Representing human influence in CESM: Global testing of a river routing and water management

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Human activities can influence the water cycle directly

- Globally, about 15% of the total annual river runoff is stored behind dams (Gornitz, 2000)
- Agriculture consumes about 87% of global fresh water withdrawal by humans
- Irrigation increases water vapor flows from land by comparable amount as reduction by deforestation globally (Gordon et al. 2005)

Global reservoirs

Global irrigation areas

Lehner et al. 2008

Siebert et al. 2005
Modeling the effects of water use and water management

- Improve and add new capabilities in Community Land Model (CLM) to represent hydrology and human – water cycle interactions in Earth System Model.
Hillslope routing accounts for event dynamics and impacts of overland flow on soil erosion, nutrient loading, etc.

Sub-network routing: scale adaptive across different resolutions to reduce scale dependence

Main channel routing: explicit estimation of in-stream status (velocity, water depth, etc).

(Li et al., JHM, 2013)
Global testing of MOSART

- CLM-MOSART driven by 4 global atmospheric forcing datasets (all 3-hourly and at $1^\circ$ resolution) to evaluate uncertainty due to forcing inputs
  - I2000 NCAR benchmarking forcing
  - Princeton forcing: rescale precipitation to match GPCC
  - Princeton forcing: Rescale precipitation to match GPCP
  - Similar to GPCC, but with HOP data for the Amazon

- CLM-MOSART driven by I2000, but with 5 variations of model structure to evaluate their impacts
  - All MOSART features
  - Turn off within grid routing
  - Further set channel velocity constant in time
  - Further set channel velocity constant in space ($\sim 0.21 \text{ m/s}$)
  - Channel velocity = 0.35 m/s from RTM

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Impacts of model structure

- Within grid routing has small effects
- All other factors, temporal and spatial variability of channel velocity and values of constant channel velocity, are important and affect timing of streamflow
- Temporal variability appears most important
- Effects seem to be larger in snow melt driven basins
Model structure does not affect mean annual flow, but its effects on annual maximum flood are very clear.

Reducing temporal and spatial variability of channel velocity generally reduces flood peak.

Using a higher constant value of channel velocity (0.35 vs 0.21) leads to higher flood peak.
Impacts of atmospheric forcing

- Forcing uncertainty has larger impacts on mean annual flow
- Forcing mostly affects monthly peak rather than timing
- Statistical tests indicate that only simulation driven by GPCP is statistically different from others
Generic operating rules

- Each reservoir has multiple purposes, separated into either:
  i) Flood control and other, ii) Irrigation, or iii) Joint irrigation and flood control
- Generic Release targets* and storage targets** for each purpose
- Configured independently for each reservoir based on hydro-climatological conditions and demand associated with the reservoir

(Voisin et al. HESS, 2013)

* Hanasaki et al. 2006, 2008
  Doell et al. 2009
* Biemans et al. 2011
** Voisin et al. 2013

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- No optimizer
- No forward simulation
- Large scale - global

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Monthly release targets at Grand Coulee for different rules scenarios
Global reservoirs and primary purposes

1,164 reservoirs; 1,425,577 Million Cubic Meters

Irrigation

Flood control

328 reservoirs; 799,701 Million Cubic Meters

Evaluate global simulations with in situ and satellite data

What sources of uncertainty can be reduced using satellite observations?

472 reservoirs; 762,924 Million Cubic Meters

Irrigation + Flood control
Reservoirs used in model evaluation

**Fort Peck Reservoir:**
Missouri River
23.6 km$^3$ capacity
Combined operation rules

**Oahe Reservoir:**
Missouri River
29.1 km$^3$ capacity
Combined operation rules

**Glen Canyon Dam**
Colorado River (Lake Powell)
25.1 km$^3$ capacity
Irrigation rules

**Hoover Dam**
Colorado River (Lake Mead)
36.7 km$^3$ capacity
Irrigation rules

1950-2004 mean annual flow (cms)
- 0
- 1 - 10
- 11 - 100
- 101 - 200
- 201 - 500
- 501 - 151,000

reservoir
Evaluate WM Reservoir Storage Simulations

- Lack seasonal variations
- Lack interannual and decadal variations
- Lack water transfer between basins

![Storage graphs for Fort Peck, Glen Canyon, Oahe, Hoover](image-url)
Cascade of uncertainties: opportunities for data to inform models

Errors in hydrologic simulations
(model, forcing)
- VIC with station-based forcing
- CLM with GFDL forcing

Errors in water demand (space, time, type)
- Irrigation demand from IAM
- Irrigation demand from ESM
- Total water demand from IAM

Fort Peck
Same total demand (IAM)

Oahe
Same CLM flow forced with GFDL

Storage (million m³)
Bias, seasonality, decadal variability

IAM = integrated assessment model
ESM = Earth system model

Errors in reservoir operations
- Irrigation rules
- Flood Control rules
- Combined Irrigation and Flood Control rules
- Obs
Comparison of WM simulated storage with in-situ and satellite observations

- MODIS: imagery, observations of reservoir extent over time
- ENVISAT: altimetry, observations of height of water over time
- Derive area-elevation relationship: time series of reservoir storage

(Gao et al. 2012 WWR)

Good agreement between satellite and observations
Simulations can be improved by defining reservoir storage targets based on satellite data.
Enabled by comprehensive hydrography datasets, MOSART can be applied globally at multiple resolutions.

Temporal and spatial variability of channel velocity has large influence on timing of streamflow and annual maximum flood – simulation differences due to model structure uncertainty are all statistically significant.

Forcing uncertainty for the datasets examined affects mainly mean annual flow, and GPCP is an outlier compared to other datasets.

Previously tested over the Columbia River Basin, WM has now been applied globally at 0.5 degree resolution using generic reservoir operating rules.

Several sources of uncertainty have been identified in the WM simulations – satellite data can be used to constrain storage for large reservoirs.
Modeling stream temperature in MOSART

Water temperature in tributary channels

Water temperature in main channels
Topographic parameters derived from HydroSHEDS DEM, including flow direction, channel length and slope etc. (Huan Wu at UMD)

Manning’s roughness derived for overland and channel flow separately based on land cover (Augusto Getirana at NASA)

Channel width and depth derived based on empirical Hydraulic Geometry relationships (Augusto Getirana at NASA)

All parameters available at 1/16, 1/10, 1/8, ¼, ½, 1 and 2 degree resolutions

Wu et al., WRR, 2012; Getirana et al., JHM, 2012