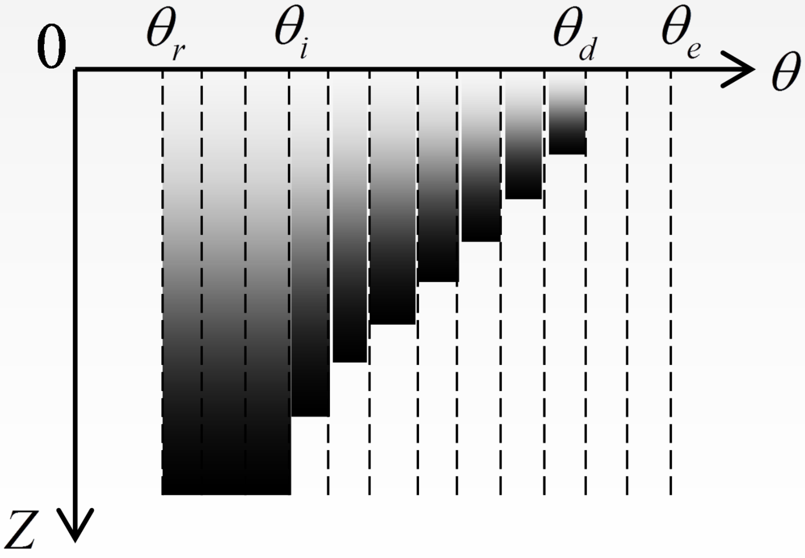
Infiltration:

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



Redistribution:





Talbot and Ogden 1-D Infiltration (2008)

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

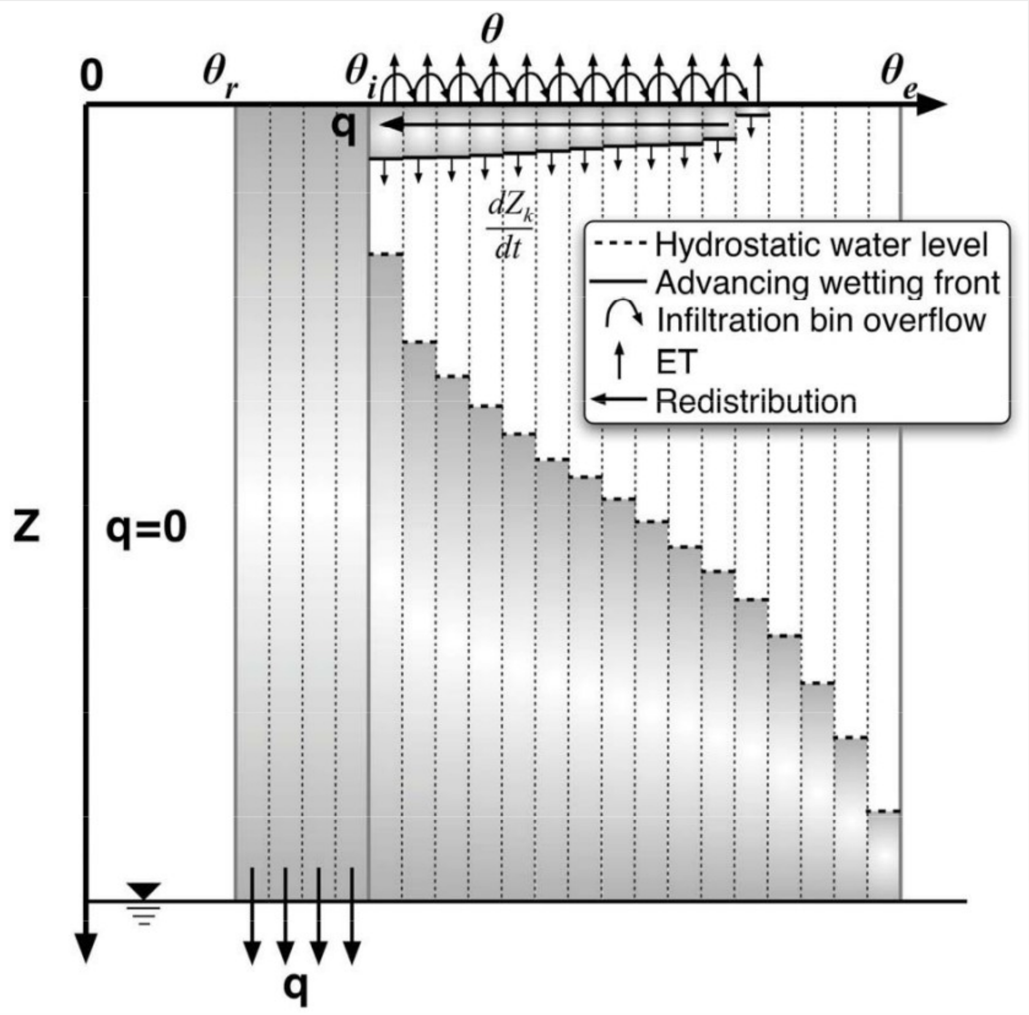
- No need to solve Richards (1931) equation:

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

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

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

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



Multi-layer T-O: Steady infiltration

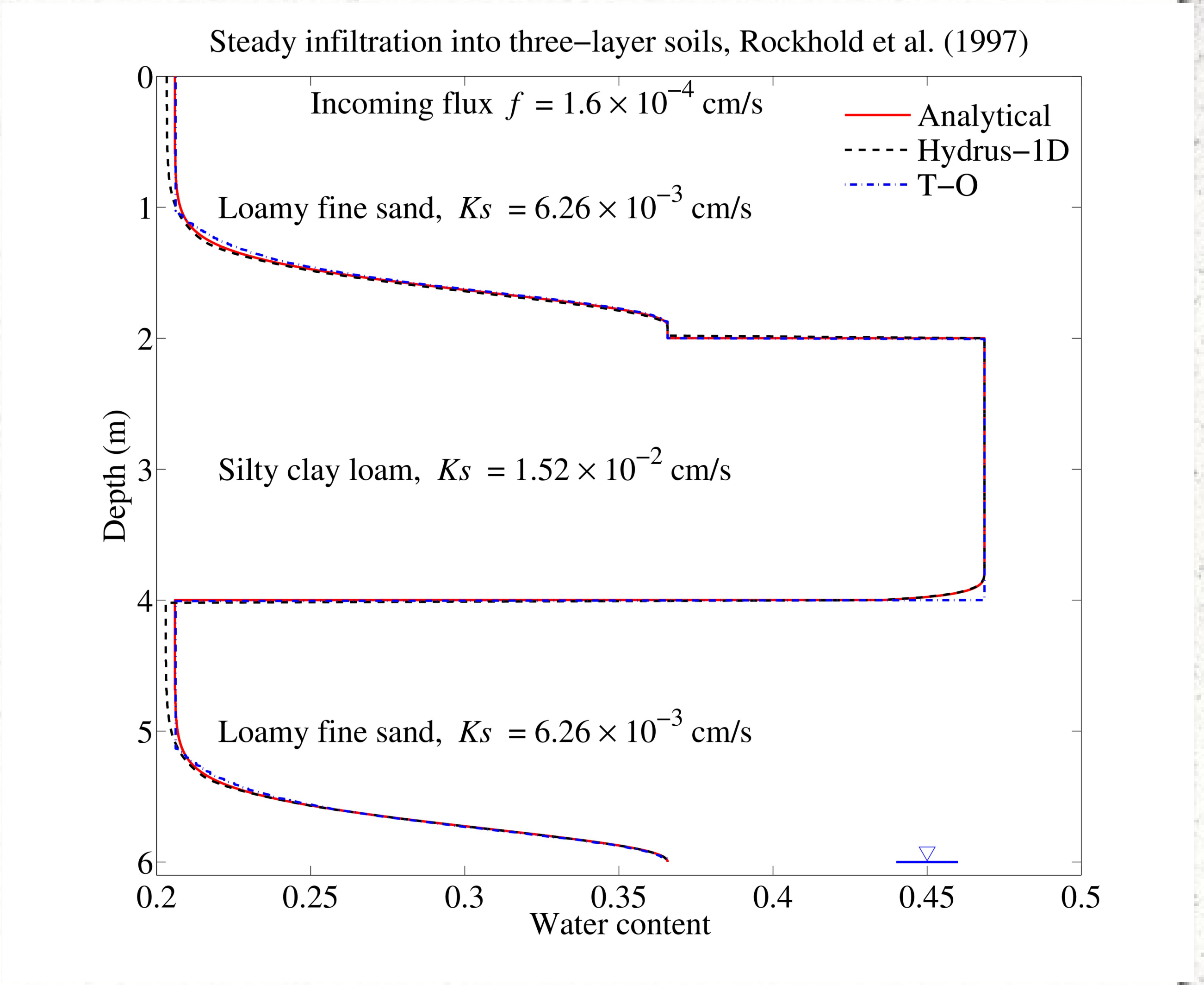
6 m deep soil column:

1st Layer: 2 m fine sand

2nd Layer: 2 m silty clay loam

3rd Layer: 2 m of fine sand

Lower boundary condition: Fixed water table

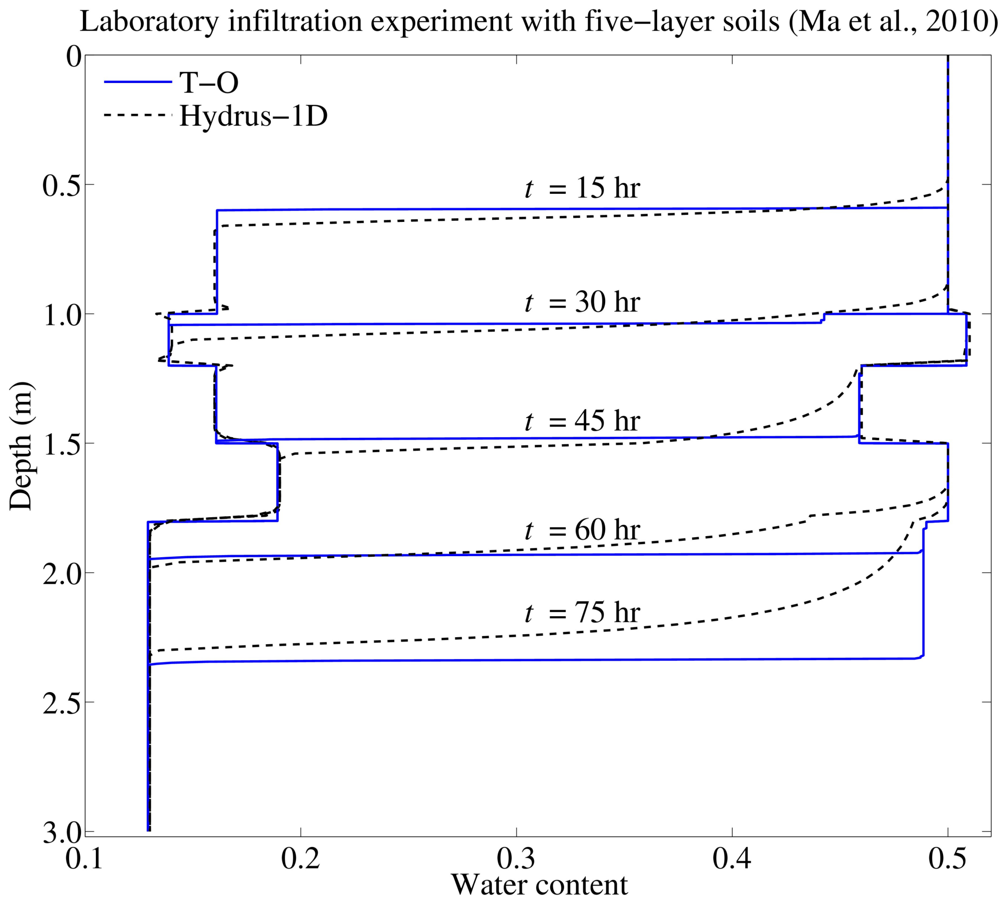

Steady infiltration into three–layer soils, Rockhold et al. (1997)

Multi-layer T-O: Laboratory infiltration

FIVE LAYERS

In a 3 m deep soil column

Soil depth (m)	Texture	K_s (cm/min)
0.0-1.0	Silt loam	0.01463
1.0-1.2	Loam	0.01924
1.2-1.5	Silt loam	0.01256
1.5-1.8	Loam	0.00505
1.8-3.0	Silt loam	0.01330

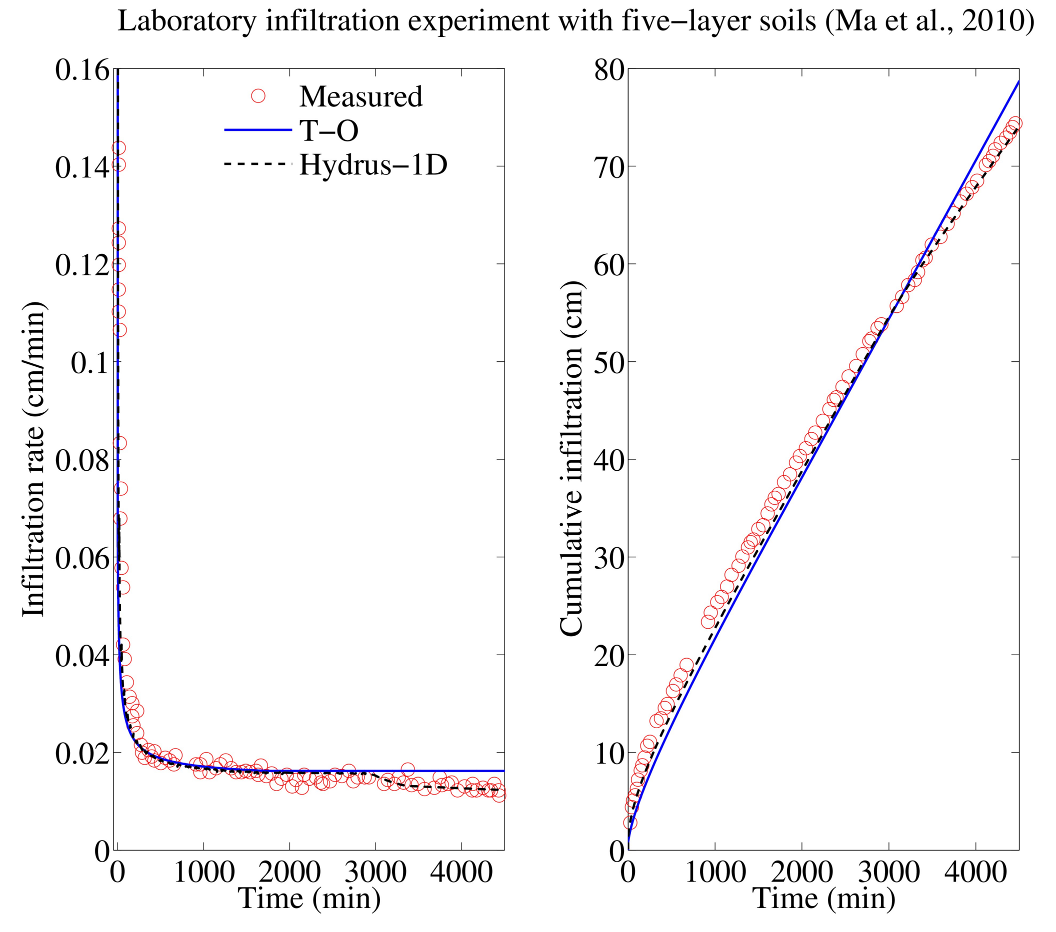


Multi-layer T-O: Five layer laboratory infiltration

Infiltration Rate &

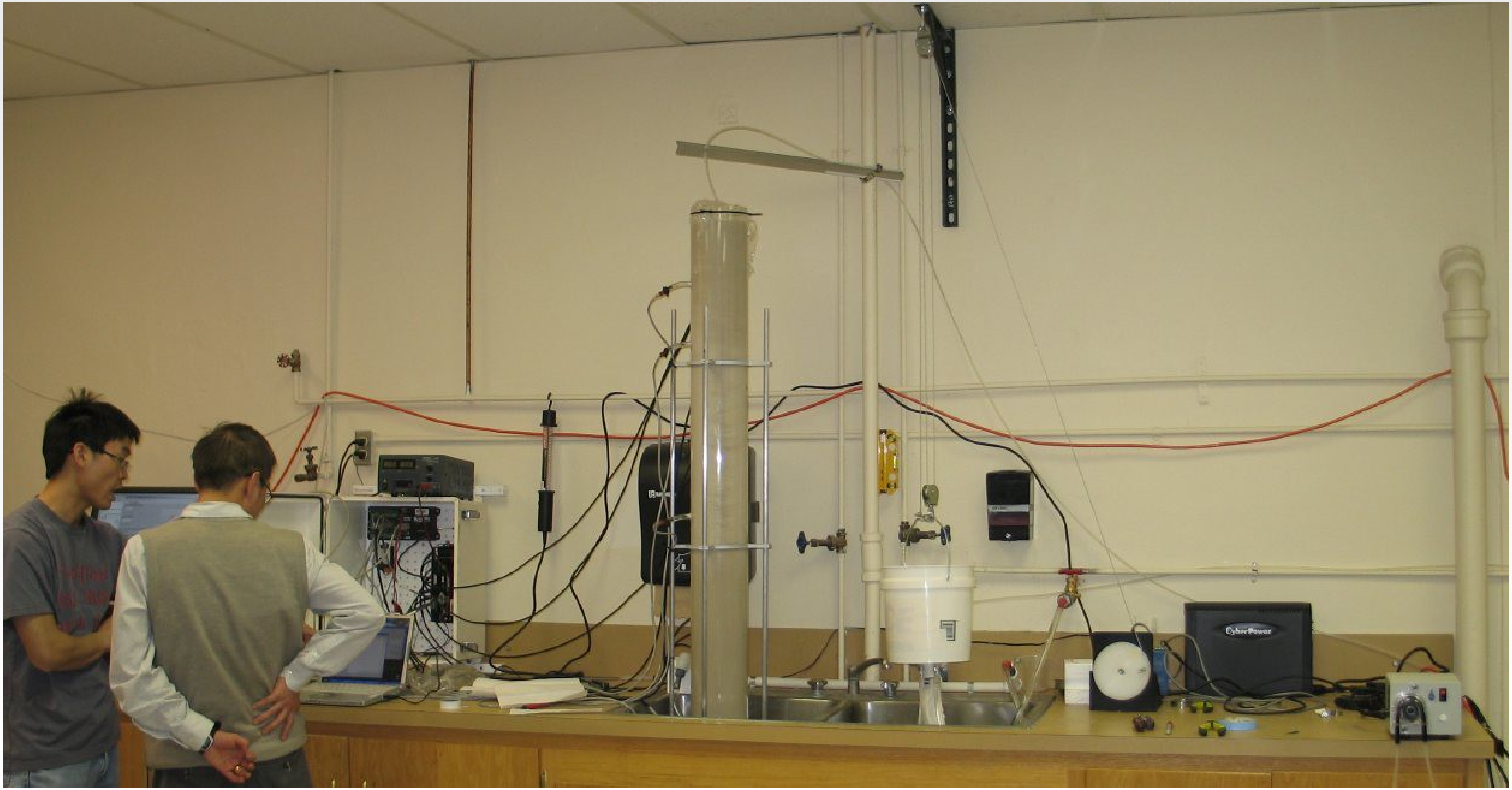
Cumulative infiltration

Soil depth (m)	Texture	K_s (cm/min)
0.0-1.0	Silt loam	0.01463
1.0-1.2	Loam	0.01924
1.2-1.5	Silt loam	0.01256
1.5-1.8	Loam	0.00505
1.8-3.0	Silt loam	0.01330



Laboratory infiltration experiment with five–layer soils (Ma et al., 2010)

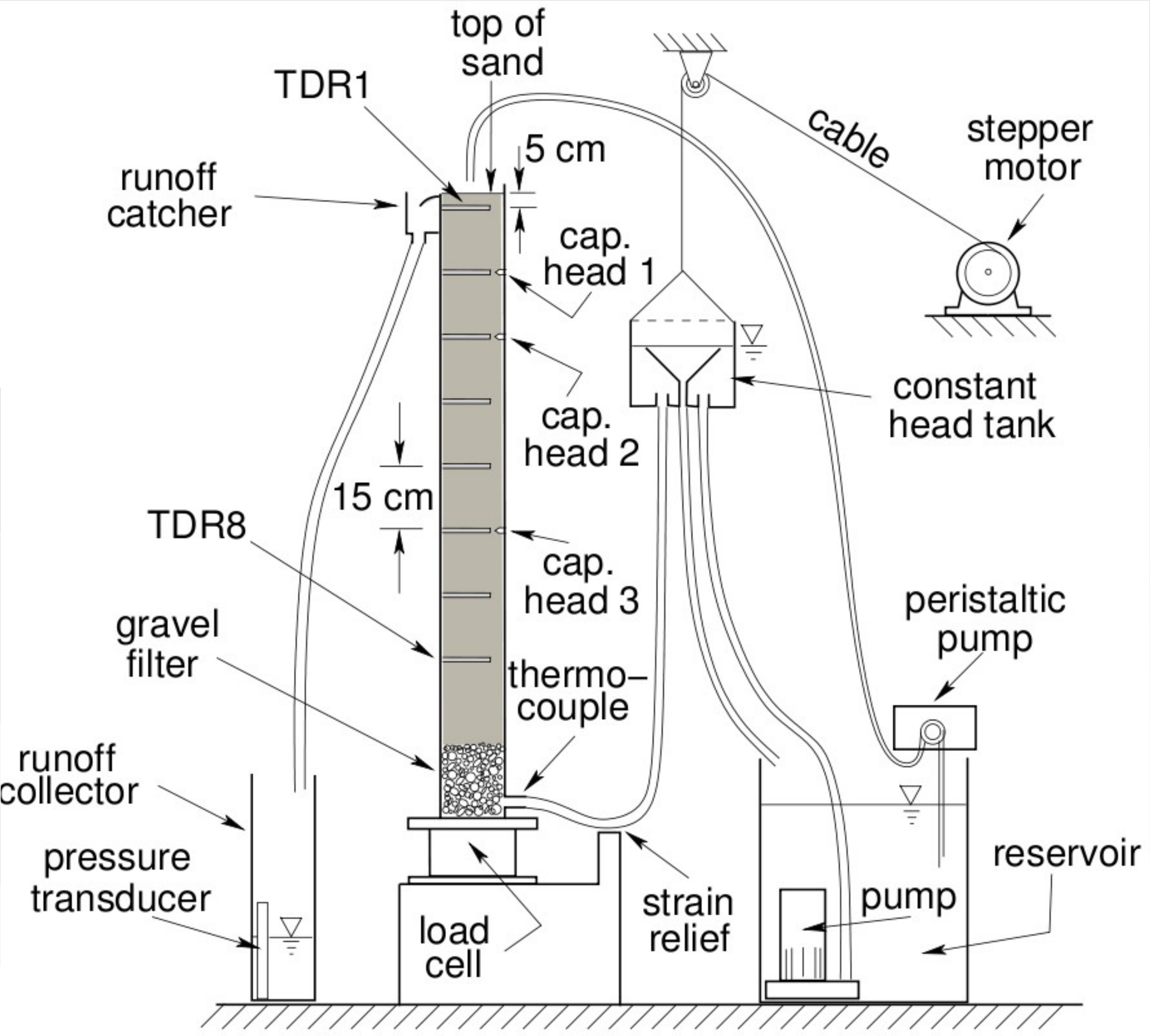
Talbot and Ogden 1-D Infiltration (2008), as modified by Ogden et al. (in review, WRR) Column-scale validation (after Childs and Poulovasillis 1962):



After Childs and Poulovasillis (1962):

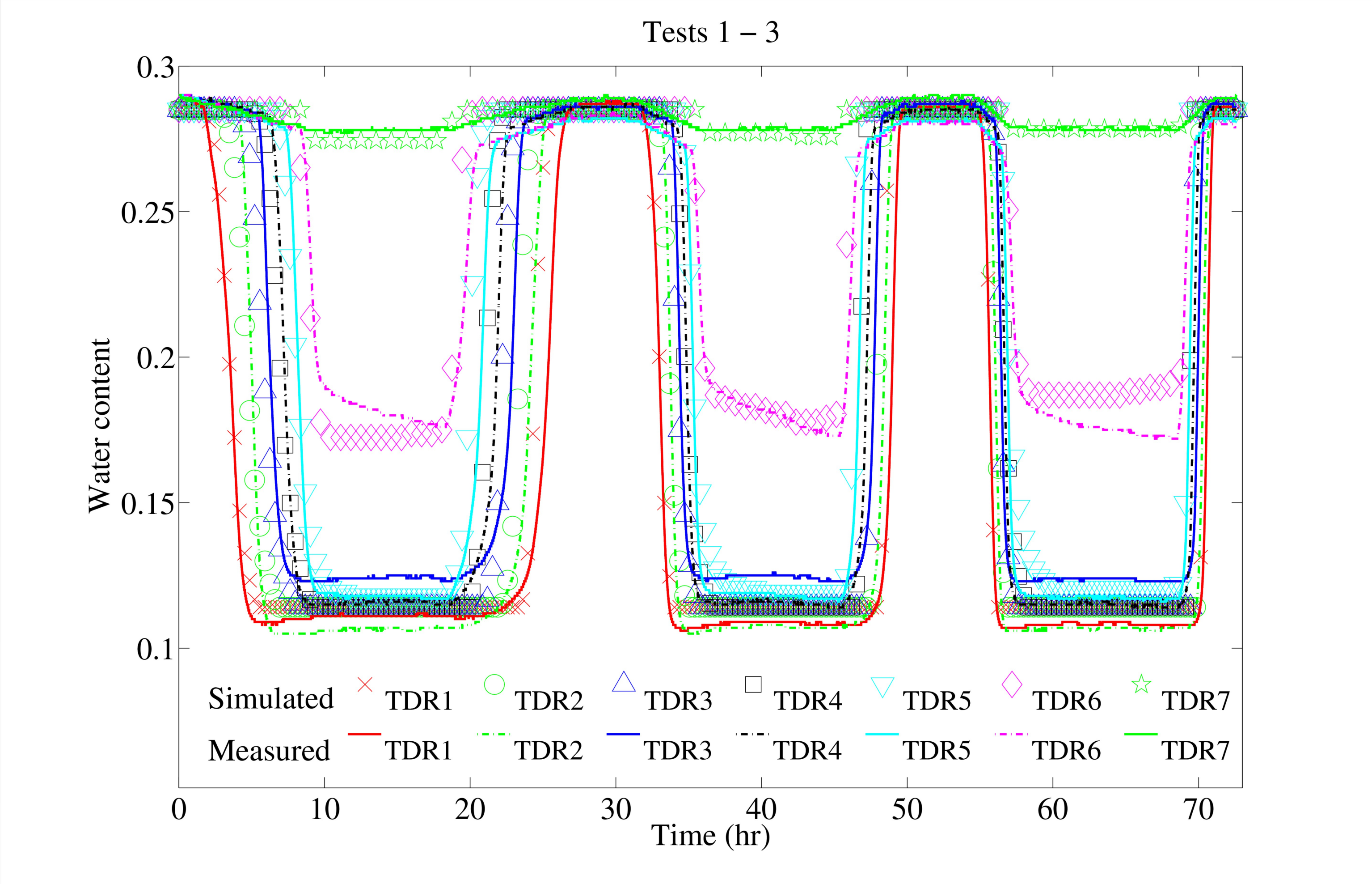
Raised and lowered water table with specified input flux.

		Flux intensity (cm/hr)		
Water table velocity (cm/hr)	2.356	4.710	7.589	16.090
13.2	Test 1	Test 4	Test 7	Test 10
27.6	Test 2	Test 5	Test 8	Test 11
55.2	Test 3	Test 6	Test 9	Test 12

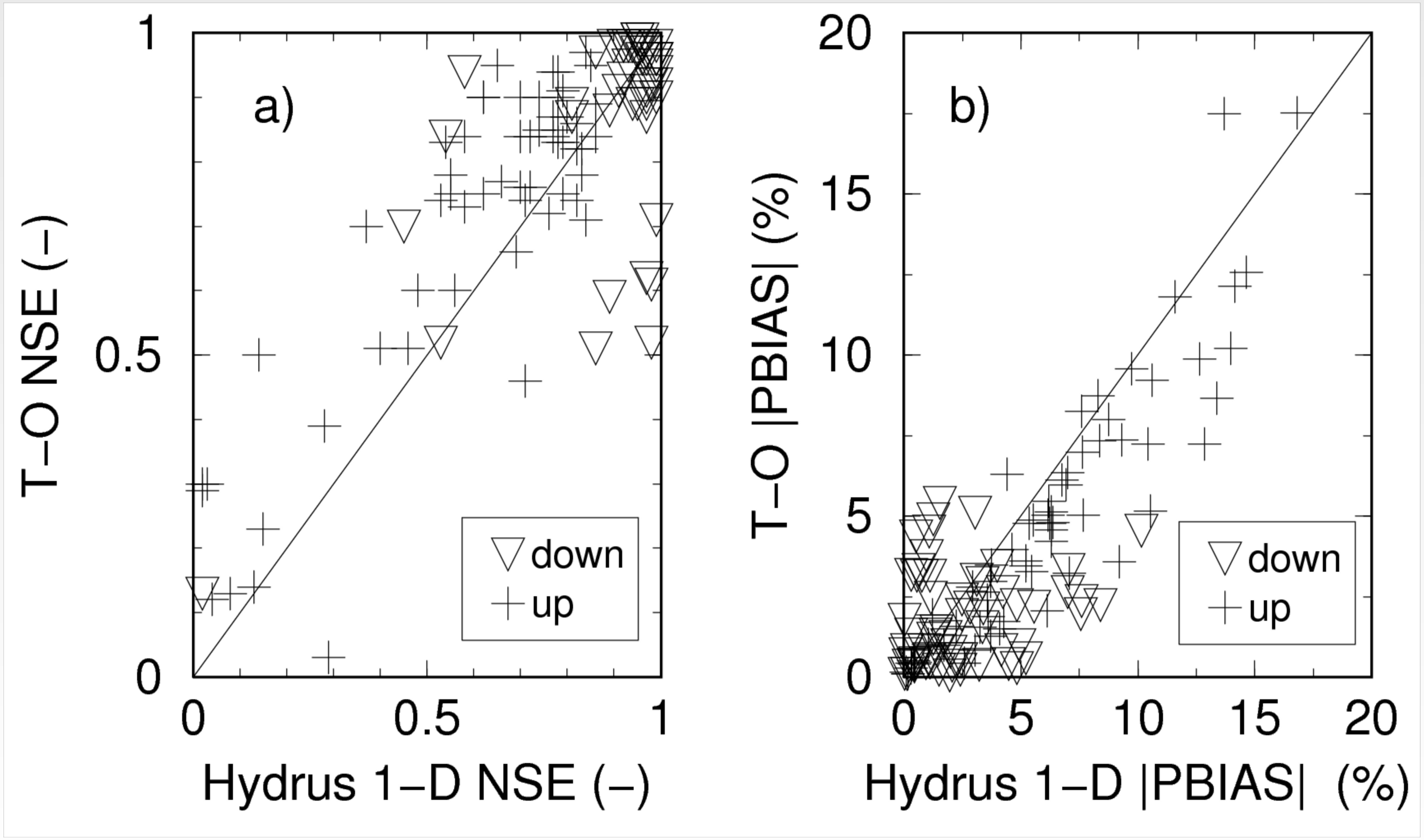


Ogden et al. (WRR in review):

$$\frac{dZ_j}{dt}=\frac{K\left(\theta_j\right)-K\left(\theta_i\right)}{\left(\theta_j-\theta_i\right)}\left(\frac{\left(\Psi\left(\theta_j\right)\right)}{Z_j}-1\right)$$



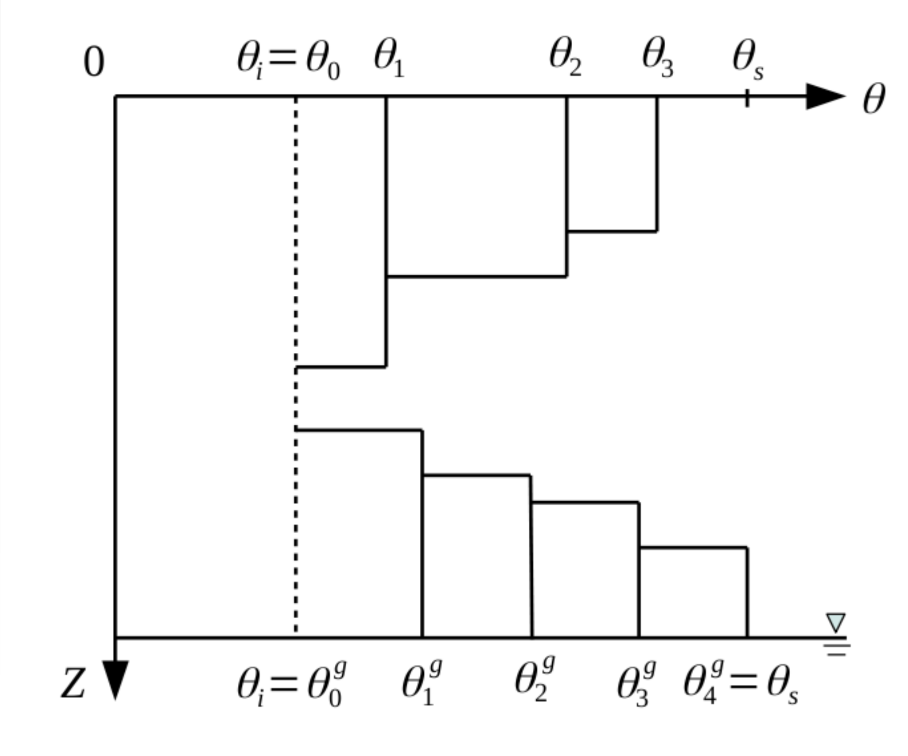
Ogden et al. (WRR in review):



“GARTO” Scheme (Lai et al., in review), 20 times faster than T-O

Infiltration: Green & Ampt with Redistribution (GAR) (Ogden & Saghafian 1997)

Finite Water Content solution (T-O) (Talbot & Ogden, WRR 2008) for vadose zone dynamics in response to changes in groundwater table elevation:

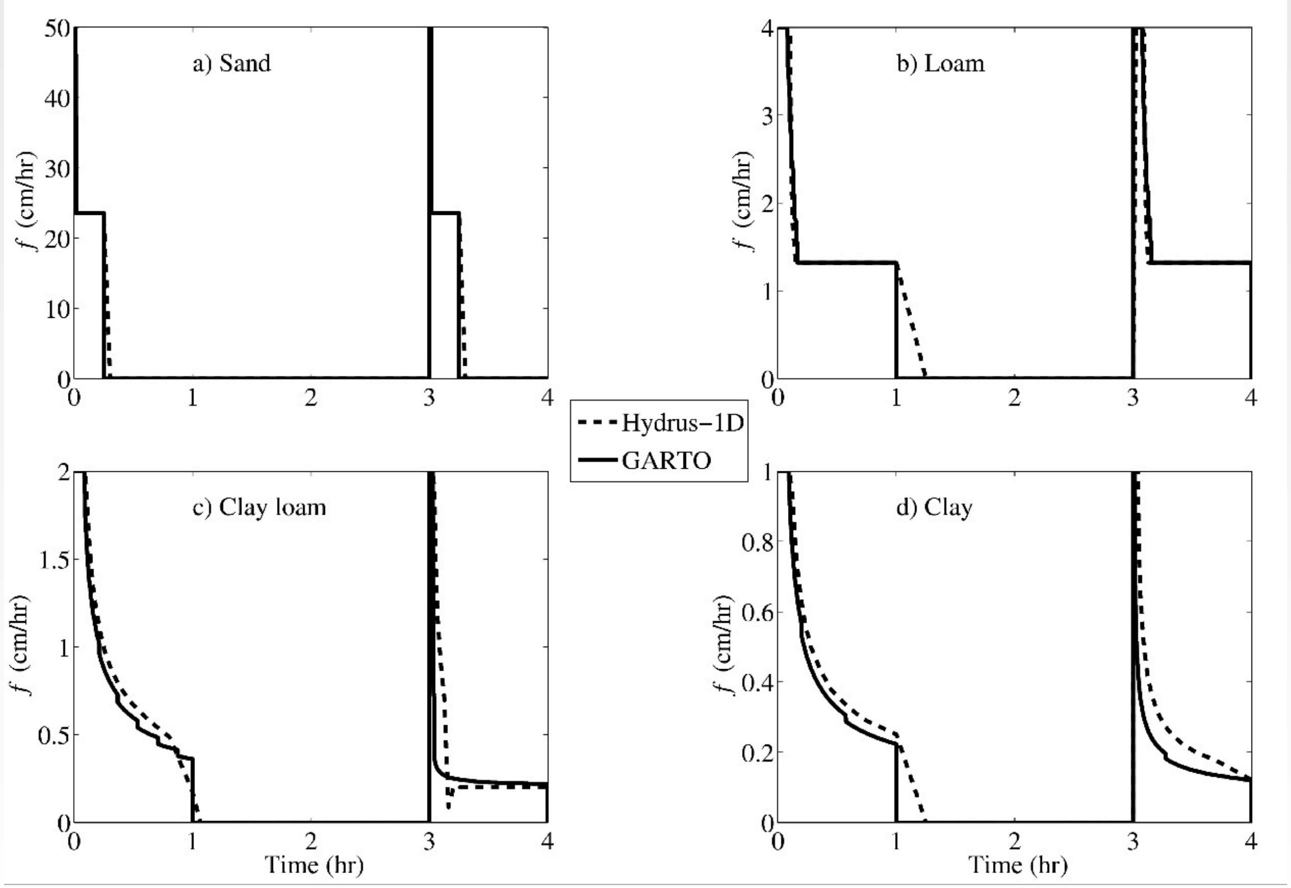


“GARTO” performance:

-two pulses of rainfall

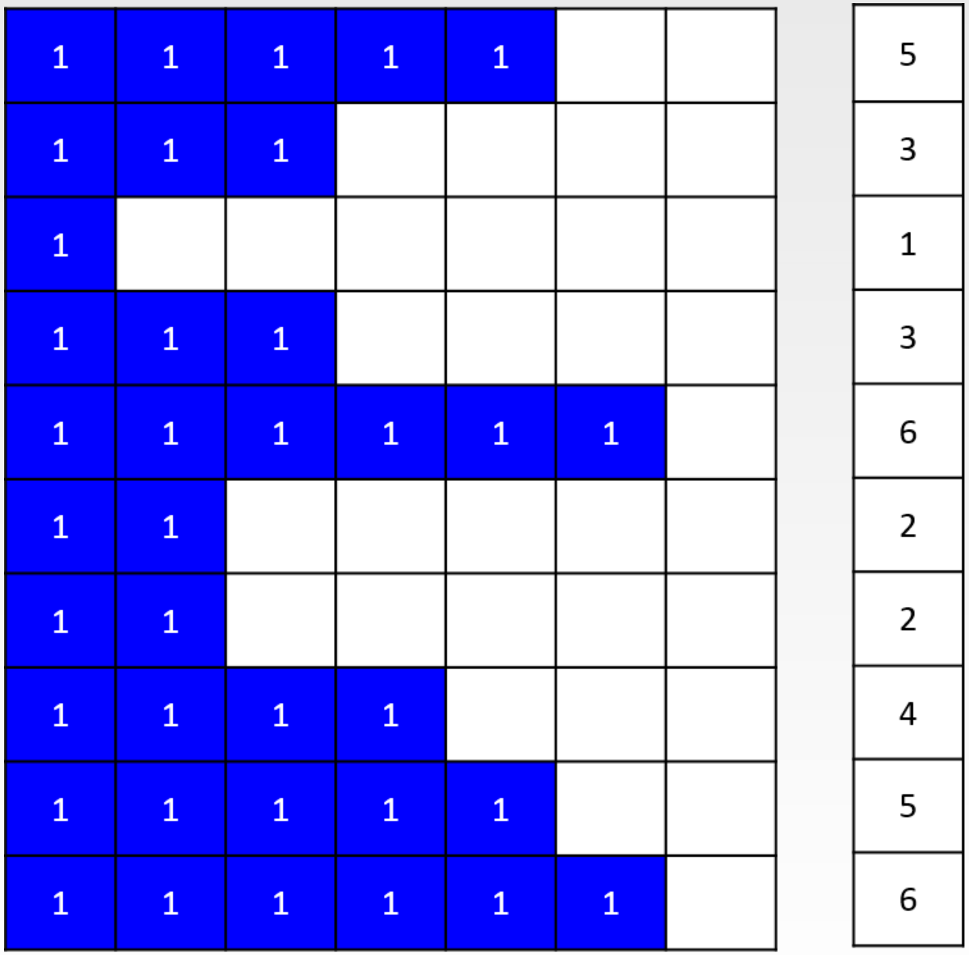
-water table set at $4\Psi_b$ below ground surface.

- advantage of GARTO scheme is that it is explicit and arithmetic, AND guaranteed to conserve mass.



Vector T-O method:

- -vertical discretization (1 cm is sufficient)
- -One vector discretized by ΔZ is sufficient to describe state of the system.
- -Considerable speedup is obtained with full physics (infiltration, slugs, groundwater).



1	1	1	1	1		
1	1	1				
1						
1	1	1				
1	1	1	1	1	1	
1	1					
1	1					
1	1	1	1			
1	1	1	1	1		
1	1	1	1	1	1	

5
3
1
3
6
2
2
4
5
6

The numerical examples were run on a 3.10 GHz quad core Intel Core i7-4930MX CPU with 32GB of RAM. The simulations are for a 1 meter deep column of coarse sand without groundwater for two example synthetic rainfall series.

Timing	Example 1	Example 2
Linked List Model	74.526	58.164
Matrix Model	13.820	20.415
Vector Model (full)	0.645	0.601
Vector Model (only slugs)	0.089735	0.089465

Rainfall	Example 1			Example 2		
	Start (hour)	Stop (hour)	Rate (cm/h)	Start (hour)	Stop (hour)	Rate (cm/h)
1	0	0.5	10.0	0	8.0	4.0
2	12.0	12.1	10.0	96.0	106.0	2.0
3	26.0	26.1	1.0			
4	37.0	37.1	1.0			
5	49.0	49.2	1.0			
6	62.0	62.1	1.0			
7	70.0	70.1	1.0			

Speedup	Example 1	Example 2
Linked List Model	1.00	1.00
Matrix Model	5.39	2.85
Vector Model (full)	115.54	96.78
Vector Model (only slugs)	830.51	650.13

Each simulation ran for a week using the above synthetic rainfall series.

The Vector method provides a significant performance increase over other implementations of the model.

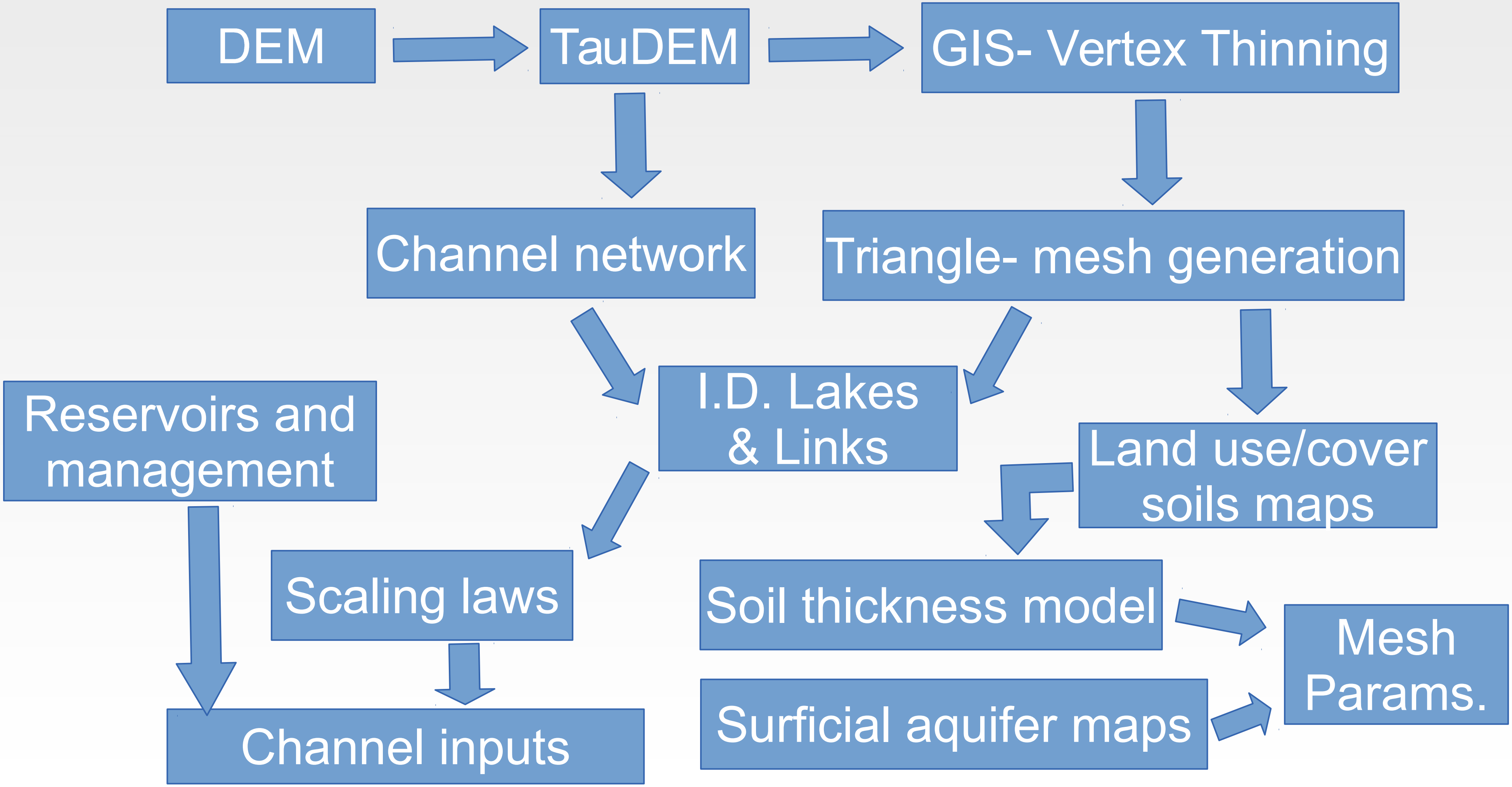
Model Design Philosophy

- Well defined and documented Application Programming Interface (API)
- Written in C with C++ and Fortran wrappers (Fortran needed to call NOAH-MP and Utah Energy Balance).
- Parallelized using CHARM++ object-oriented run time system, with one of several load balancers (e.g. METIS)
- Open source
- Designed to allow addition of alternative process mathematical descriptions

Inputs

- Topography: USGS NED, SRTM
- Land use/land cover: airborne, satellite or modeled.
- Soils: texture, layers, thicknesses
- Aquifers: alluvial and tributary extent and transmissivity
- Streams: thalweg elevation, cross section, roughness distribution (from scaling laws)
- Reservoirs, diversions, irrigated areas, water rights
- Forcing: dynamically downscaled climate simulations using Weather Research Forecasting (WRF) model

Mesh/Channel work flow (simplified)



DEM

TauDEM

GIS- Vertex Thinning

Channel network

Triangle- mesh generation

I.D. Lakes & Links

Reservoirs and management

Land use/cover soils maps

Scaling laws

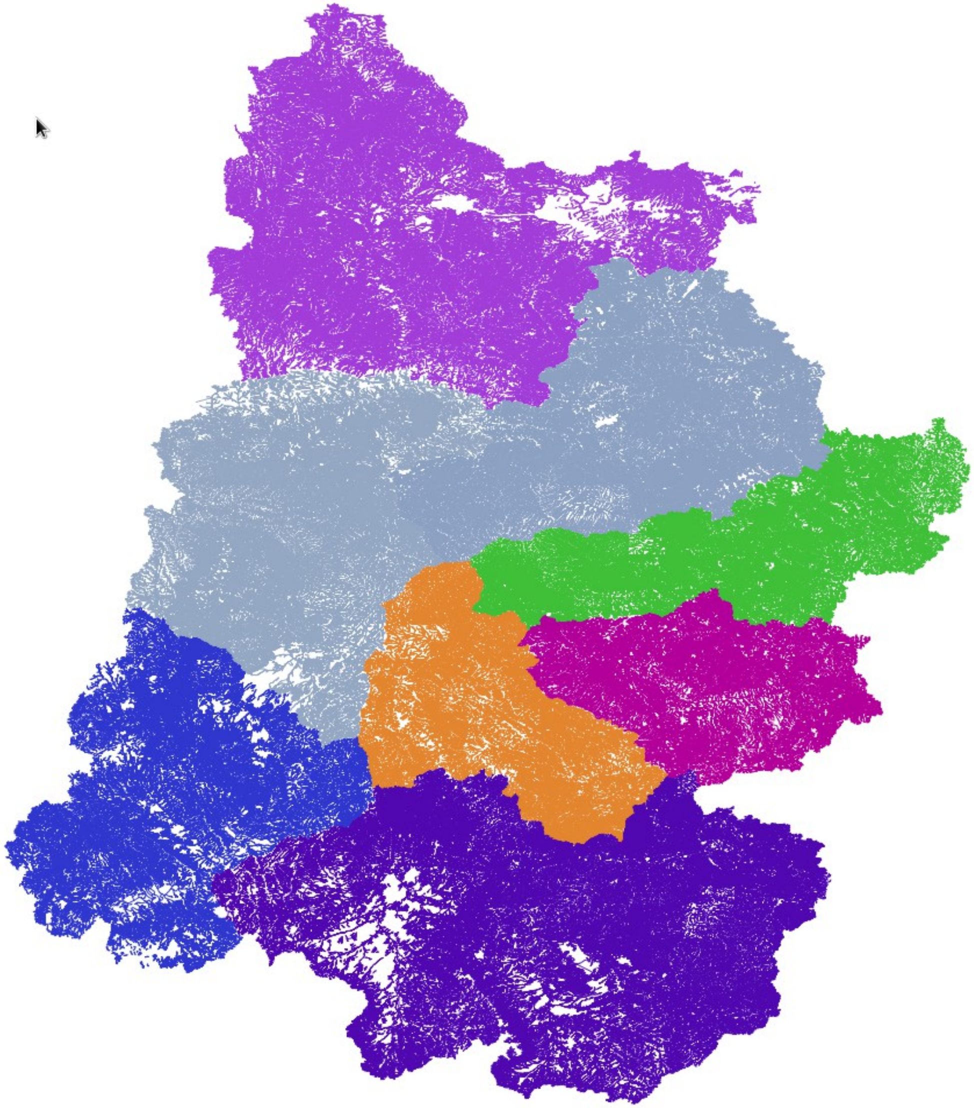
Soil thickness model

Mesh Params.

Surficial aquifer maps

Channel inputs

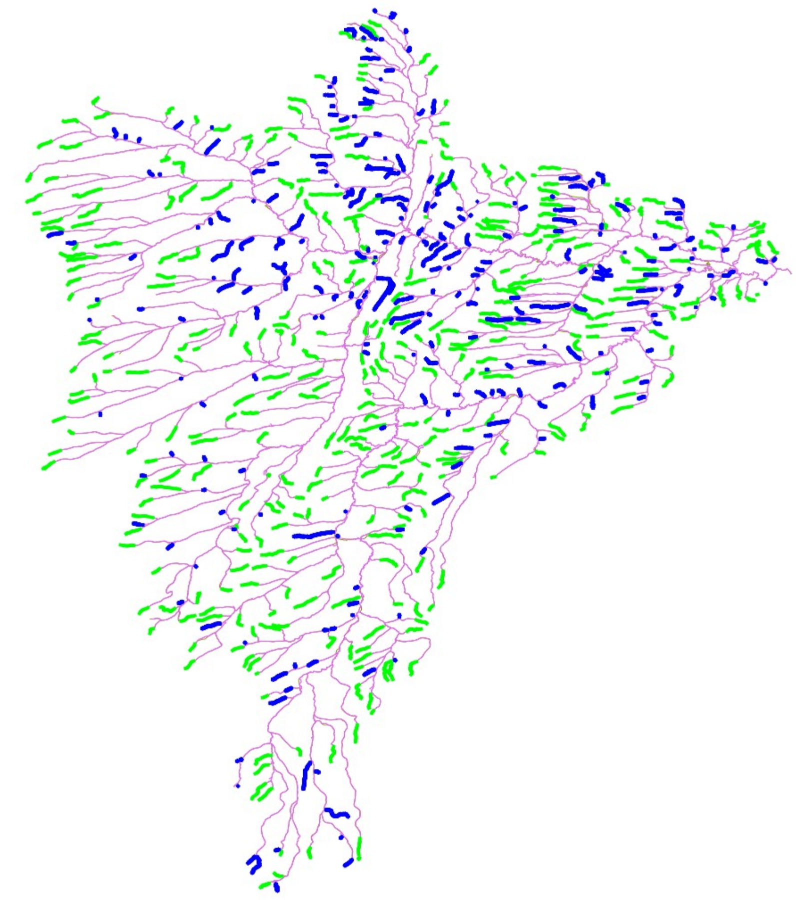
Upper Colorado River Stream Network



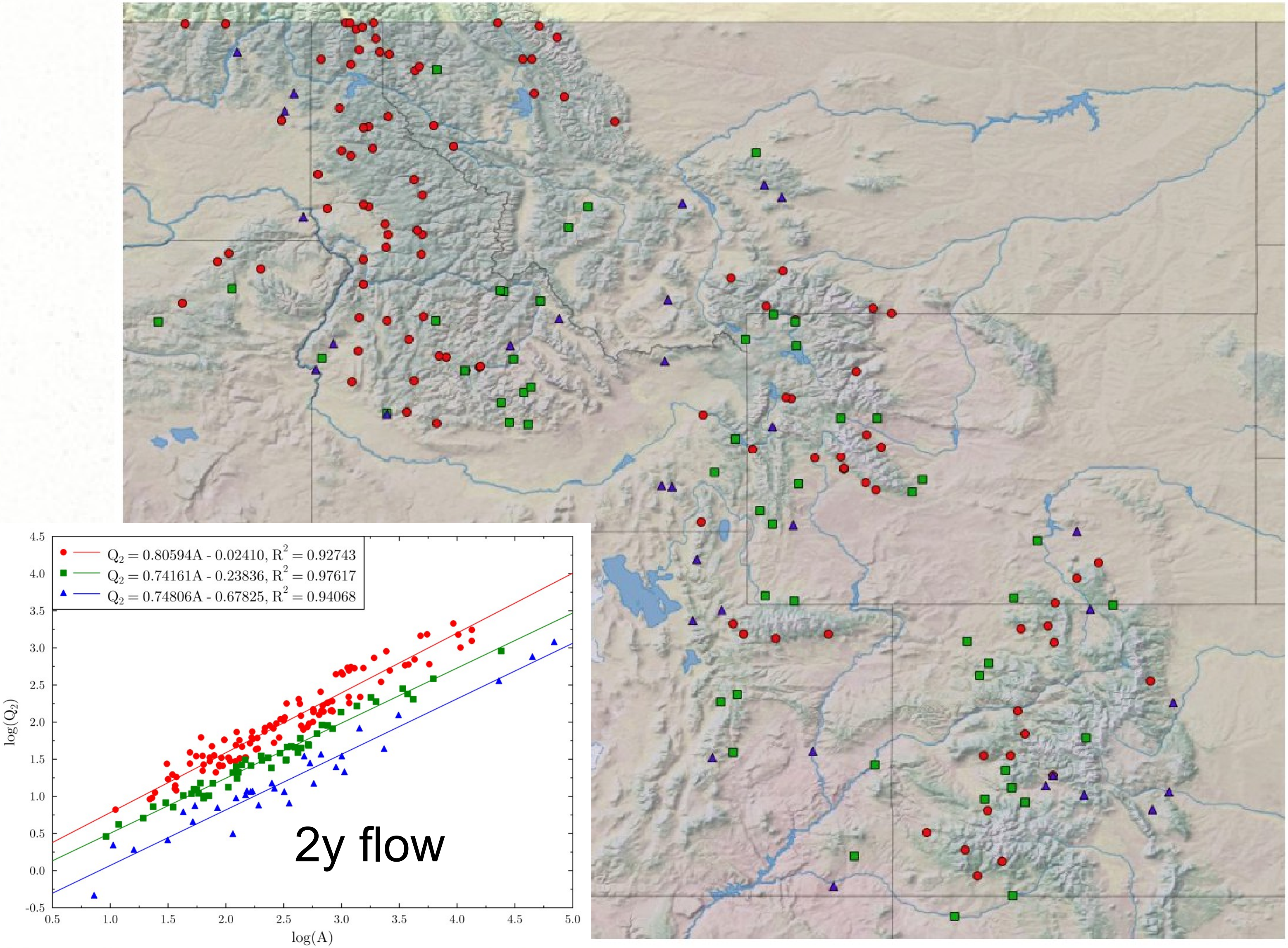
- -National Hydrography Data Set (NHD)
- - Use geomorphological cross-section predictors & scaling laws
- - Almost 500,000 km of streams in NHD
- - River data set impossible to create manually

TauDEM vs. NHDPlus

Selected TauDEM threshold to match stream density of NHDPlus
Green and blue lines show where there is no match within 100 meters

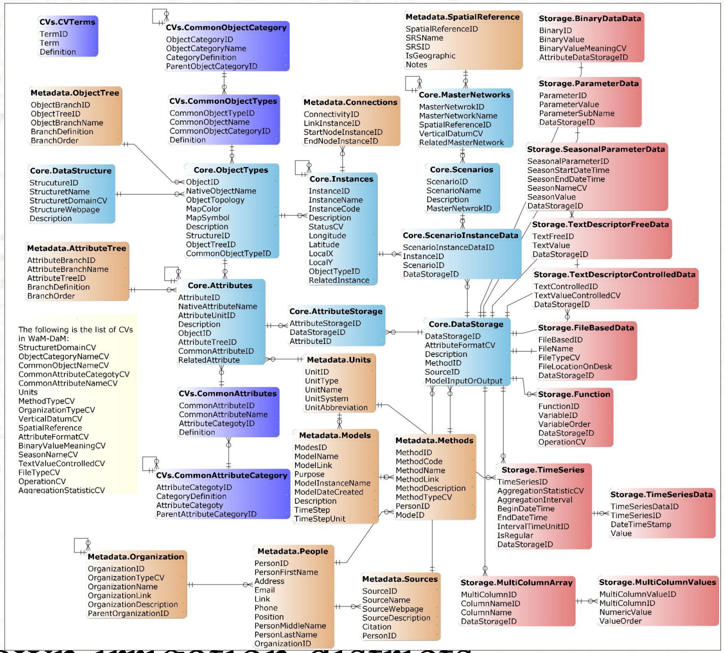


USGS Historical Climatological Network



Water Management Layer (in development)

- Data and rules stored using WaM-DaM (USU)
- ADHydro simulates reservoir operations for:
    - Storage
    - Flood control
    - Instream flows
- Diversions:
    - Irrigation canals
    - trans-basin

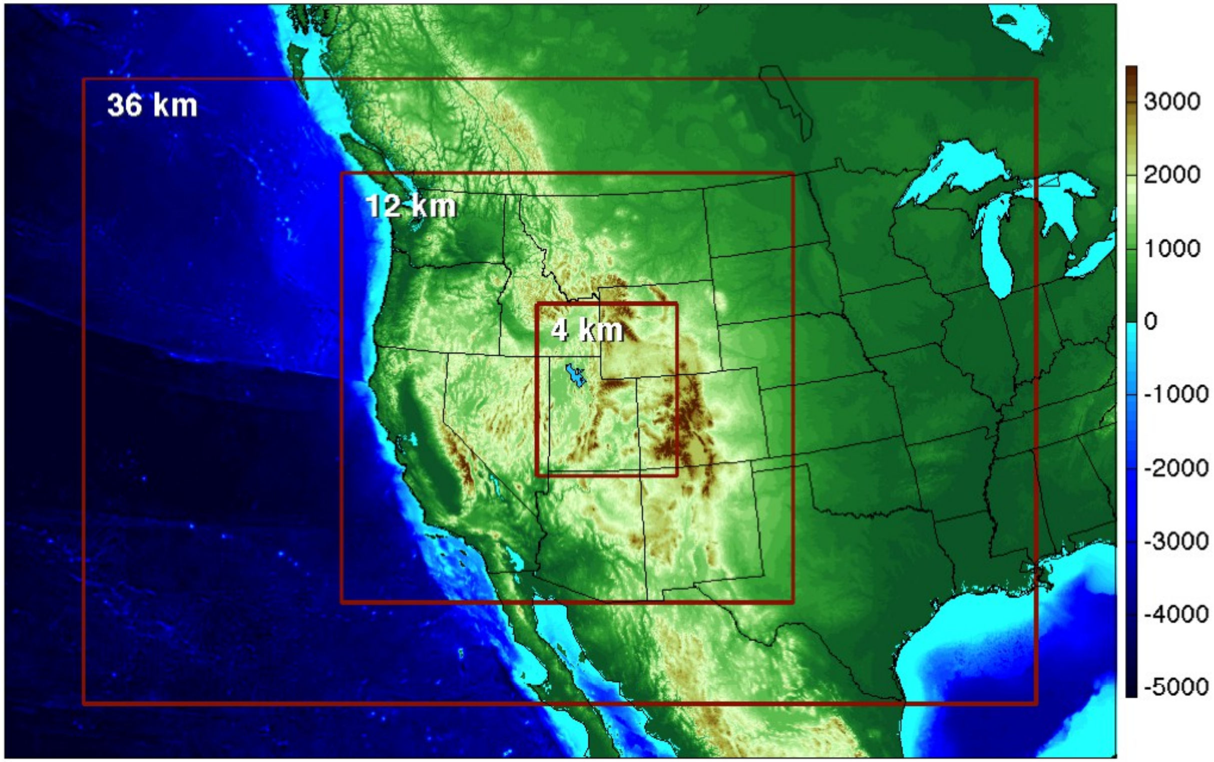


- Irrigation at the polygon level within known irrigation districts.

ADHydro Forcing: Dynamical Downscaling- U. of Utah

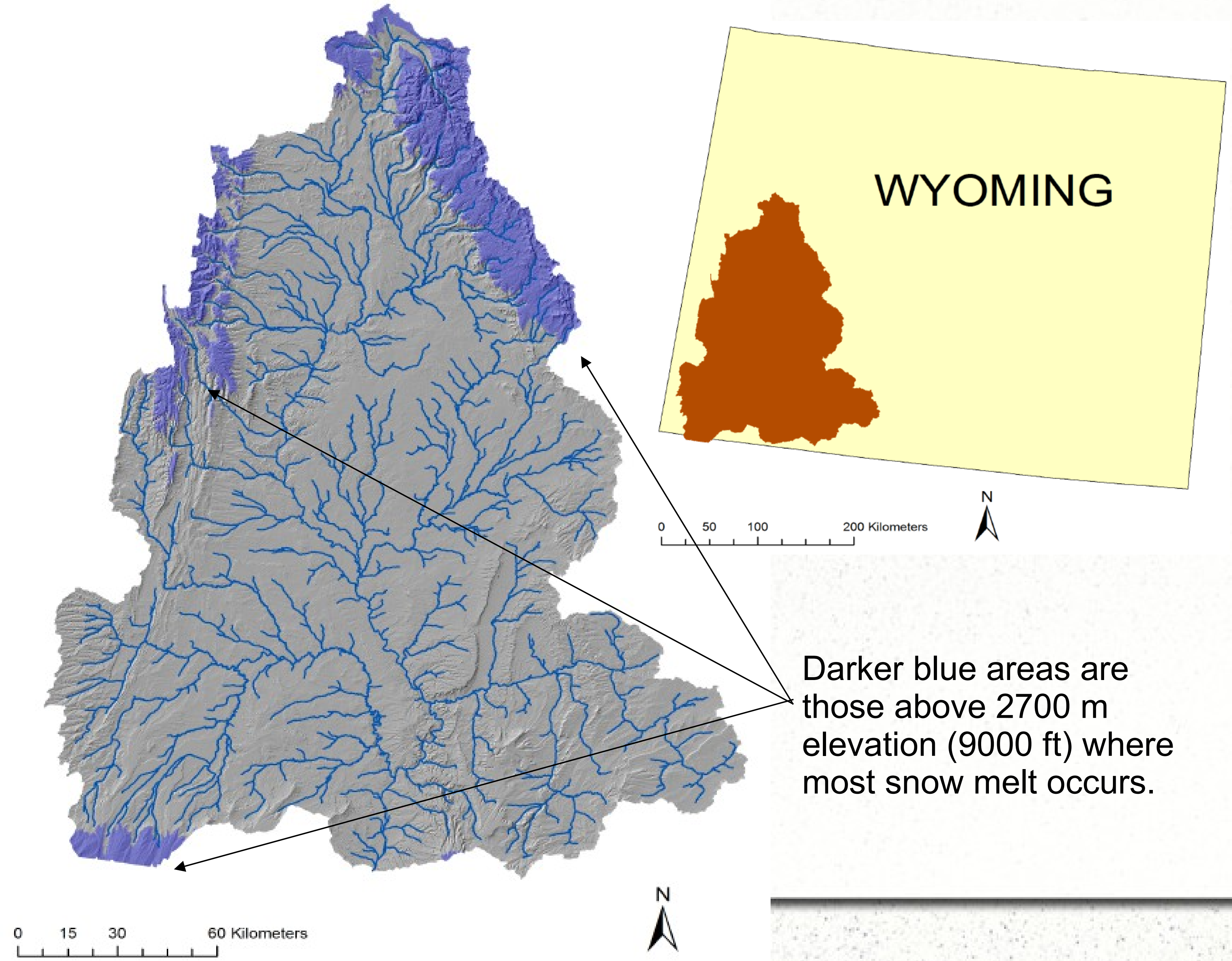
- Simulations use WRF model with three nested domains running on NWSC

Boundary conditions:
6-hourly NCEP CFSR
~36 km resolution
    1985-1994
    1995-present
CMIP5 (~1°)
    2025-2035
    2055-2065
    2085-2095
Customizations related to water:
Saturation vapor pressure
Urban irrigation
Lake model



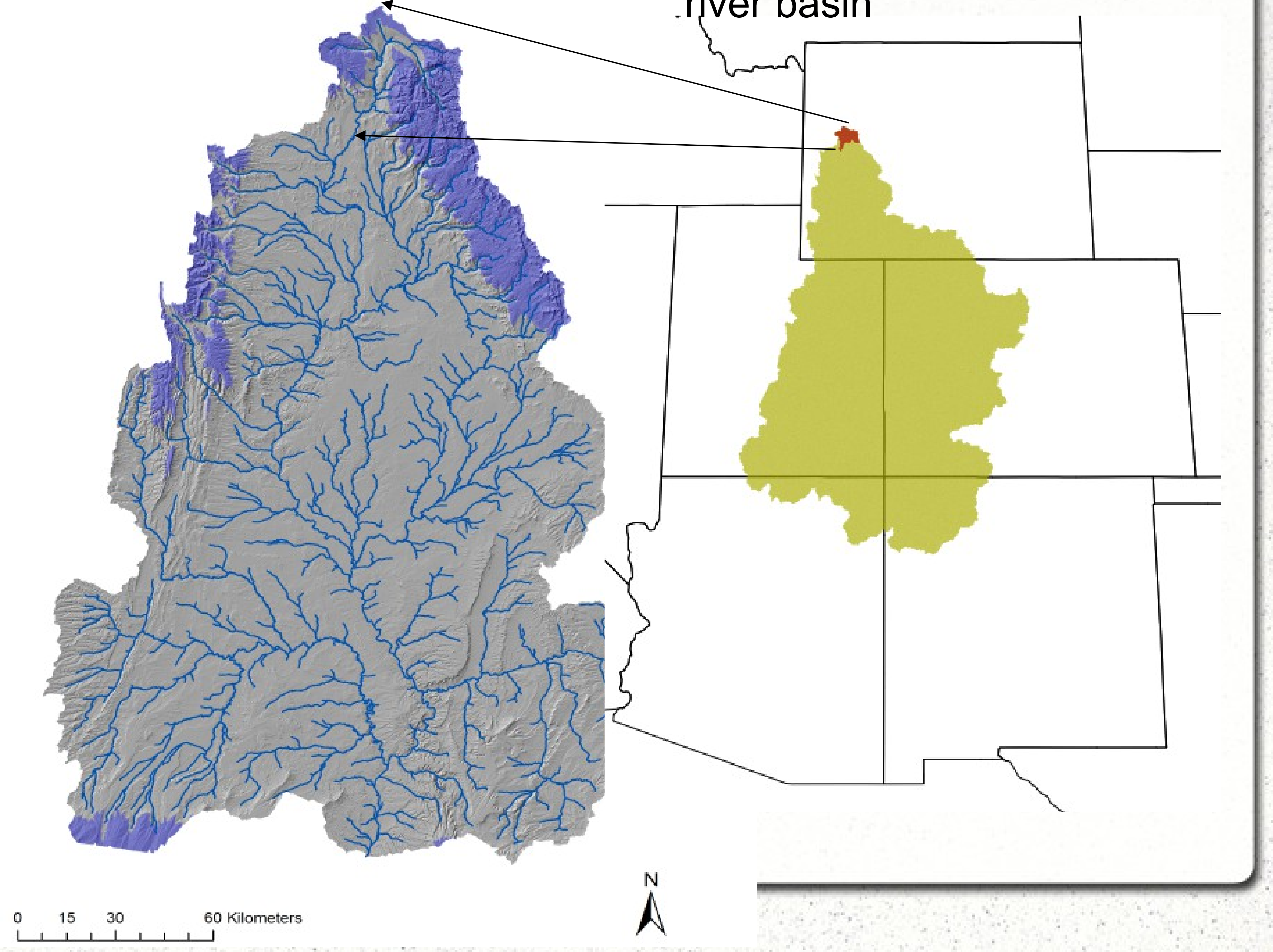
10y = 17 TB of WRF output!!!

Test Area: Green River Basin in Wyoming



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

Detailed Study Area ~1000 km^2 About 0.4% of Upper Colorado river basin



ADHydro Status

- After 28 months of development, the ADHydro code is running in parallel on Mt. Moran on 480 cores.

- We are running ADHydro using dynamically-downscaled climate simulation output from WRF produced by U of Utah group.

- ADHydro is calling NOAH-MP for ET estimates, snow capture in canopy and snow sublimation.

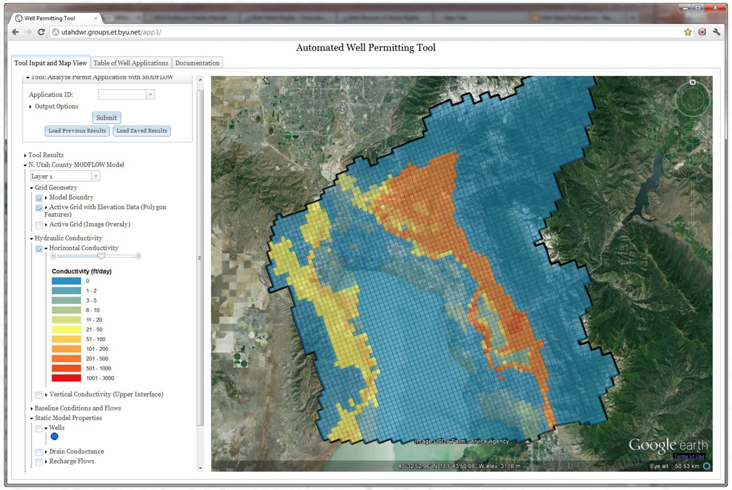
- Water management layer is under development.

- Code is being optimized to reduce run times using variable time step by location and process, with global sync time (e.g. 1 h).

ADHydro Future

- Scenario-based ADHdyro simulations using www interface by summer 2015.

  - Variable climate scenarios
  - Changes in diversion or irrigation
  - Changes in reservoir operations



- Code release, August, 2015.

- Sept. 2015, Collaborate with EPSCoR Track I project- water management layer, socioeconomics, fracture groundwater flow.

- 2015: Begin incorporating in WRF-Hydro (2-way coupling).

- 2015-2016 Collaboration with joint NOAA/NWS, USGS, USACE, National Water Center to transfer CI-WATER tools to use.

- Sustainability of ADHydro is long-term goal through UW Center for Computational Hydrology and Hydrosciences.

Thank you