ADHydro: High-Resolution Process Based Hydrological Modeling in a High Performance Computing Environment

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3rd CUAHSI Hydroinformatics Conference and 4th year CI-WATER project meeting
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Project Staff & Students

Drs. Kristi Hansen, Craig Douglas, Scott Miller, Ye Zhang co-I's
Dr. Robert Steinke: Lead software developer
Dr. Wencong Lai: Hydrodynamics
Dr. Hernan Moreno: Land-atmosphere interaction
Mr. Yoshiyuki Igarashi: Socio-econ./water mgmt.
Nels Frazier (M.S.): workflows, scaling/parameter est.
Leticia Pureza (M.S.): workflows, NOAA-MP coupling, testing
Yanyan Cheng (Ph.D): formulation additions/testing
Jason Regina (M.S./Ph.D.) formulation additions/testing
Located in Laramie, Pop. 30,000
#1-Ranked University in Terms of:

- Elevation (7200 ft)
- Percentage of students from tiny high schools
- Petaflops per capita thanks to NWSC

Center for Computational Hydrology and Hydrosciences, founded 2013.

New Engineering Initiative ($18M this biennium) plus new 60,000 sq. ft building.
Computing Resources:
Mt. Moran Campus Cluster
3480 i7 cores
400 TB storage

NCAR-Wyoming Supercomputing Center (NWSC)
~74,000 i7 cores

UWyo allocation 20%
A Digital Divide

Engineers/Researchers
- Experimentalists
- Modelers/forecasters

HPC Specialists

```
#!/bin/bash
vi
chmod
grep
awk
mpiexec

#PBS -l nodes=4:ppn=8
```
CI-WATER Project

- NSF RII Track 2 Cyberinfrastructure Cooperative Agreement joint between NSF EPSCoR and Utah and Wyoming EPSCoR jurisdictions. Total budget $6.0M

- Focused on acquisition of hardware, development of software, capacity building, education, and outreach.

Project Objectives:

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.
Team and Partners

U. of Utah
- Data Storage
- Utah Outreach
- Urban Hydrology
- Climate simulations and downscaling

U. of Wyoming
- Hydrologic Modeling
- Software Engineering
- HPC, Wyoming Outreach

Utah State U.
- Hydrologic Modeling
- Hydrologic Information Systems
- Water Resources Decision Support

BYU
- Hydrologic Modeling
- Geospatial data models
- Integrated modeling software

NCAR Research Applications Lab.

US Army Corps of Engineers

US National Water Center

NWSC
- Hydrologic Modeling
- Software Engineering
- HPC, Wyoming Outreach
Enhance access to high-performance computing for water resources research, engineering, and management.
Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model

http://www.gsshawiki.com
GSSHA

- Square grid (5 to 90 m typical grid size)
- Multi-solver.
- Multi-physics
- 2D overland flow, wetland and groundwater flow
- 1D channel routing with hydraulic structures
- Richards’ Eqn. or Green-Ampt Redistribution coupling between overland flow and groundwater
- Erosion/deposition, sediment transport, nutrients

GSSHA is an excellent hydrologic engineering tool.
GSSHA Applications

Supported by the DoD Watershed Modeling System (WMS)
- 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 Applications

Storm surge GSSHA simulation output (U.S. Army Corps of Engineers, Coastal & Hydraulics Laboratory, ERDC)
GSSHA Model Simulations

We have published numerous papers showing importance of:

- Runoff generation mechanism
- Where things are located in the watershed
- Soils hydraulic parameters

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

But- GSSHA is not efficient for simulating LARGE watersheds because of its square grid formulation.
A LARGE watershed problem:
- Upper Colorado River Basin: 280,000 km$^2$
- $3.1 \times 10^8$ grids at 30 m square grid size
- High resolution important in mountains
- Low resolution in broad and extensive basins
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
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 coming decades?
I DON'T ALWAYS MODEL HUGE WATERSHEDS

BUT WHEN I DO, I USE AN UNSTRUCTURED MESH AND A SUPERCOMPUTER
Interrupted Sinusoidal Projection

- Preserves area perfectly
- Lines of latitude are horizontal lines
- Longitudes converge towards the pole
- Can describe Amazon basin with minimal distortion
- Inset shows 10 m Digital Elevation Model (32 GB)
Quasi-3D variable resolution large watershed model on an unstructured grid
High Altitude Complexity
Diverse Process-Based Runoff Generation

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

1D vadose zone flow
\[ \left( \frac{dz}{d\theta} \right)_\theta = \frac{\partial K |\theta|}{\partial \theta} \left( 1 + \frac{\partial \psi |\theta|}{\partial z} \right) \]
(Ogden et al. 2015 ODE)

2D groundwater flow
\[ S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left( K_x (H - z_b) \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y (H - z_b) \frac{\partial H}{\partial y} \right) + R \]
(parabolic diffusive)
Numerical model

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

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

\[
\int \frac{\partial U}{\partial t} d\Omega + \oint \nabla \cdot F d\Gamma = \int S d\Omega
\]

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

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

Upwind Riemann solver for convective flux in overland flow

Central difference for diffusion term in groundwater equation
1-D Finite water-content infiltration Ogden et al. (2015)

\[ \frac{dz_j}{dt} = \frac{K(\theta_{d}) - K(\theta_{i})}{\theta_{d} - \theta_{i}} \left( 1 + \frac{G_{eff} + h_{p}}{z_{j}} \right) \]

\[ \frac{dz_j}{dt} = \frac{K(\theta_{j}) - K(\theta_{j-1})}{\Delta\theta} \]

\[ \frac{dH_j}{dt} = \frac{K(\theta_{j}) - K(\theta_{i})}{\theta_{j} - \theta_{i}} \left( \frac{|\psi(\theta_{j})|}{H_{j}} - 1 \right) \]

8 month simulation with 263 cm of rainfall and 1m depth to water table.
“GARTO” Scheme (Lai, Ogden, Steinke, Talbot, WRR 2015), 200 times faster than T-O and up to 2000 times faster than Richards' (1931) equation with guaranteed mass conservation.

Infiltration: Green & Ampt with Redistribution (GAR) (Ogden & Saghaian 1997) enhanced.

Finite Water Content solution (T-O) (Ogden et al., WRR 2015) 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, arithmetic, AND guaranteed to conserve mass.

- fully coupled surface to groundwater table
Model Design Philosophy

- Well defined and documented Application Programming Interface (API)

- Written in C with C++ and Fortran wrappers needed to call NOAH-MP.

- Parallelized using CHARM++ object-oriented run time system, with optional 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
Upper Colorado River Stream Network

- TauDEM verified using 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
Mesh/Channel work flow (simplified)

DEM → TauDEM → GIS- Vertex Thinning

Channel network → Triangle- mesh generation

I.D. Lakes & Links

Land use/cover soils maps

Reservoirs and management → Scaling laws → I.D. Lakes & Links

Soil thickness model

Surficial aquifer maps → Mesh Params.
Conclusions

• We have created a quasi-3D variable resolution HPC large watershed simulator that we call ADHydro.

• The model uses state-of-the-art RELIABLE vadose zone solver that is many many times faster than Richards' equation.

• Key features of the model include:
  • Water management layer.
  • NOAH-MP land surface scheme.
  • Forced by WRF
  • Load balancing provided by CHARM++

• ADHydro Workshop, Friday, July 17, NWC.
Acknowledgements

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References


