Component 3:
Advance High-Resolution Hydrological Modeling

Fred Ogden, P.I.
Craig Douglas, Kristi Hansen,
Scott Miller, Ye Zhang, co-P.I.'s

Julian Zhu, Senior Personnel

Bob Steinke, Lead Software Developer

Wencong Lai, Derek Cerwinski, Hernan Moreno
Postdoctoral Associates

Leticia Pureza, Nels Frazier, Mookwan Seo, Guy Litt
graduate students

Yoshiyuki Igarashi, pre-doctoral assoc.

AAAS Review Nov. 17, 2014
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.
Motivating Example: Utah DWR Web-Based Groundwater Simulation Tool

Norm Jones, BYU
Model Output Visualization

Norm Jones, BYU
Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model

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
GSSH A 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 GSSH A using the Watershed Modeling System (WMS) software in less than one week.
A big watershed problem:

- Upper Colorado River Basin: \(280,000 \text{ km}^2 = 3.1 \times 10^8\) 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
Upper Colorado River Basin

Basin Area: 288,000 km²

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

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

plus

Mexico- 1.5 MAF/y

Note: 1 AF = 1.233 MI
Water Use in the Colorado River Basin

Numbers from the Colorado River Accounting and Water Use Report 2009.
High Altitude Complexity
Compelling socioeconomic issues

Table 1. State Population Growth as Dramatic as Municipal Growth

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>539,700</td>
<td>1,325,089</td>
<td>3,294,394</td>
<td>4,301,261</td>
<td>4,861,515</td>
</tr>
<tr>
<td>Arizona</td>
<td>122,931</td>
<td>749,587</td>
<td>3,665,228</td>
<td>5,130,652</td>
<td>6,338,755</td>
</tr>
<tr>
<td>California</td>
<td>1,485,053</td>
<td>10,586,223</td>
<td>29,760,021</td>
<td>33,871,648</td>
<td>36,553,217</td>
</tr>
<tr>
<td>Utah</td>
<td>276,749</td>
<td>688,862</td>
<td>1,722,850</td>
<td>2,233,169</td>
<td>2,645,330</td>
</tr>
<tr>
<td>Nevada</td>
<td>42,335</td>
<td>160,083</td>
<td>1,201,838</td>
<td>1,998,257</td>
<td>2,565,382</td>
</tr>
<tr>
<td>New Mexico</td>
<td>195,310</td>
<td>681,187</td>
<td>1,515,069</td>
<td>1,819,046</td>
<td>2,499,481</td>
</tr>
<tr>
<td>Wyoming</td>
<td>92,531</td>
<td>290,529</td>
<td>453,588</td>
<td>493,782</td>
<td>532,668</td>
</tr>
</tbody>
</table>

Source: U.S. Census Bureau.

Fire and land use changes:

This’ll only cost you $9 BILLION

Planned diversions:

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:

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

- 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)

\[ x = R(\lambda - \lambda_o) \cos \varphi \quad y = R \varphi \]
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:
\[
\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0
\]
(hyperbolic convective)

\[
\begin{align*}
\frac{\partial hu}{\partial t} + \frac{\partial huu}{\partial x} + \frac{\partial huv}{\partial y} &= -gh \frac{\partial z}{\partial x} - \frac{gn_x^2 u \sqrt{u^2 + v^2}}{h^{1/3}} \\
\frac{\partial hv}{\partial t} + \frac{\partial huv}{\partial x} + \frac{\partial hvv}{\partial y} &= -gh \frac{\partial z}{\partial y} - \frac{gn_y^2 v \sqrt{u^2 + v^2}}{h^{1/3}}
\end{align*}
\]

1D vadose zone flow

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

(ODE)

2D groundwater flow

\[
y S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left( K_x (H - z_b) \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y (H - z_b) \frac{\partial H}{\partial y} \right) + R
\]
(parabolic diffusive)
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
• 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)

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

- 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:

\[
\theta = \theta_r + \frac{\psi - \psi_r}{1 + \left( \frac{\alpha \psi}{\rho_w g} \right)^n \theta} \left( 1 - \frac{1}{\theta^{1/m}} \right)^m
\]

\[
K(\theta) = \theta^{1/2} \left( 1 - \left( 1 - \theta^{1/2} \right)^m \right)
\]

\[
m = 1 - 1/n \quad \theta = \frac{\theta - \theta_r}{\theta_e - \theta_r}
\]
Multi-layer T-O: Steady infiltration

6 m deep soil column:
1\textsuperscript{st} Layer: 2 m fine sand
2\textsuperscript{nd} Layer: 2 m silty clay loam
3\textsuperscript{rd} Layer: 2 m of fine sand

Lower boundary condition: Fixed water table
Multi-layer T-O: Laboratory infiltration

FIVE LAYERS
In a 3 m deep soil column

<table>
<thead>
<tr>
<th>Soil depth (m)</th>
<th>Texture</th>
<th>$K_v$ (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-1.0</td>
<td>Silt loam</td>
<td>0.01463</td>
</tr>
<tr>
<td>1.0-1.2</td>
<td>Loam</td>
<td>0.01924</td>
</tr>
<tr>
<td>1.2-1.5</td>
<td>Silt loam</td>
<td>0.01256</td>
</tr>
<tr>
<td>1.5-1.8</td>
<td>Loam</td>
<td>0.00505</td>
</tr>
<tr>
<td>1.8-3.0</td>
<td>Silt loam</td>
<td>0.01330</td>
</tr>
</tbody>
</table>
Multi-layer T-O: Five layer laboratory infiltration

Infiltration Rate & Cumulative infiltration

<table>
<thead>
<tr>
<th>Soil depth (m)</th>
<th>Texture</th>
<th>$K_s$ (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-1.0</td>
<td>Silt loam</td>
<td>0.01463</td>
</tr>
<tr>
<td>1.0-1.2</td>
<td>Loam</td>
<td>0.01924</td>
</tr>
<tr>
<td>1.2-1.5</td>
<td>Silt loam</td>
<td>0.01256</td>
</tr>
<tr>
<td>1.5-1.8</td>
<td>Loam</td>
<td>0.00505</td>
</tr>
<tr>
<td>1.8-3.0</td>
<td>Silt loam</td>
<td>0.01330</td>
</tr>
</tbody>
</table>
Talbot and Ogden 1-D Infiltration (2008), as modified by Ogden et al. (in review, WRR) Column-scale validation (after Childs and Poulosillis 1962):
After Childs and Poulouvasillis (1962):

Raised and lowered water table with specified input flux.

| Flux intensity (cm/hr) | Water table velocity
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
</tr>
<tr>
<td>2.356</td>
<td>13.2</td>
</tr>
<tr>
<td>4.710</td>
<td></td>
</tr>
<tr>
<td>7.589</td>
<td></td>
</tr>
<tr>
<td>16.090</td>
<td></td>
</tr>
<tr>
<td>27.6</td>
<td>Test 2</td>
</tr>
<tr>
<td>55.2</td>
<td>Test 3</td>
</tr>
</tbody>
</table>
Ogden et al. (WRR in review):

\[
\frac{dZ_j}{dt} = \frac{K(\theta_j) - K(\theta_i)}{(\theta_j - \theta_i)} \left( \frac{\Psi(\theta_j)}{Z_j} - 1 \right)
\]
Ogden et al. (WRR in review):

![Graphs showing T-O NSE and T-O |PBIAS|](image-url)
“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 $\Delta Z$ is sufficient to describe state of the system.
- Considerable speedup is obtained with full physics (infiltration, slugs, groundwater).
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. Each simulation ran for a week using the above synthetic rainfall series.

<table>
<thead>
<tr>
<th>Rainfall</th>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start (hour)</td>
<td>Stop (hour)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>12.0</td>
<td>12.1</td>
</tr>
<tr>
<td>3</td>
<td>26.0</td>
<td>26.1</td>
</tr>
<tr>
<td>4</td>
<td>37.0</td>
<td>37.1</td>
</tr>
<tr>
<td>5</td>
<td>49.0</td>
<td>49.2</td>
</tr>
<tr>
<td>6</td>
<td>62.0</td>
<td>62.1</td>
</tr>
<tr>
<td>7</td>
<td>70.0</td>
<td>70.1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Timing</th>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linked List Model</td>
<td>74.526</td>
<td>58.164</td>
</tr>
<tr>
<td>Matrix Model</td>
<td>13.820</td>
<td>20.415</td>
</tr>
<tr>
<td>Vector Model (full)</td>
<td>0.645</td>
<td>0.601</td>
</tr>
<tr>
<td>Vector Model (only slugs)</td>
<td>0.089735</td>
<td>0.089465</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speedup</th>
<th>Example 1</th>
<th>Example 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linked List Model</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Matrix Model</td>
<td>5.39</td>
<td>2.85</td>
</tr>
<tr>
<td>Vector Model (full)</td>
<td>115.54</td>
<td>96.78</td>
</tr>
<tr>
<td>Vector Model (only slugs)</td>
<td>830.51</td>
<td>650.13</td>
</tr>
</tbody>
</table>
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

Reservoirs and management → I.D. Lakes & Links

Scaling laws → Land use/cover soils maps

Channel inputs → Soil thickness model

Surficial aquifer maps → Mesh Params.
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

2y flow

Q = 0.80594A - 0.02410, R^2 = 0.92743
Q = 0.74161A - 0.23836, R^2 = 0.97617
Q = 0.74806A - 0.67825, R^2 = 0.94068
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!!!
Darker blue areas are those above 2700 m elevation (9000 ft) where most snow melt occurs.
Darker blue areas are those above 2700 m
elevation (9000 ft) where most snow melt occurs.

Detailed Study Area ~1000 km²
About 0.4% of Upper Colorado
river basin
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).
- Scenario-based ADHydro simulations using www interface by summer 2015.
  - Variable climate scenarios
  - Changes in diversion or irrigation
  - Changes in reservoir operations


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


- 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