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River and Lake

The mizuRoute river model in CESM

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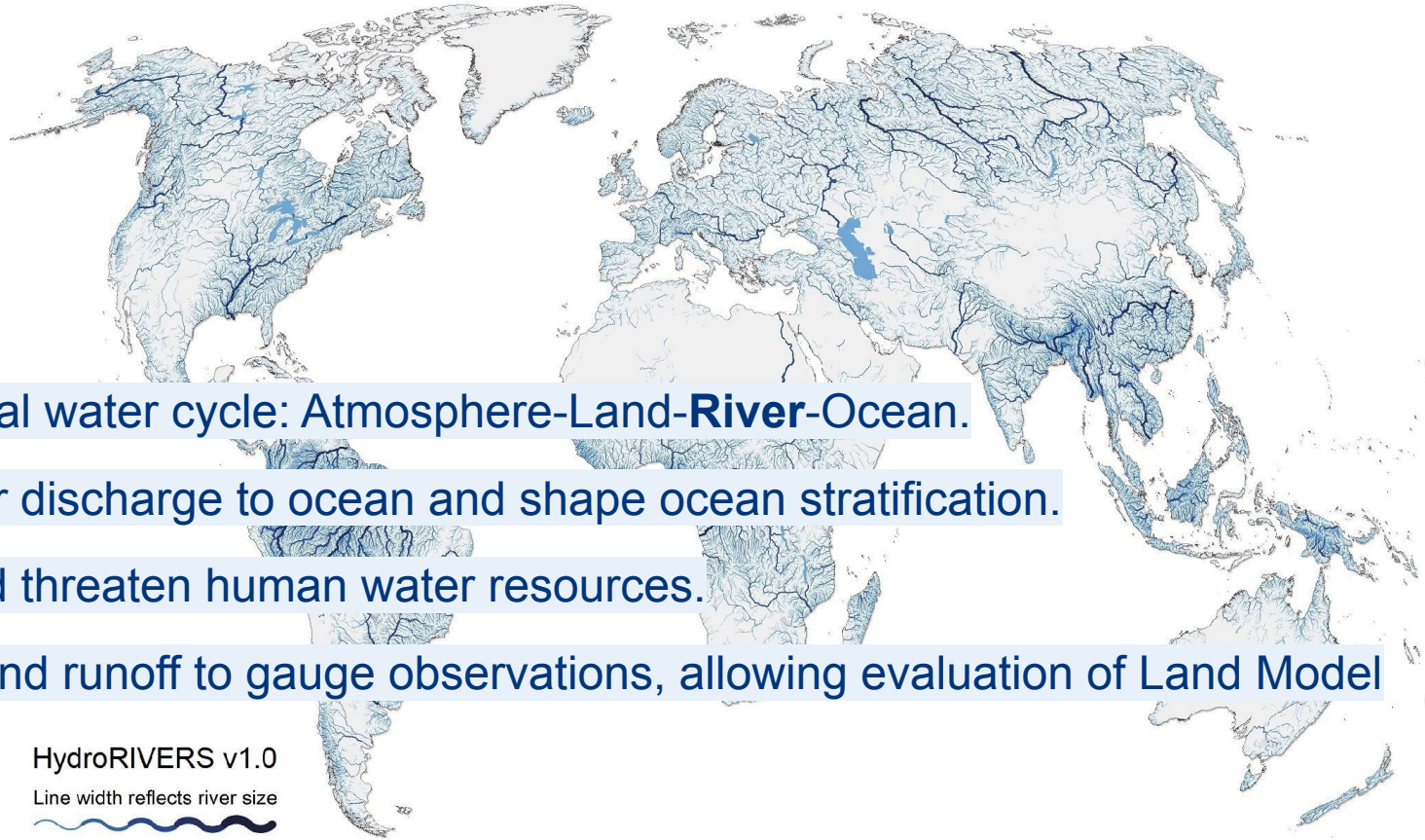
2026 CTSM Tutorial

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Outline

1. **Why rivers matter**
   Roles of rivers in the Earth system and hydrologic applications
2. **mizuRoute in CESM**
   A model component in CESM
3. **River model mechanics**
   How the model represents river network, navigates it, and route water from upstream to downstream.
4. **Recent added capabilities**
   Lake and irrigation water takes; river tracer
5. **Application: streamflow evaluation**
   Routing runoff to river gauges for land model evaluation
6. **Resources**
   Documentation, and GitHub location

Why rivers matter in the Earth System



Close global water cycle: Atmosphere-Land-**River**-Ocean.

Freshwater discharge to ocean and shape ocean stratification.

Supply and threaten human water resources.

Connect land runoff to gauge observations, allowing evaluation of Land Model hydrology.

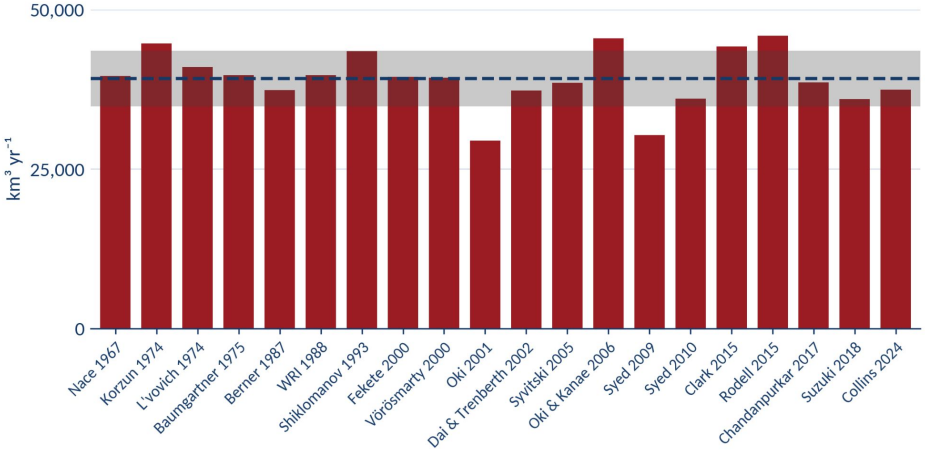
Global river discharge and storage

Published estimates (gauges-, satellite- and model-based)

River discharge to oceans

39,200 ± 4,400 km³ yr⁻¹

mean ± 1 s.d. of 20 published estimates

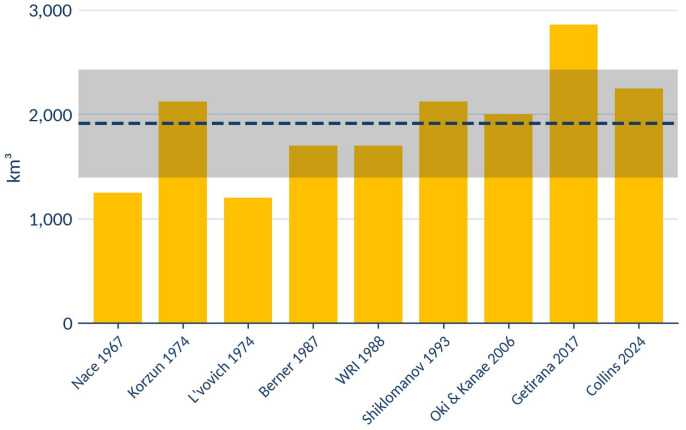


29-38% of land annual precipitation

Global mean river storage

1,910 ± 520 km³

mean ± 1 s.d. of 9 published estimates



Major uncertainty sources:

- Observations: Sparse and biased streamflow gauges; satellite budgets requires evaporation and precipitation data.
- Land model uncertainty: Land-surface runoff is poorly observed; estimates vary among land models.
- River model uncertainty: Flow velocity estimates control inferred discharge and storage.

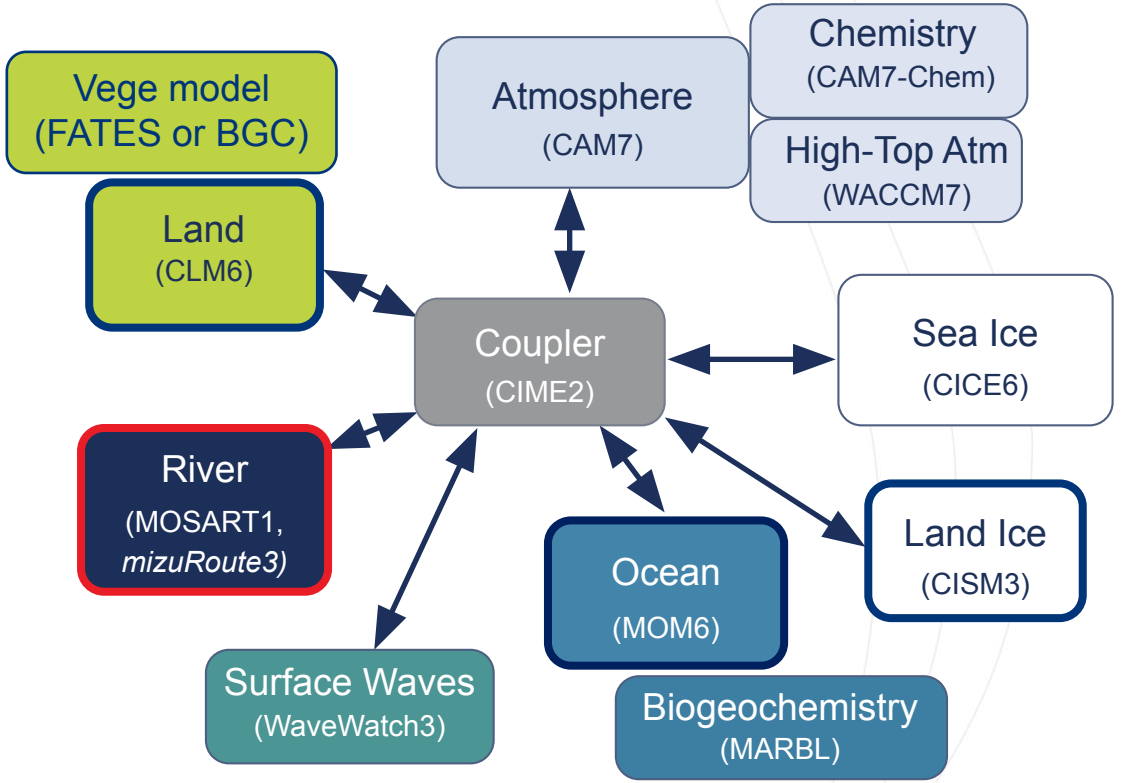
Collins et al. (2024), Nat. Geosci, 17, 433–439, https://doi.org/10.1038/s41561-024-01421-5

Where is the river model in CESM or CTSM

River model is one of independent CESM components

River component exchanges with:

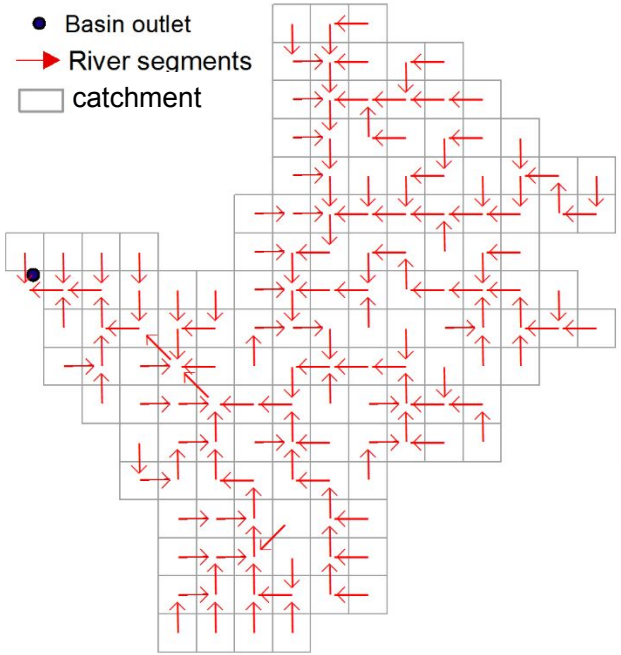
- Land
  - total runoff (land → river)
  - irrigation demand (land → river)
  - river water storage (river → land)
  - flood volume (river → land)
- Land Ice (Fully-coupled only)
  - Ice runoff (land-ice → river)
- Ocean (Fully-coupled only)
  - streamflow at river outlet (river → ocean)



Thick blue outline: exchange with river

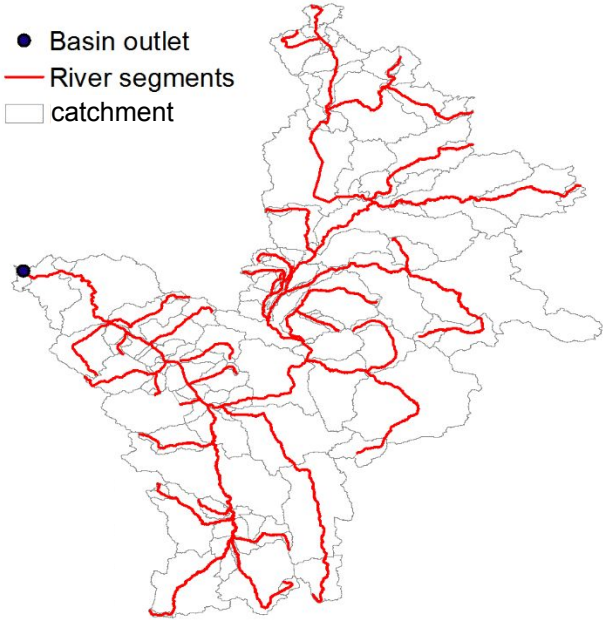
How is river network represented in model?

Gridded river network



- Traditionally used for many ESMs (e.g., MOSART).
- Water moves to one of 8 neighboring grid cells.

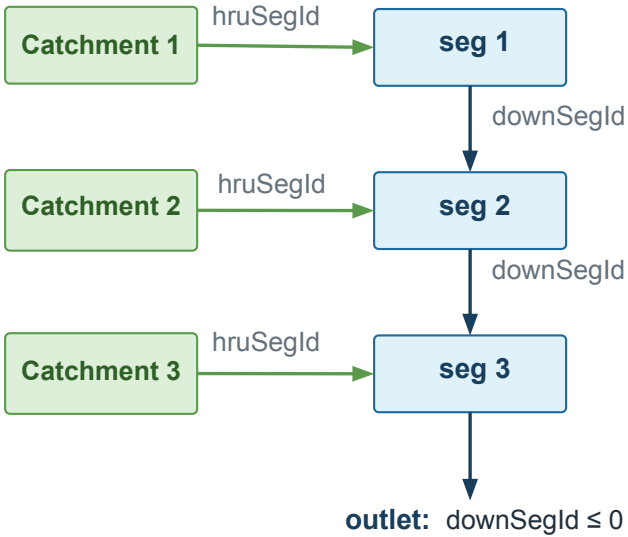
Vector river network

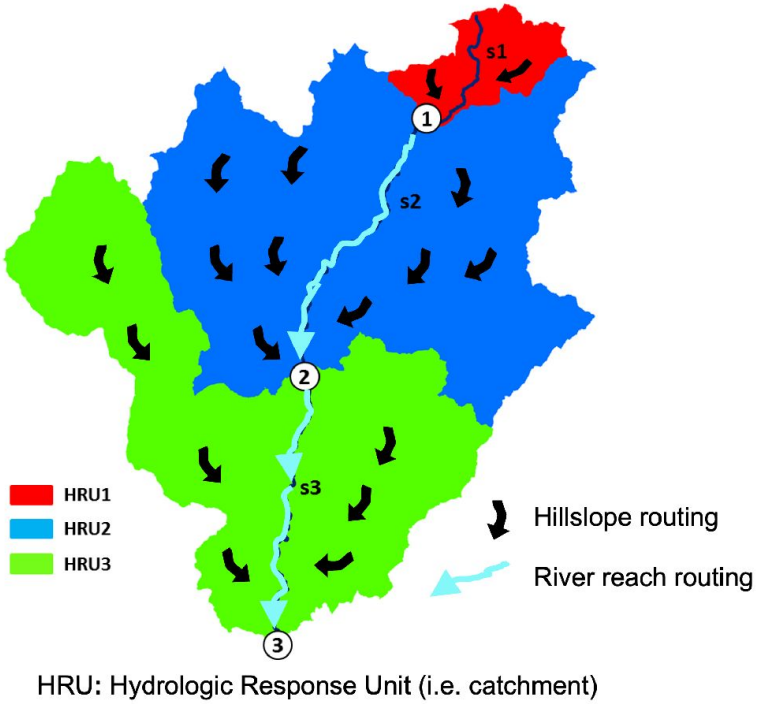


- Realistic catchment and river reaches.
- Water moves downstream, reach by reach.

Moving water through river network

Catchment and river segment connection

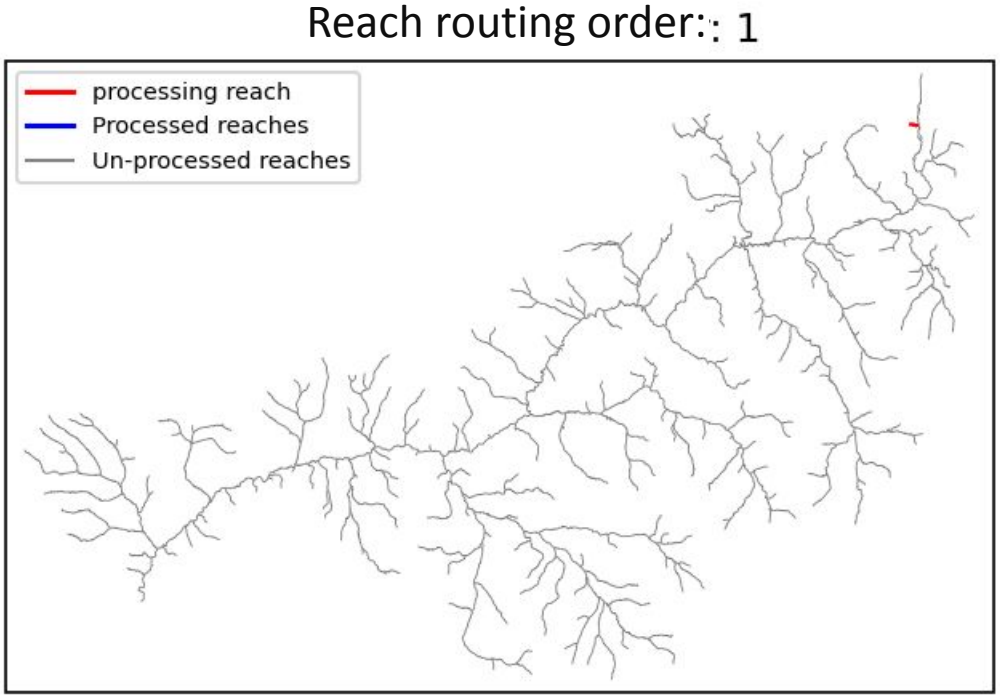




HRU: Hydrologic Response Unit (i.e. catchment)

Navigate river network

Use **segID** and **downSegID** to build routing order from headwater to outlet internally.

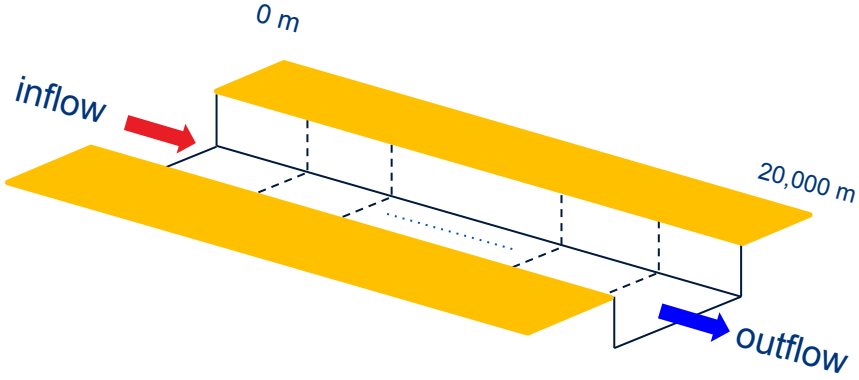


Solving physical flow equation for each reach

Advection-diffusion equation

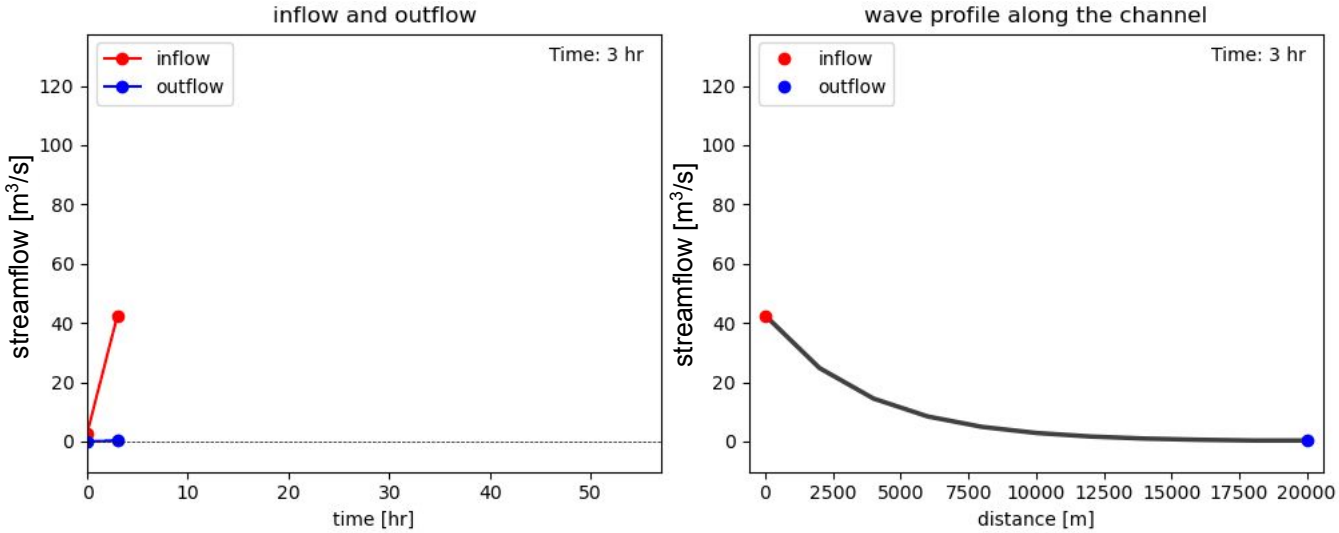
$$\frac{\partial Q}{\partial t} + C\frac{\partial Q}{\partial x} = D\frac{\partial^2 Q}{\partial x^2}$$

Solve fully implicitly at 20 sub-reaches



Routing synthetic inflow with one rectangular reach

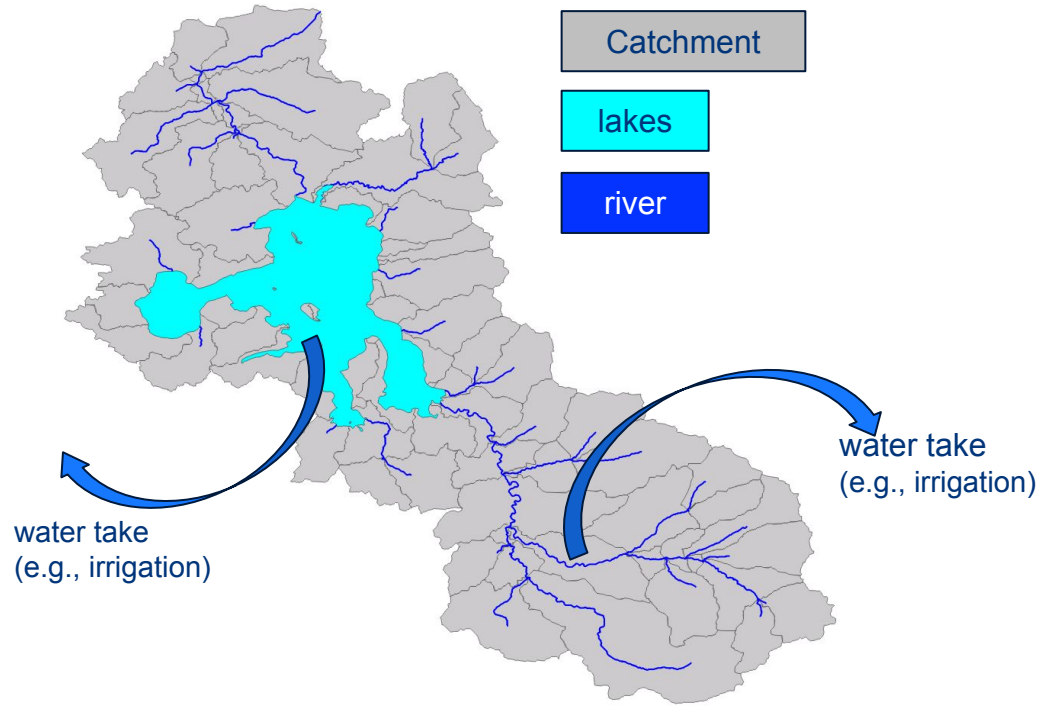
- L=20,000 m
- w=100 m (rectangular channel width)
- S_0=0.0001 (reach slope)
- n=0.035 (river-bed friction)

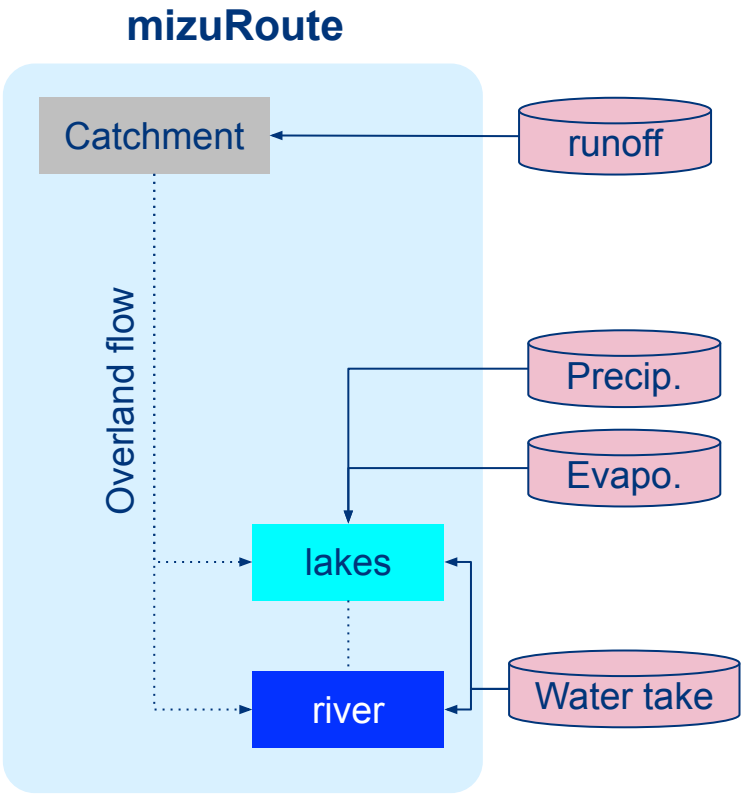


Additional features

- River – Lake routing
- River tracer

Lakes and irrigation take modify the natural flow





Storage–outflow relationships delay peaks and change seasonal flow timing.

Irrigation water take is based on irrigation demand from land model

New capability: tracers

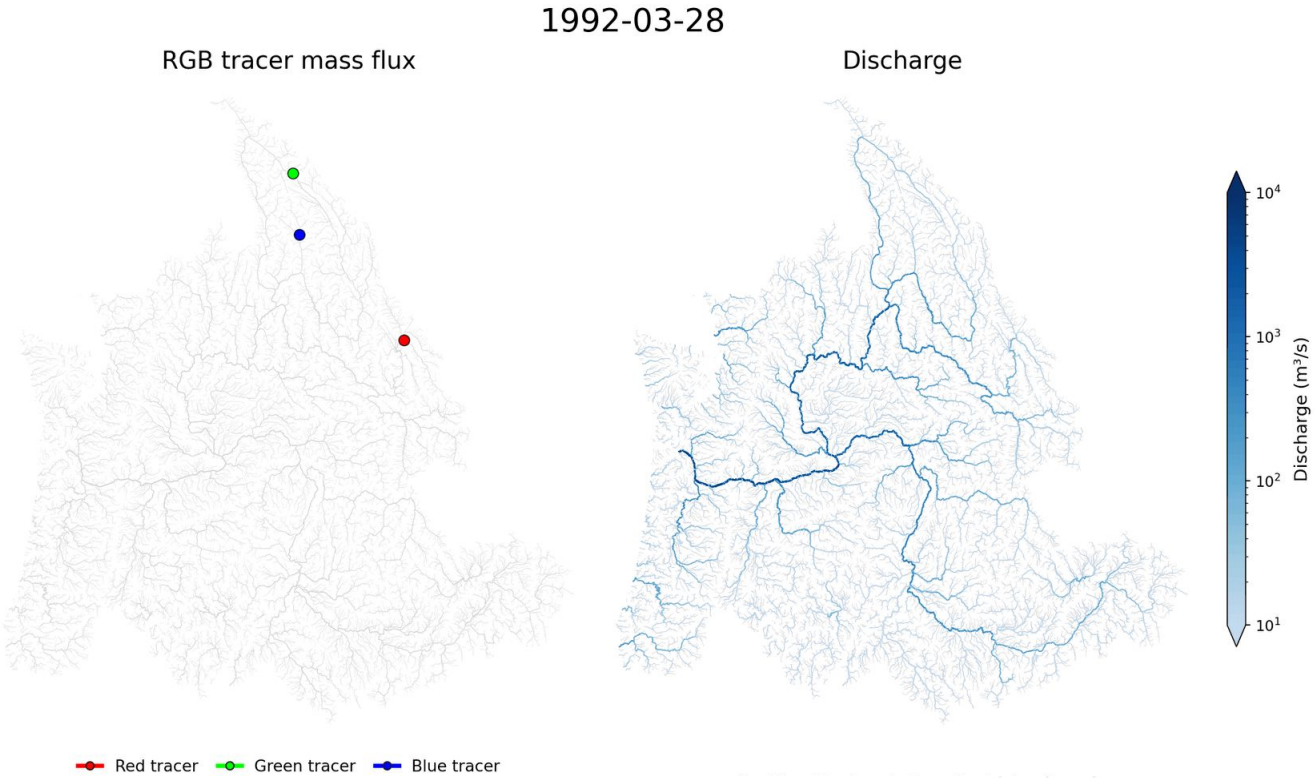
Advection-diffusion equation: the same physics equation as streamflow

Synthetic experiment:

Add 100mg/s of Red, Green, Blue dyes in a river reach on 1992/4/1 (for one day period)

Science goals

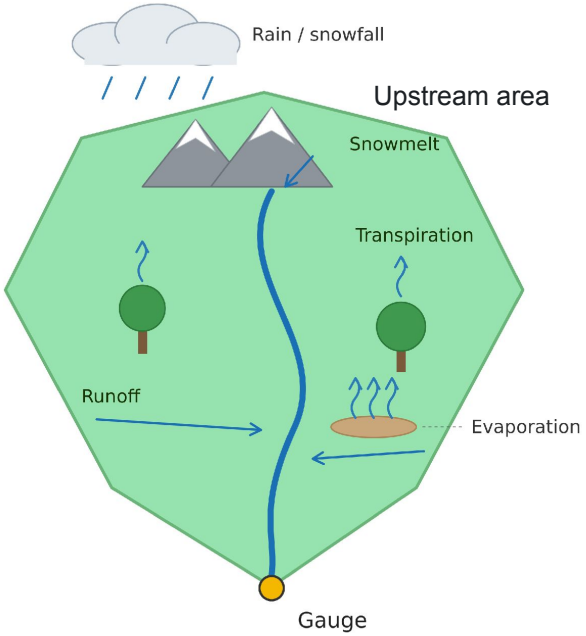
- Dissolve carbon transport (Carbon cycle)
- Water isotopes tracking
- Heat transfer (stream temperature)

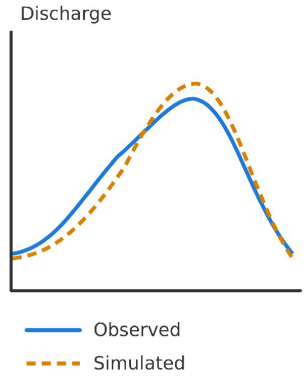


Common application: Hydrologic evaluation

Why route to gauges?

- Evaluate land-surface hydrology.
- Runoff isn't observed at grid scale, but streamflow is observed at point in river.
- Streamflow is integrated runoff over all upstream area of a gauge.
- Provide basin-scale metrics for water-resource studies





Example of hydrologic evaluations

High-resolution (1/8°) CTSM CONUS-wide hydrology evaluation

CTSM + mizuRoute, five configurations, ~2,300 stream gauges, 227,247 MERIT-Hydro river reaches

Which CTSM configuration choices most influence fine-scale CONUS land and hydrology simulation performance, and how do the resulting simulations compare with observations?

Configuration choices

CTSM offers satellite phenology (SP) or prognostic phenology, static or evolving land cover, irrigation and hillslope hydrology, but these choices had not been evaluated at fine scale for CTSM over CONUS.

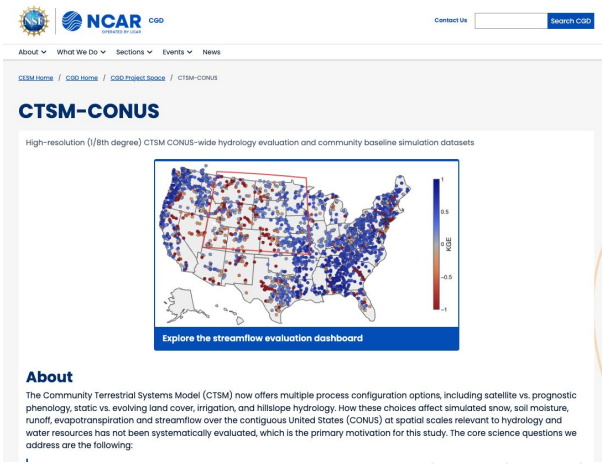
Configuration	Change	Contrast shown
Control	SP phenology, static 2000 land cover, irrigation off, no hillslope	baseline
Irrigation	irrigate = .true.	irrigation_on - control
Evolving land cover	Transient land use 1850–2023; irrigation on by default	evolving_landcover - irrigation_on
Hillslope	Hillslope hydrology with lateral flow and hillslope routing	hillslope_eval - control
Prognostic phenology	Prognostic (BGC) phenology in place of SP	prog_phenology - control

Example of hydrologic evaluations

High-resolution (1/8°) CTSM CONUS-wide hydrology evaluation

CTSM + mizuRoute, five configurations, ~2,300 stream gauges, 227,247 MERIT-Hydro river reaches

Item	Setting
Model	CTSM ctsm5.4.049 (CLM6.0 physics)
Grid	NLDAS-2 0.125° (224 × 464), 80,439 land cells
River network	MERIT-Hydro, 227,247 reaches
Forcing	NLDAS-2, 1980–2018
Soil	20 layers, 8.5 m deep
Tuning	No NLDAS-2 tuning exists; falls back to the GSWP3 tuning
Spinup	22 years (24 for hillslope) of transient NLDAS-2 from 1980; control has 60 (22 + one extra 38-year pass)
Evaluation	Hybrid restart, 38 water years (Oct 1980 – Sep 2018); monthly output
Routing	MizuRoute v3.1.1



https://project.cgd.ucar.edu/projects/ctsm-conus/

Scan for the project page

Resources for mizuRoute

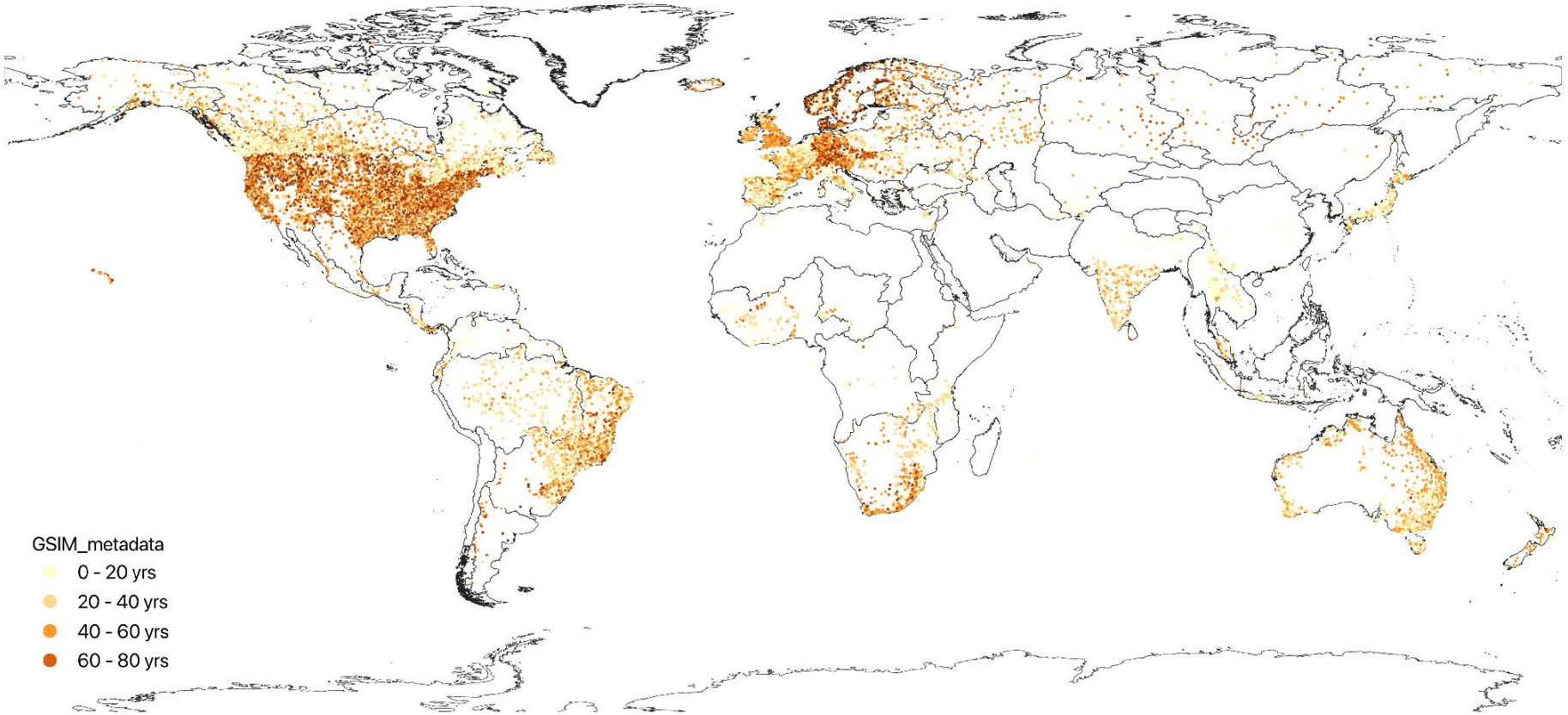
- GitHub for mizuRoute: getting code: https://github.com/ESCOMP/mizuRoute
- Online documentation: https://mizuroute.readthedocs.io/en/latest/

Question?

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Extra slides

Stream gauges are sparse & geographically biased



Do et al. (2018), ESSD, 10(2), 765-785, https://doi.org/10.5194/essd-10-765-2018

Running CTSM with mizuRoute

Same CIME workflow as CTSM: create case, build, user_nl mod, and submit

./create_newcase → ./case.setup → ./case.build → ./case.submit

01 CHOOSE: compset and grid

```
./create_newcase --case mycase \
  --mach derecho \
  --res f09_f09_rHDMAIk_mg17 \
  --compset I2000Clm60SpMizGs
```

--res

f09_f09 atm/land grid, 0.9°×1.25°
rHDMAIk river network (HDMA+lakes)
mg17 ocean mask grid

--compset

I2000Clm60Sp land-only, CTSM6, satellite phenology
Miz mizuRoute river component
Gs stub glacier

Find options: >./query_config --compsets | grep MIZU >./query_config --grids | grep MIZU

02 SET: mizuRoute settings

user_nl_mizuroute_control

Configuration and input/output settings in toml format (soon)

user_nl_mizuroute

River-routing parameters

03 READ: history output

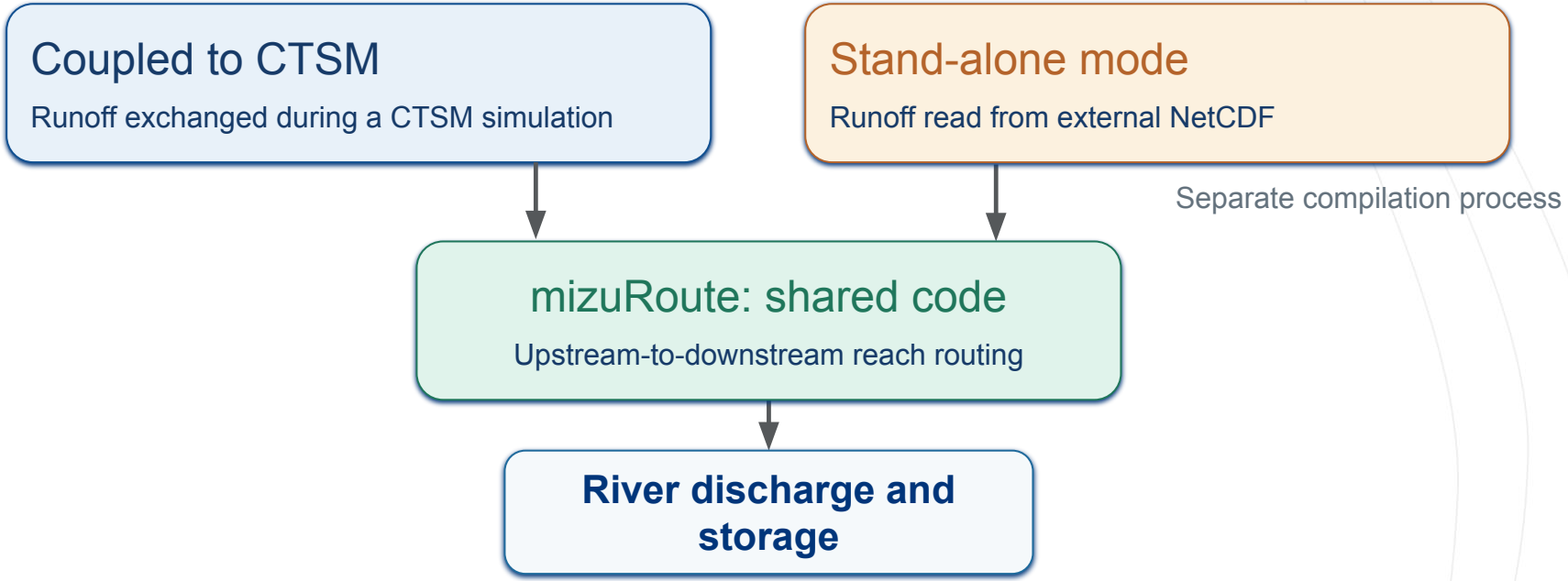
History Files: *.h.*.nc

- One value per reach (vector), not lat/lon
- Reach ID
- Discharge [m³/s]: discharge
- Reach storage [m³]: volume

Map to the network via reach IDs in the river file

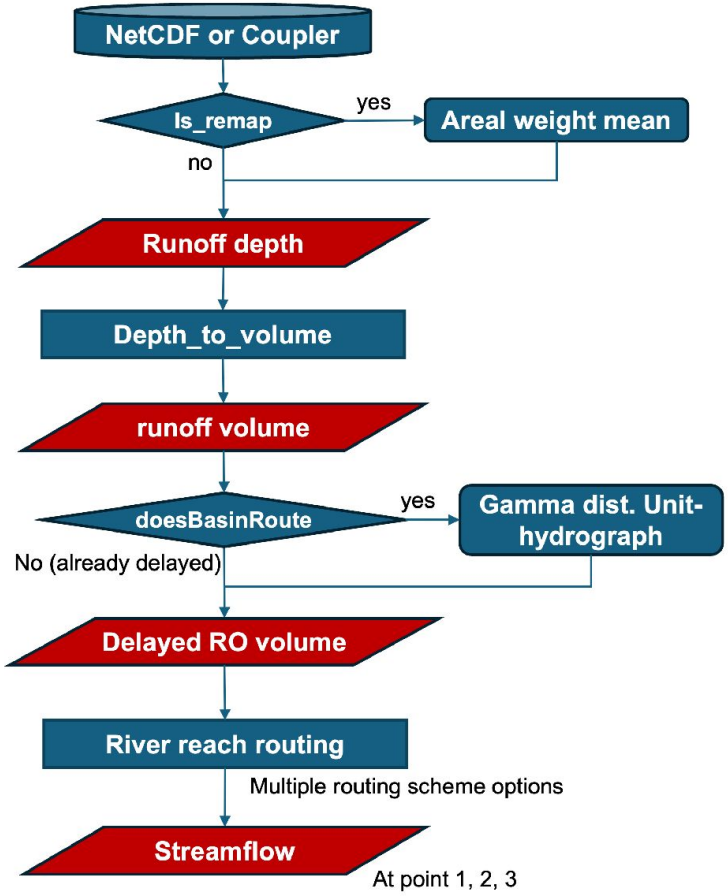
Coupled and stand-alone simulation

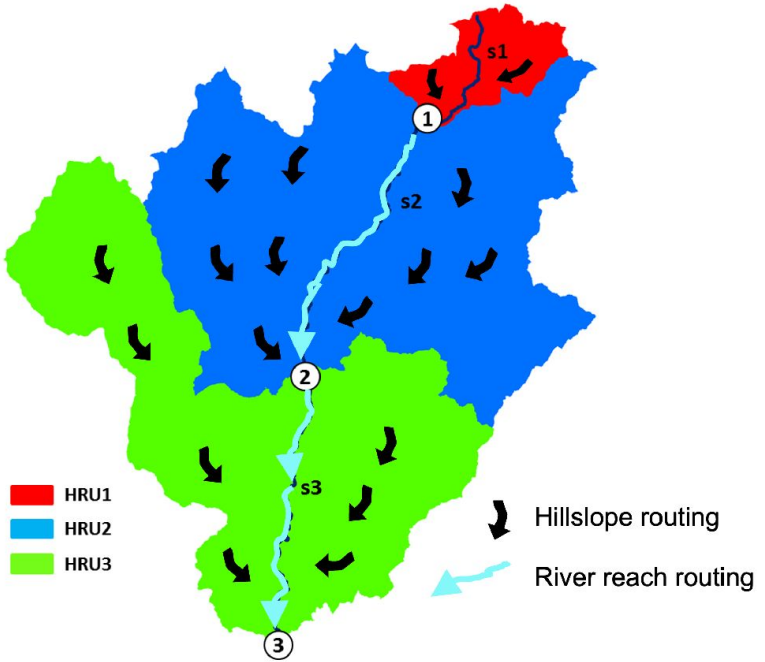
Different runoff sources; a common river-routing framework



Stand-alone runs can test alternative runoff inputs without rerunning CTSM.

Overall model flow





HRU: Hydrologic Response Unit (i.e. catchment)

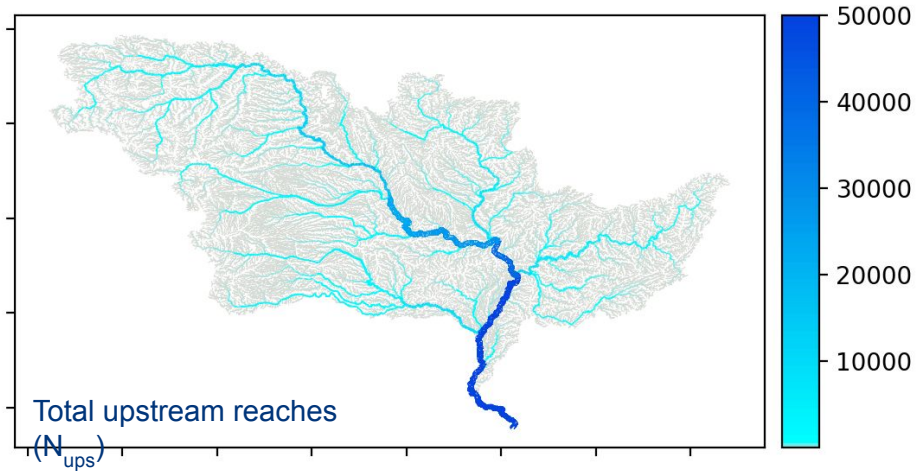
choice

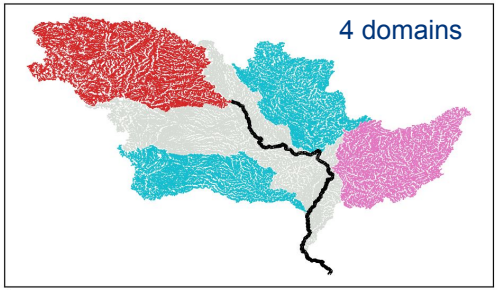
Operation

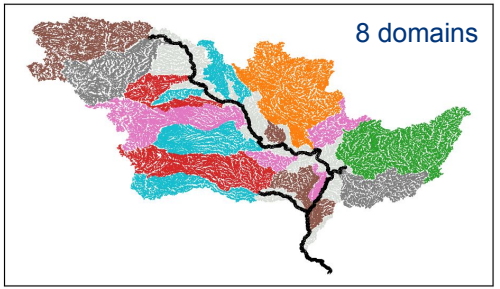
Internal data

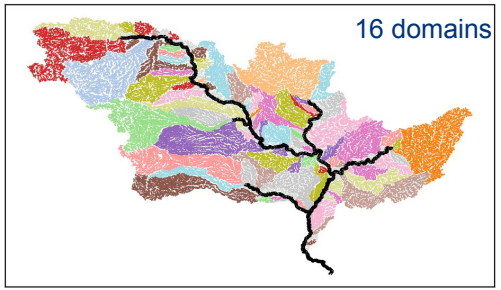
Parallelization: domain decomposition

Example: Mississippi river basins (total 64,500 reaches)









Split a river network into ***tributaries*** and ***mainstems*** (left panels) based on N_{trib_max}

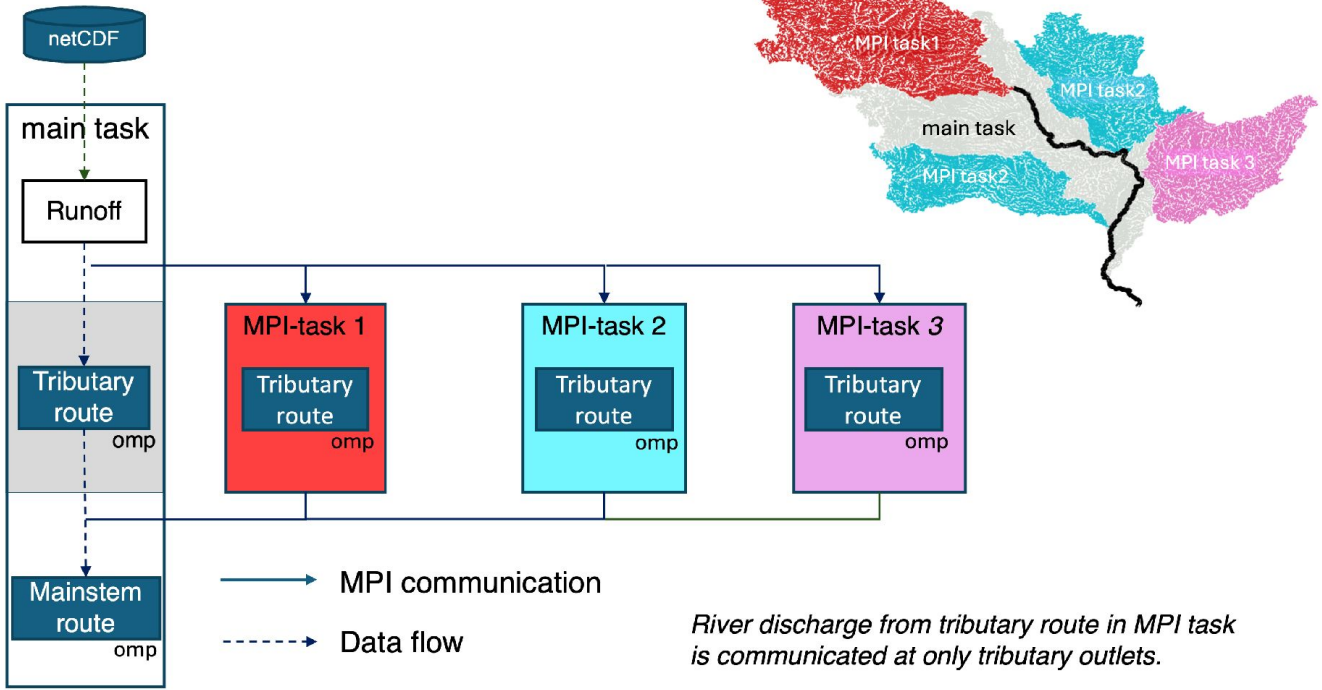
- Compute N_{trib_max} = Total reaches / number of domains (=MPI tasks)
- Mainstem (black): Reaches where $N_{ups} > N_{trib_max}$
- Tributaries (colors including light gray): Reaches where Nups <= N_{trib_max}
- Tributaries are assigned into tasks or domains. Light gray tributaries (lots of small tributary) are assigned to main task (mainstem is assigned to main task).

Mizukami et al. (2021), JAMES; doi:https://doi.org/10.1029/2020MS002434

Parallelization: computing flow

Routing processes with distributed memory computing (MPI)

Example: 4 MPI processors



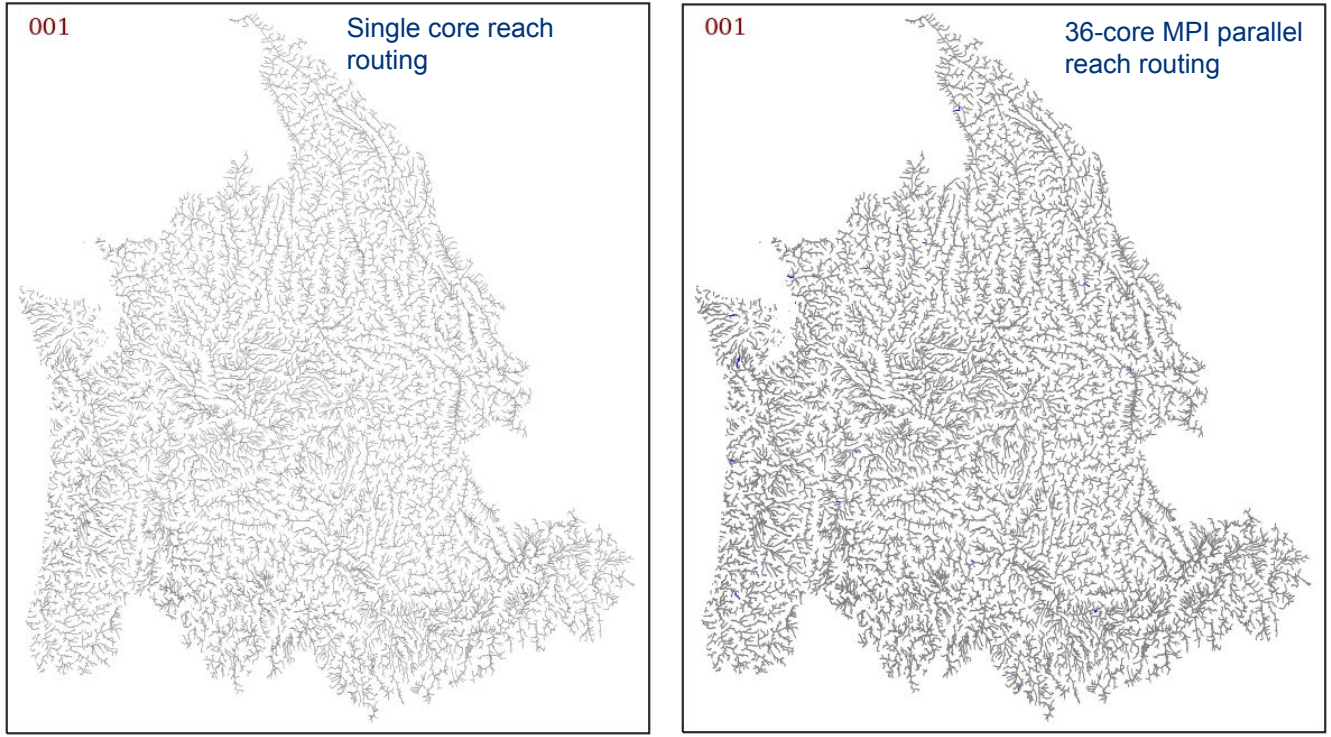
River discharge from tributary route in MPI task is communicated at only tributary outlets.

Mizukami et al. (2021), JAMES; doi:https://doi.org/10.1029/2020MS002434

Navigate river network

Route independent tributaries simultaneously.

Routing progression over the domain: serial run versus parallel run

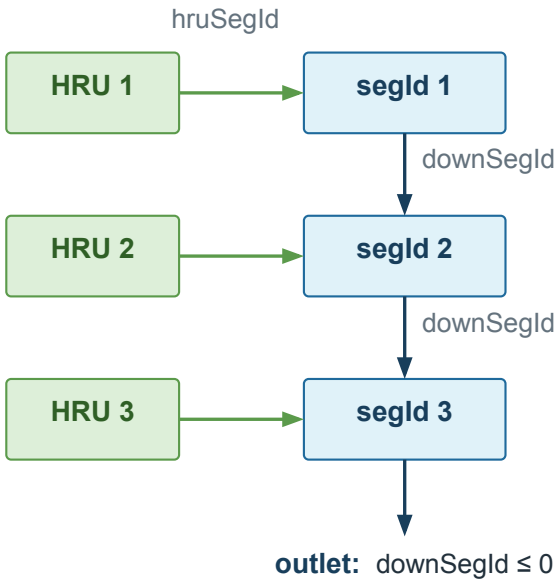


Reach routing schemes in mizuRoute

Routing method	Main concept	Characteristic
Impulse-response function	Unit hydrograph	Prescribed wave response
Lagrangian kinematic wave	Track moving water parcels	Travel-time representation
Muskingum-Cunge	Storage based routing	Translation and attenuation, commonly used
Kinematic-wave equation	Slove advection equation	Wave propagation
Diffusive-wave equation	Solve advection-diffusion equation	Wave propagation and spreading

River network file: minimum variables

How the IDs connect



Reach topology plus a few physical parameters

Variable	Type	Unit	Description
Reach variables (dimension: seg)			
segId	int	–	Reach ID (positive integer)
downSegId	int	–	ID of the downstream reach (≤ 0: basin outlet)
length	real	m	Reach length
slope	real	m/m	Reach slope (elevation drop / length)
HRU variables (dimension: hru)			
HRUid	int	–	HRU ID
hruSegId	int	–	Reach the HRU drains into (≤ 0: closed HRU)
area	real	m²	HRU area

mizuRoute computes : routing order from downSegId; Channel geometry parameters: bottom width and bankfull depth from simple functions; defaults for other parameters.

Optional: give per-reach width, depth, Manning's n, etc. to override defaults.

Basis of River flow

Open-channel flow: a liquid flow within a conduit or waterway with a free surface.

Open-channel hydraulics: Fluid dynamics for open-channel flow.





1-D Saint Venant equation

- Continuity equation

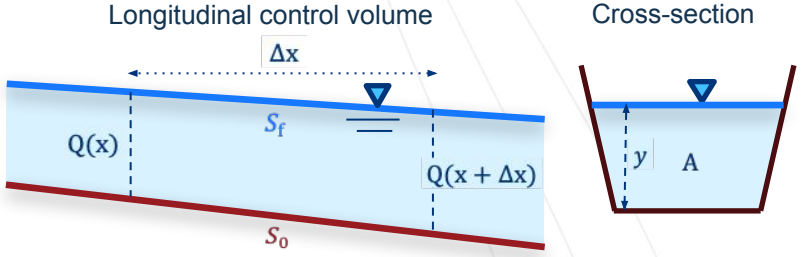
$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x} + \mathrm{ql}$$

- Momentum equation

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$$

Local acceleration | Advective acceleration | Pressure | Gravity | Friction

Inertia term



A: Cross-sectional flow area

Friction slope: $S_f = \frac{v^2}{f(n, A, y)}$

1-D Saint Venant equation

- Continuity equation

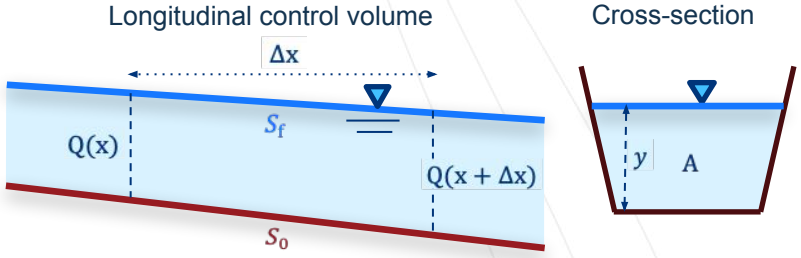
$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x} + \mathrm{ql}$$

- Momentum equation

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$$

Local acceleration | Advective acceleration | Pressure | Gravity | Friction

Inertia term



A: Cross-sectional flow area

Friction slope: $S_f = \frac{v^2}{f(n, A, y)}$

Dynamic Wave

1-D Saint Venant equation

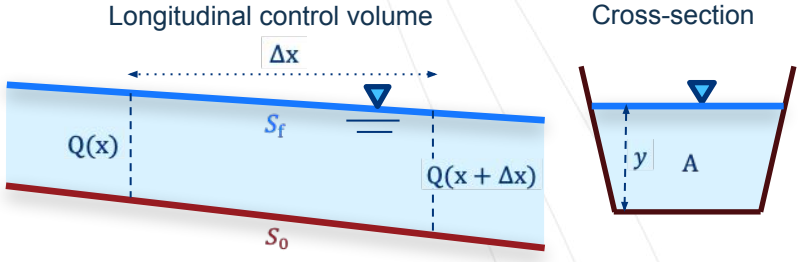
- Continuity equation

$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x} + \mathrm{ql}$$

- Momentum equation

$$g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$$

Pressure Gravity Friction



A: Cross-sectional flow area

Friction slope: $S_f = \frac{v^2}{f(n, A, y)}$

Diffusive Wave (peak attenuation)

1-D Saint Venant equation

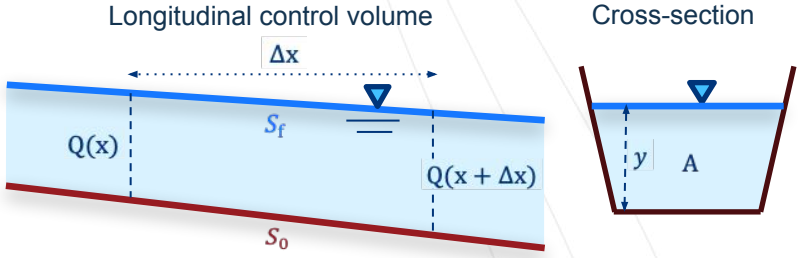
- Continuity equation

$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x} + \mathrm{ql}$$

- Momentum equation

$$g(S_0 - S_f) = 0$$

Gravity Friction



A: Cross-sectional flow area

Friction slope: $S_f = \frac{v^2}{f(n, A, y)}$

Kinematic wave (translation only)

Physics: Advection-Diffusion equation

- Continuity equation

$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x} + \mathrm{ql}$$

- Simplified momentum equation

$$g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$$

Pressure gradient | Gravity | Friction

Advection-Diffusion (Diffusive wave) equation

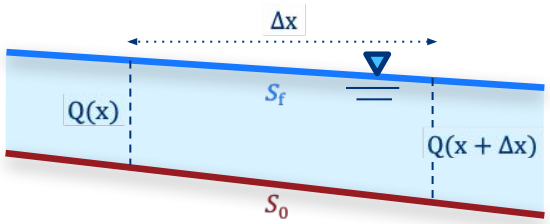
$$\frac{\partial Q}{\partial t} + C\frac{\partial Q}{\partial x} = D\frac{\partial^2 Q}{\partial x^2} + \mathrm{C} \cdot \mathrm{q_l}$$

$D = \frac{K^2}{2Qw}$ Diffusivity[m^2/s]

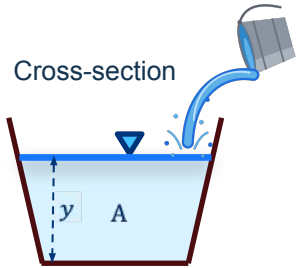
$C = \frac{Q}{K}\frac{\partial K}{\partial A}$ Wave celerity [m/s]

$K = \frac{A}{n}R^{\frac{2}{3}}$ Channel conveyance

Longitudinal control volume



Cross-section



ql: lateral flow

Friction slope: $S_f = \frac{v^2}{f(n, A, y)}$

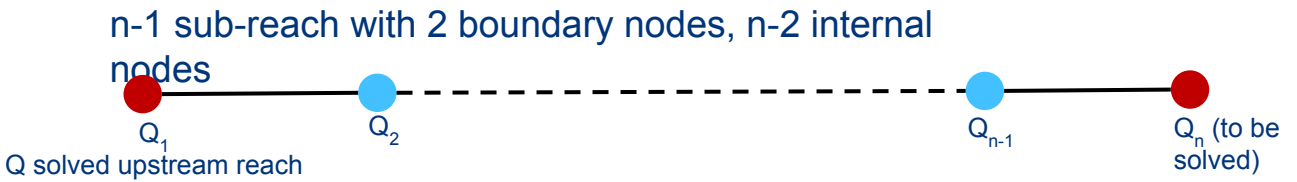
A: Flow area

y: water height

Some details:

- Linearized diffusive wave equation with constant C and D at a time step and reach.
- When D=0, the equation reduces to an advection equation, consistent with the kinematic-wave approximation

Reach sub-section and channel geometry





- Reach is split into sub-reaches.
- Discharge (Q) is solved at the nodes.
- Q at upstream node (inflow) is known
- Q at downstream node becomes the next reach's inflow.

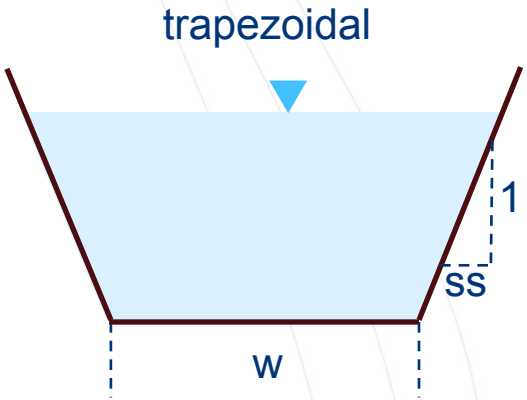
Channel cross-section

Man-made



Natural

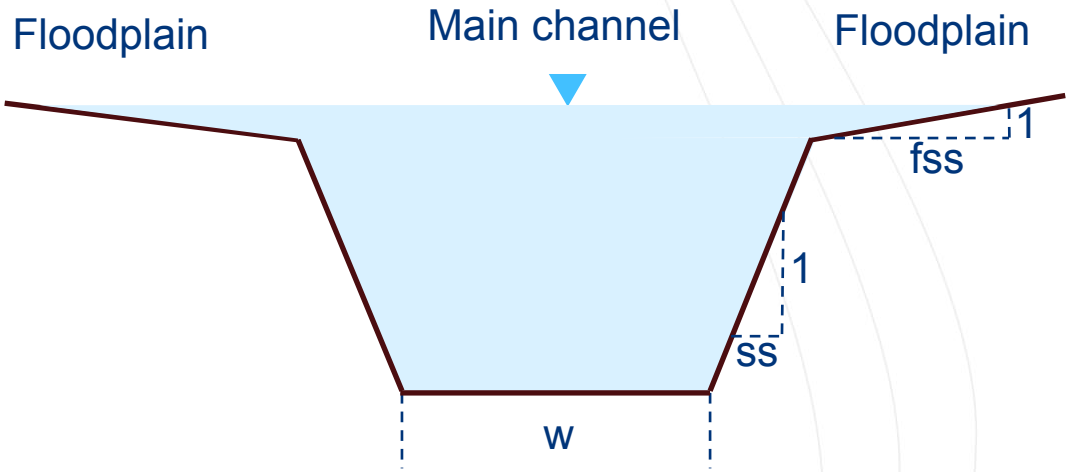




w: Width [m]
ss: Side-slope [-]

ss = 0 → Rectangular
w = 0 → Triangular

Channel cross-section



w: Width [m]
ss: Side-slope [-]

ss = 0 → Rectangular
w = 0 → Triangular