Vector river network routing ~ mizuRoute ~

Naoki Mizukami and Martyn Clark

mizu = "water" in Japanese

LMWG meeting, 11th February, 2019

Outline

NCAR UCAR

- Background
  - Existing river model in CLM
- mizuRoute
  - Routing methods
  - Pfafstetter coding system
- Simulation examples
  - Network routing over the CONUS
  - Network routing for the planet
- Working in progress

Existing routing model in CLM

1. River Transport Model (RTM)

- Close global hydrological cycle (atmosphere-land-ocean)
- Gridded river network: 8 directional river network at a coarse resolution (e.g., 0.5º)
- Hydrologic routing scheme: Linear transport model.

$$\frac{dS}{dt} = \sum F_{in} - F_{out} + R$$

$$F = \frac{v}{d} S$$

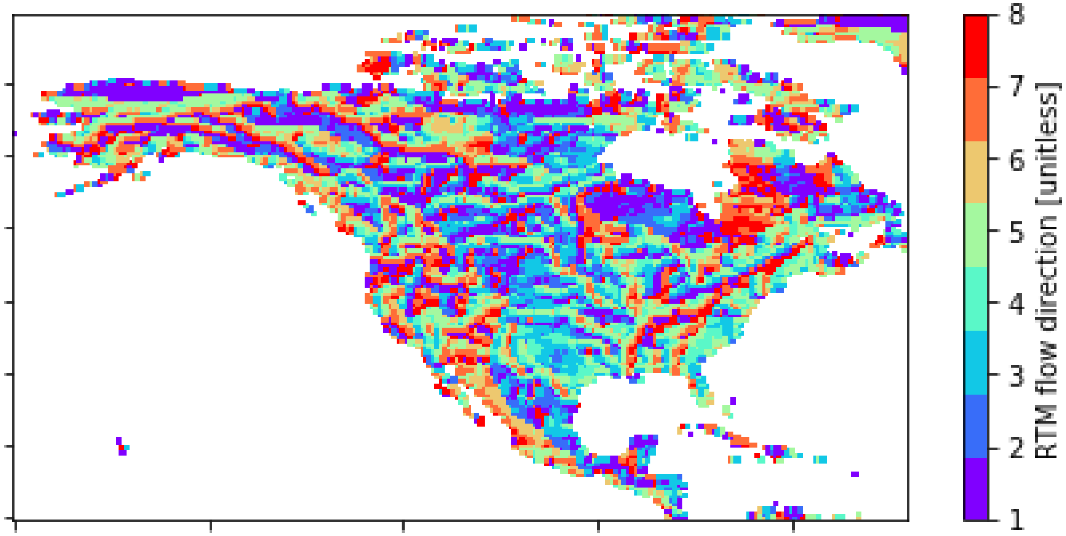
S : River water storage within cell (m3)

v : Effective flow velocity = $\max\left(0.05, \sqrt{slope}\right)$

d : Distance between cells

R : runoff from CLM

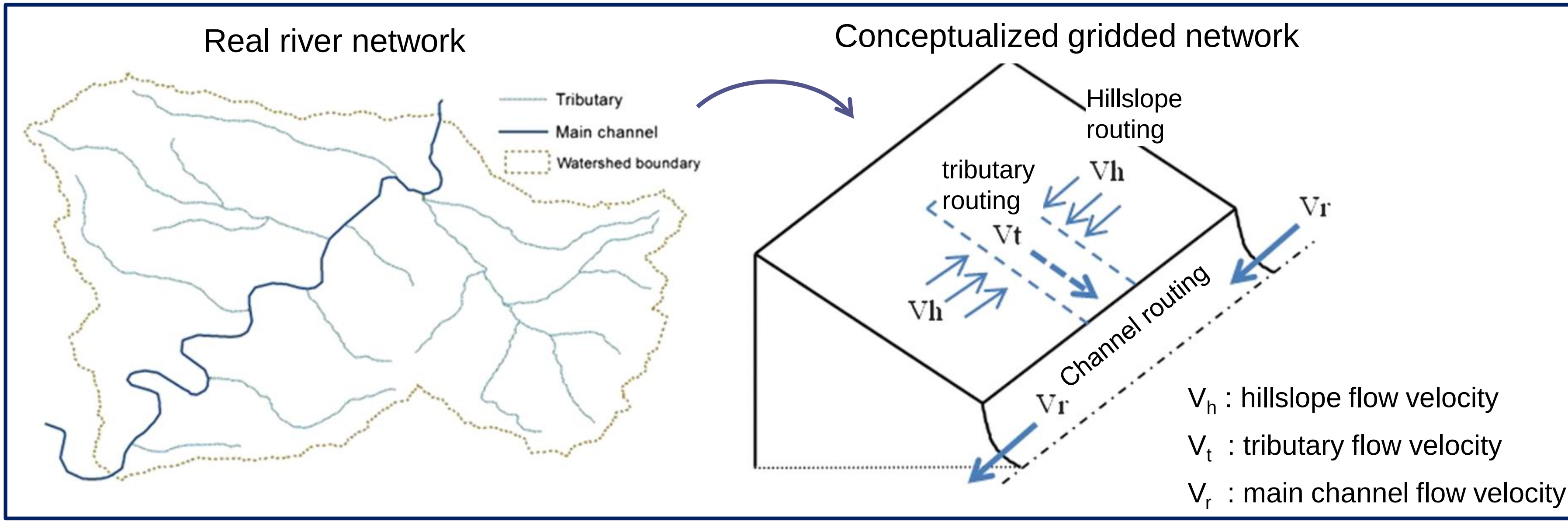
North America 0.5º flow direction



Oleson et al., Technical description of CLM4.5, NCAR Technical Note, 2013

Existing routing model in CLM

2. MOSART (Model for Scale Adaptive River Transport)



Conceptualization of river network in MOSART.

1. Hillslope routing (only surface runoff).
2. Tributary routing: conceptualized as a single equivalent channel (scale adaptive).
3. Main channel routing: explicitly estimate channel status (velocity, water depth, etc).

Li and Wigmosta, Journal of Hydrometeorology, 2013

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mizuRoute

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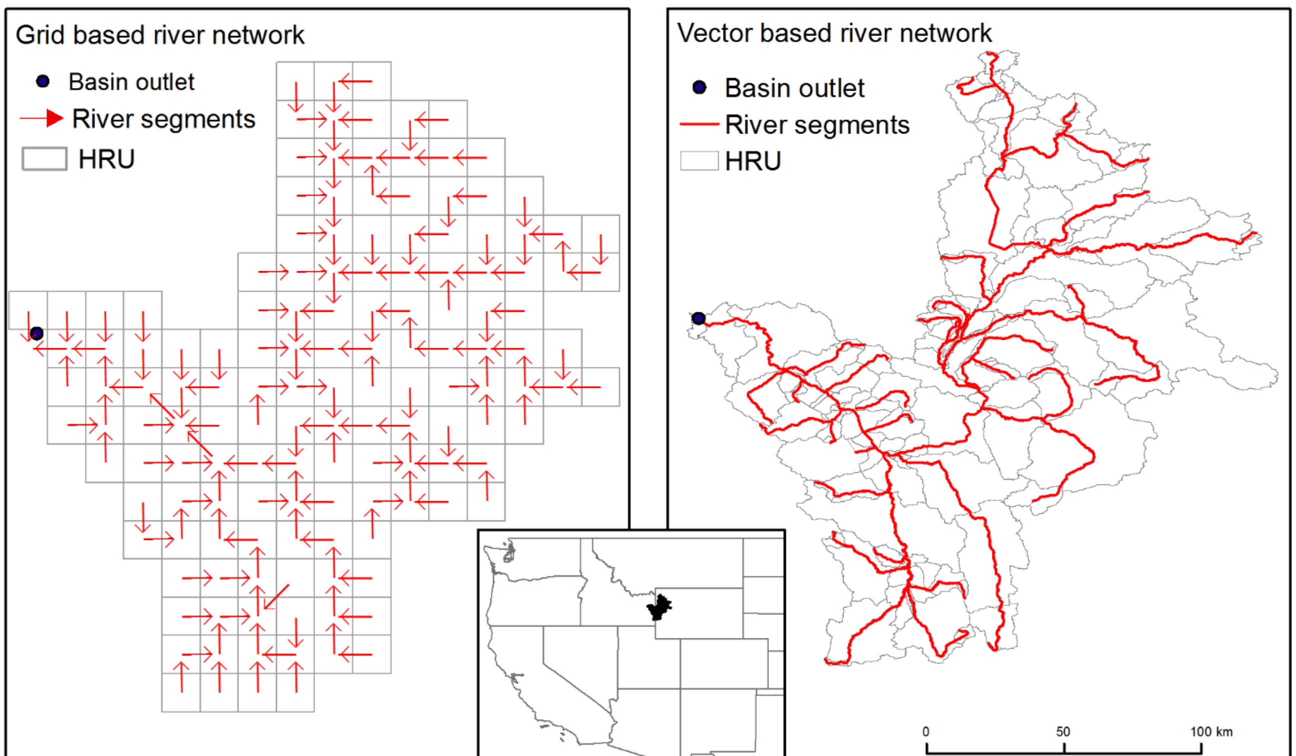
Developed as a stand-alone routing tool for *large-domain* and *multi-decadal* streamflow estimates based on runoff outputs from *hydrologic models or LSMs,* routing through *real river network.*

Lohmann (1996)

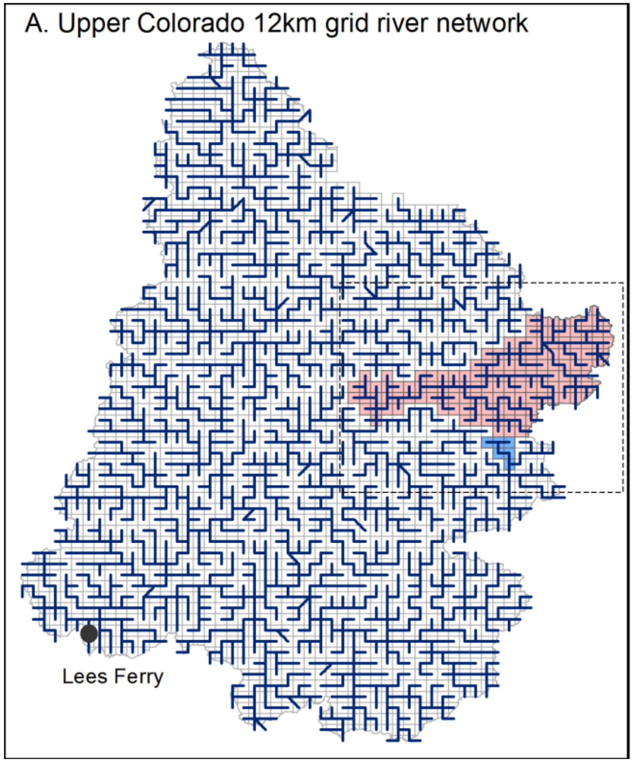
- Gridded river network
- Unit-hydrograph (source-to-sink)

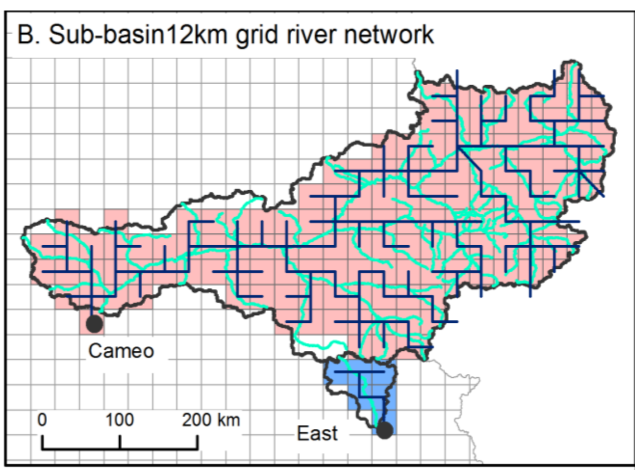
mizuRoute (2016)

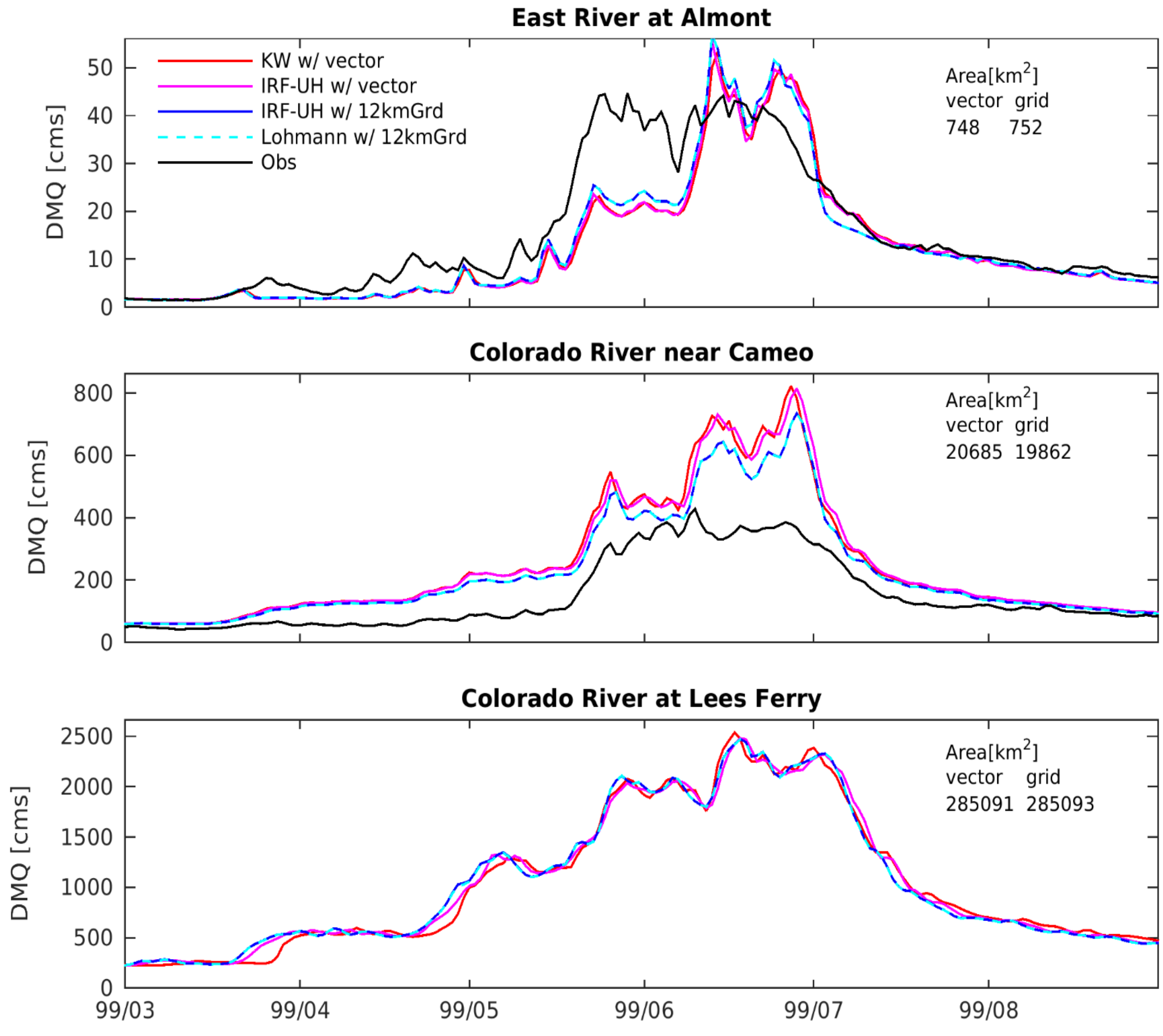
- Vector river network
- Unit-hydrograph or Kinematic Wave



Routed flow- gridded vs vector network







mizuRoute - overall procedure

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HRU average runoff

↓

Hill-slope routing — Gamma distribution UH

HRU1 to ① -> Q1
Put runoff over HRU2 to ② -> Q2
HRU3 to ③ -> Q3

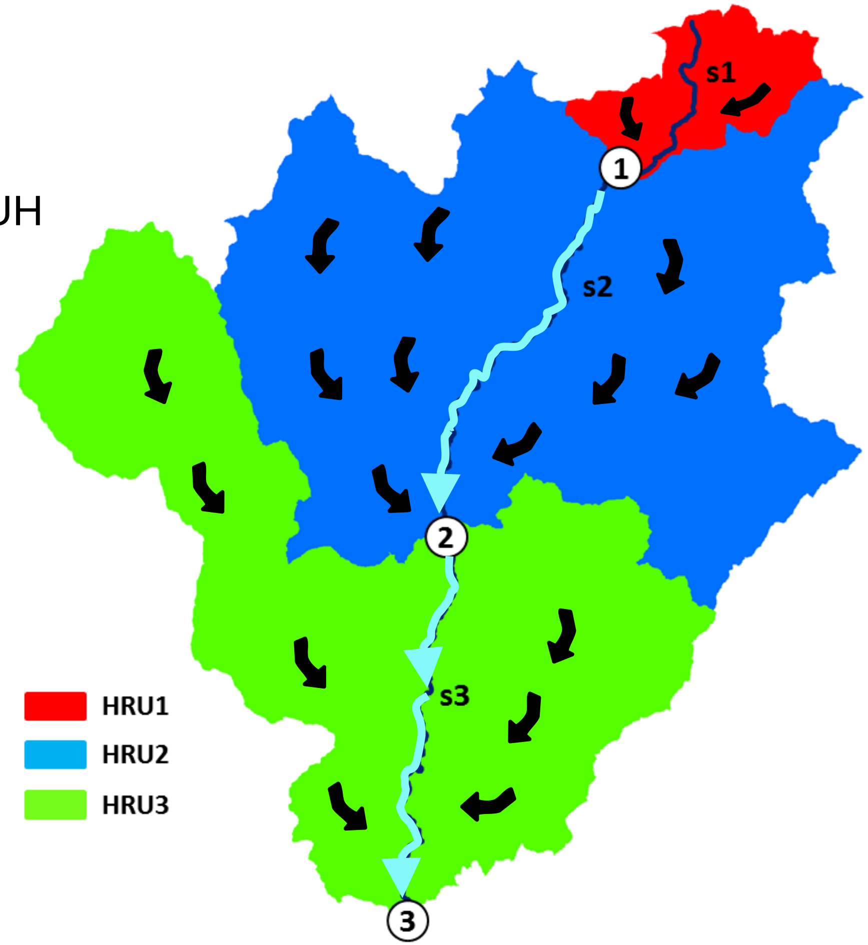
↓

River channel routing
1. Kinematic Wave
2. Unit Hydrograph
3. …

Route Q1 through s2 to ②
Route Q1 & Q2 through s3 to ③

↓

Streamflow



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

Channel routing (physics)

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St. Venant equation (1Dimensional equation of water motion)

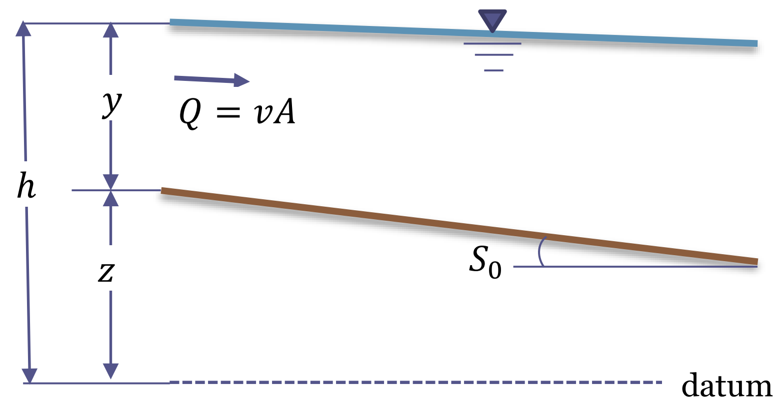
- Continuity equation

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

- Momentum equation

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

Local acceleration | Convective acceleration | Pressure force | Gravity force | Friction force



A: Cross-sectional flow area

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

$$g\left(S_0 - S_f\right) = 0$$

Dynamic Wave (unsteady, nonuniform)

Diffusive Wave (steady, nonuniform)

Kinematic Wave (steady, uniform)

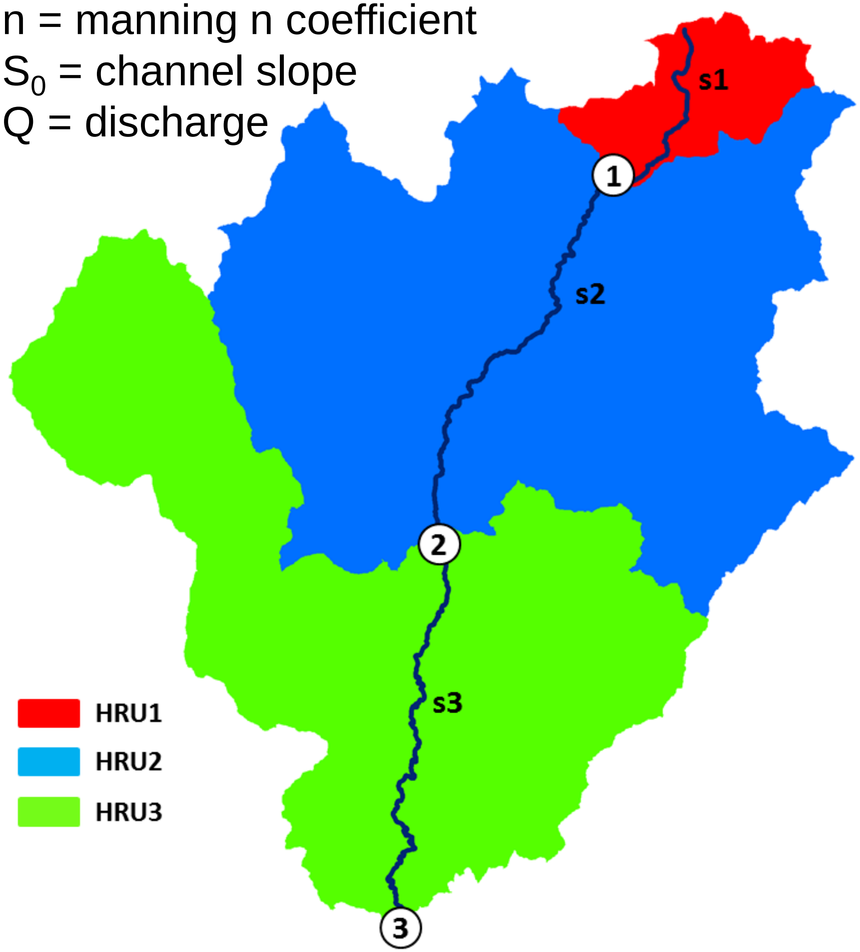
$$\mathrm{v} = \sqrt{S_0}\, f(n,A,y)$$

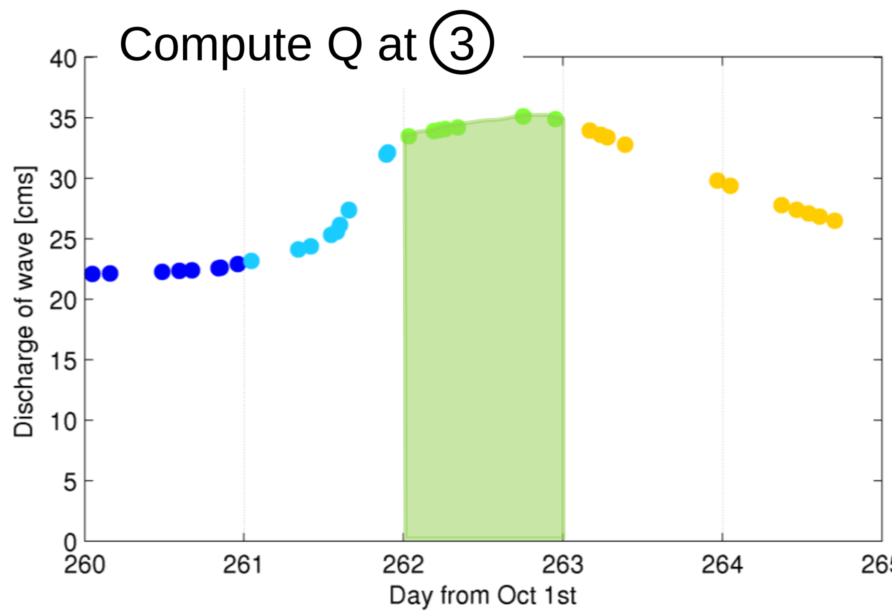
Kinematic wave

Track runoff entering a “rectangle” channel as a ”particle” with celerity, *c* [L T^{-1}] along river network.

$$c = \frac{\mathrm{d}Q}{\mathrm{d}A} = f(Q, S_0, n, w)$$

w = channel width
n = manning n coefficient
S_0 = channel slope
Q = discharge



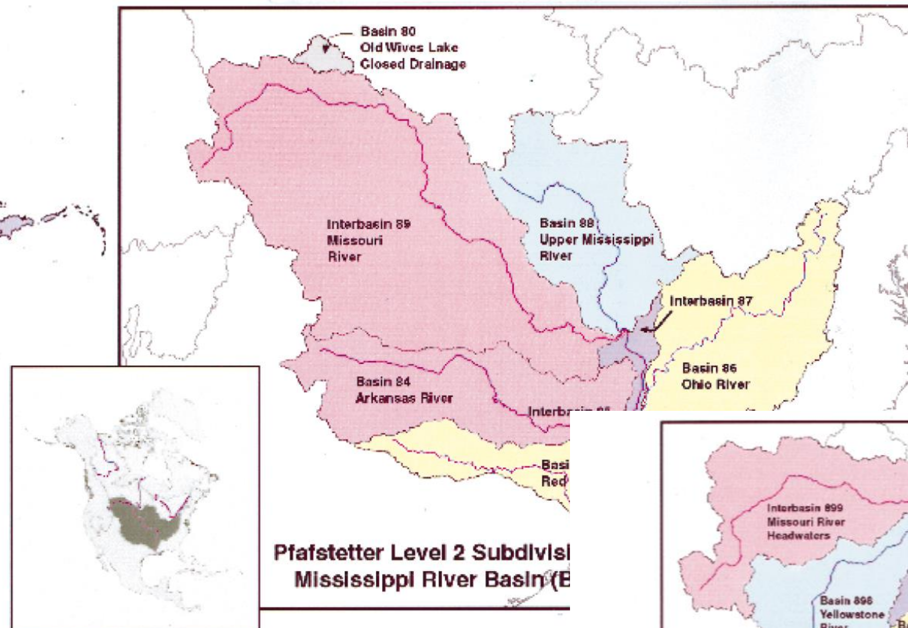


Find waves that exit a segment during each time step.
Q(s=3, t=263) = Green area

Pfafstetter coding system

A hierarchical method of coding (IDing) river basins, developed by the Brazilian engineer Otto Pfafstetter.

It is designed such that topological information is embedded in the code



Verdin and Verdin, Journal of Hydrology, 1999

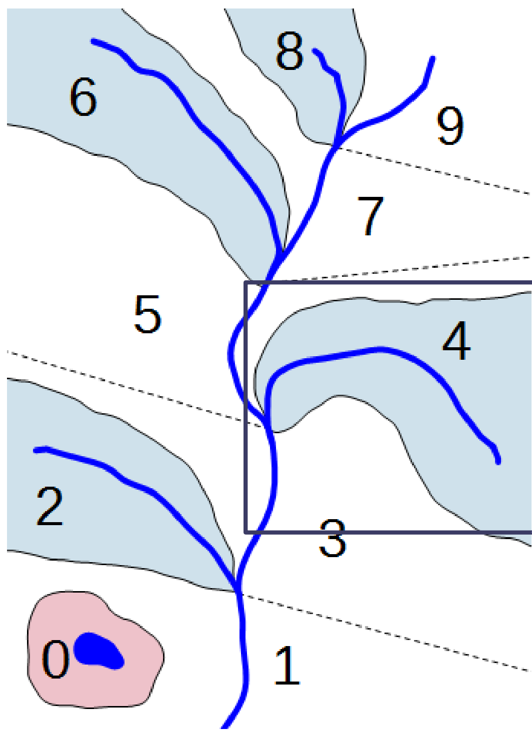
Pfafstetter coding system property

Number of digits = level

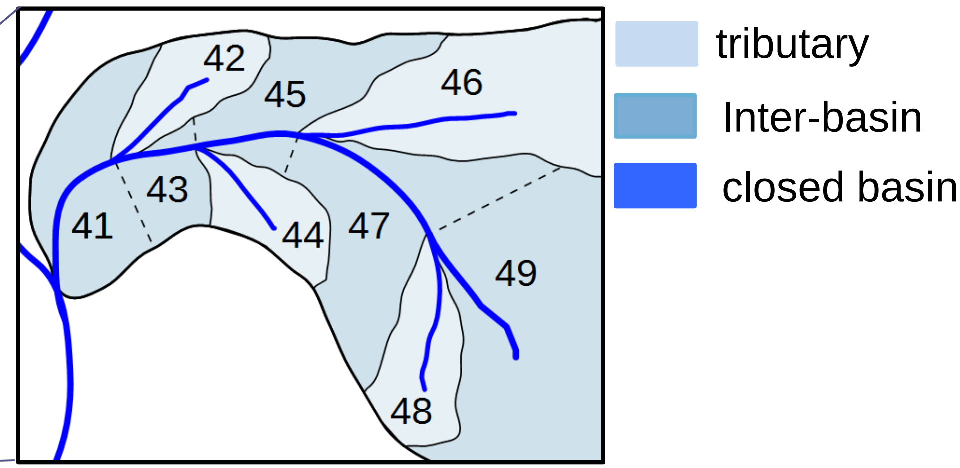
At each level, higher digits denote upstream reaches

At each level, a digit is

even = tributary
odd = inter-basin (mainstem)
0 = closed basin



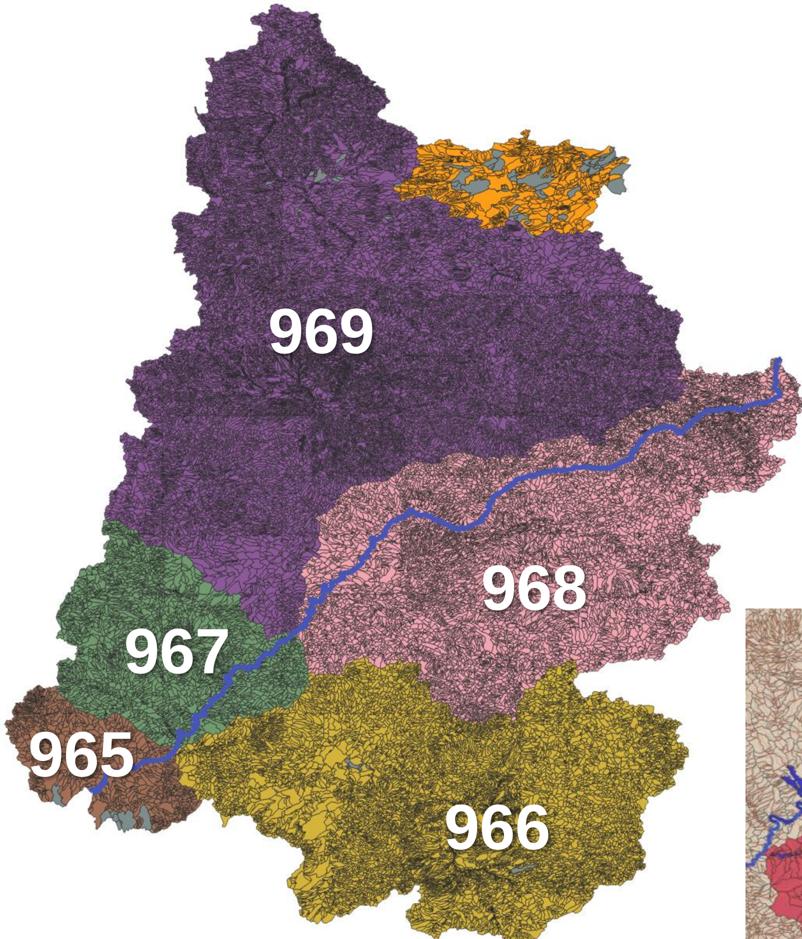
1st level



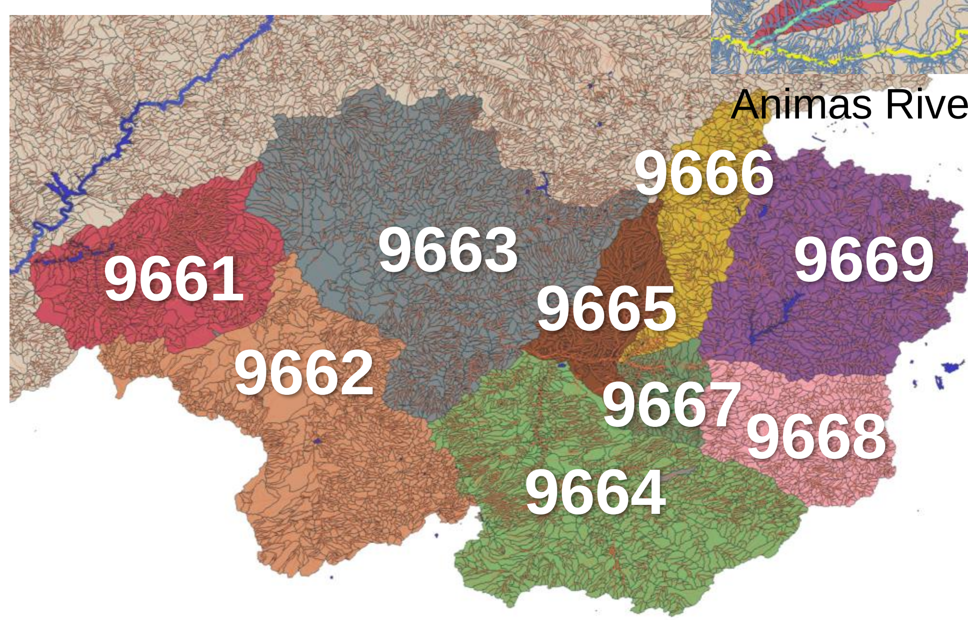
2nd level

Source https://en.wikipedia.org/wiki/Pfafstetter_Coding_System

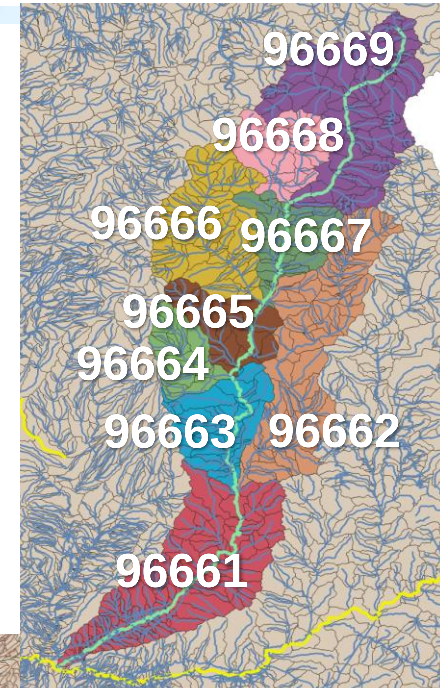
Pfafstetter coding system (NHD+)



Colorado River above Lees Ferry (3rd level)



San Juan River (4th level)



Animas River (5th level)

Pfafstetter applications

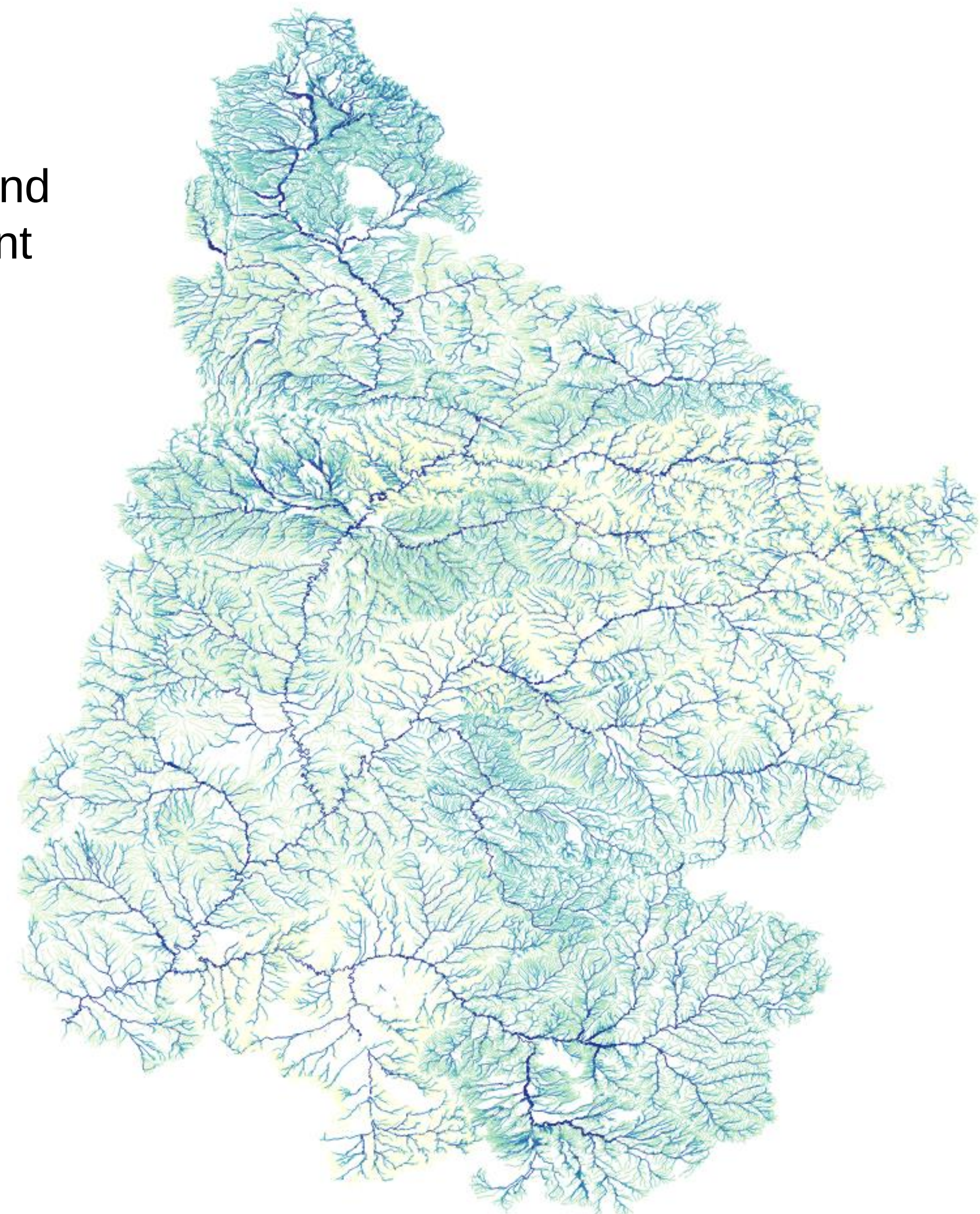
- River network topology
- Subsetting
- Parallelization
- Aggregation

Application 1: River network topology

Identify locational relationships

1. Determine immediate downstream and upstream segments for each segment

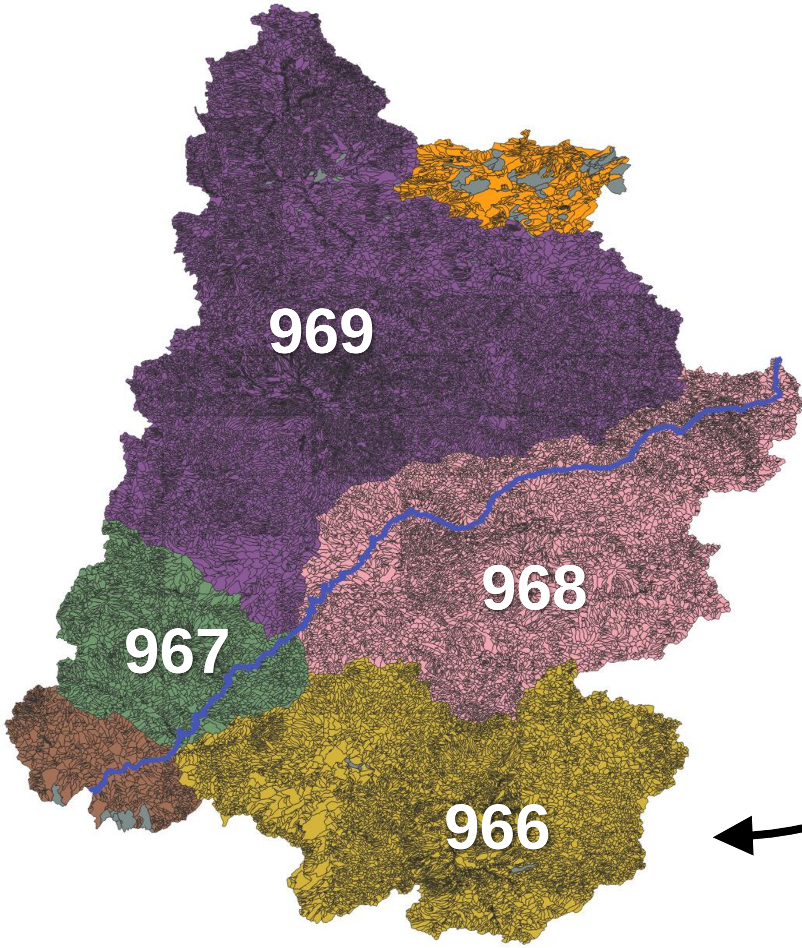
2. Routing-processing order



Process order

- 1 - 8256
- 8256 - 16511
- 16511 - 24766
- 24766 - 33021
- 33021 - 41276
- 41276 - 49531
- 49531 - 57786
- 57786 - 66041
- 66041 - 74296
- 74296 - 82551

Application 2: Subsetting



Colorado River above Lees Ferry

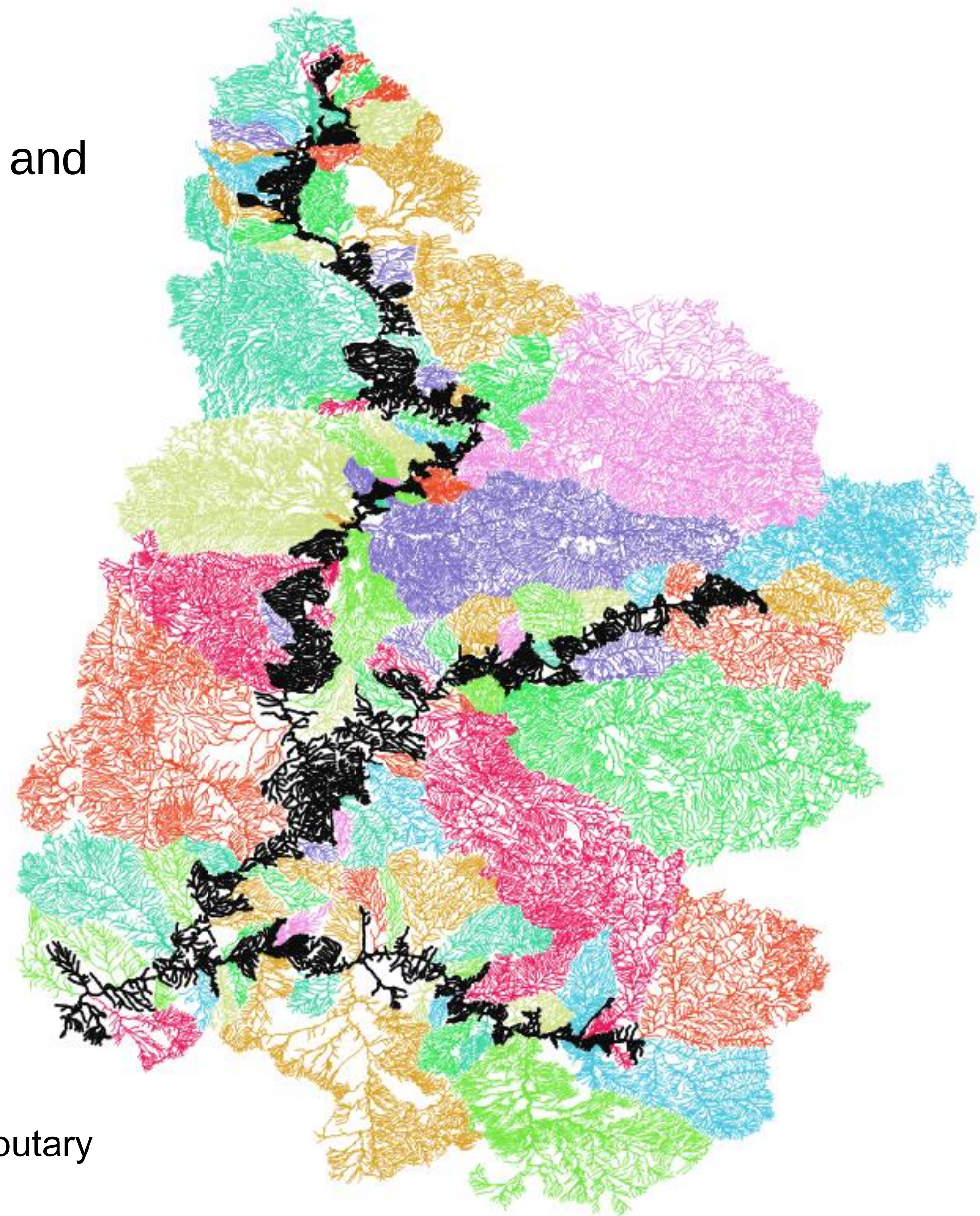
All basins starting with '96' are in the Colorado River basin

The San Juan River includes all reaches starting with '966'

Application 3: Parallelization

River network decomposition

1. Split a river network into *tributaries* and *mainstems*
2. Assign them to computing nodes



Node assignment (11 nodes)

1
2
3
4
5
6
7
8
9
10
"Large" tributary

0 Mainstems + "small" tributary

Application 4: Aggregation

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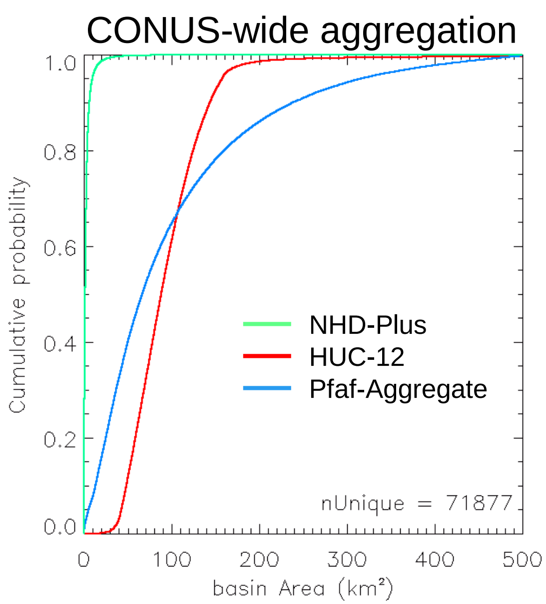
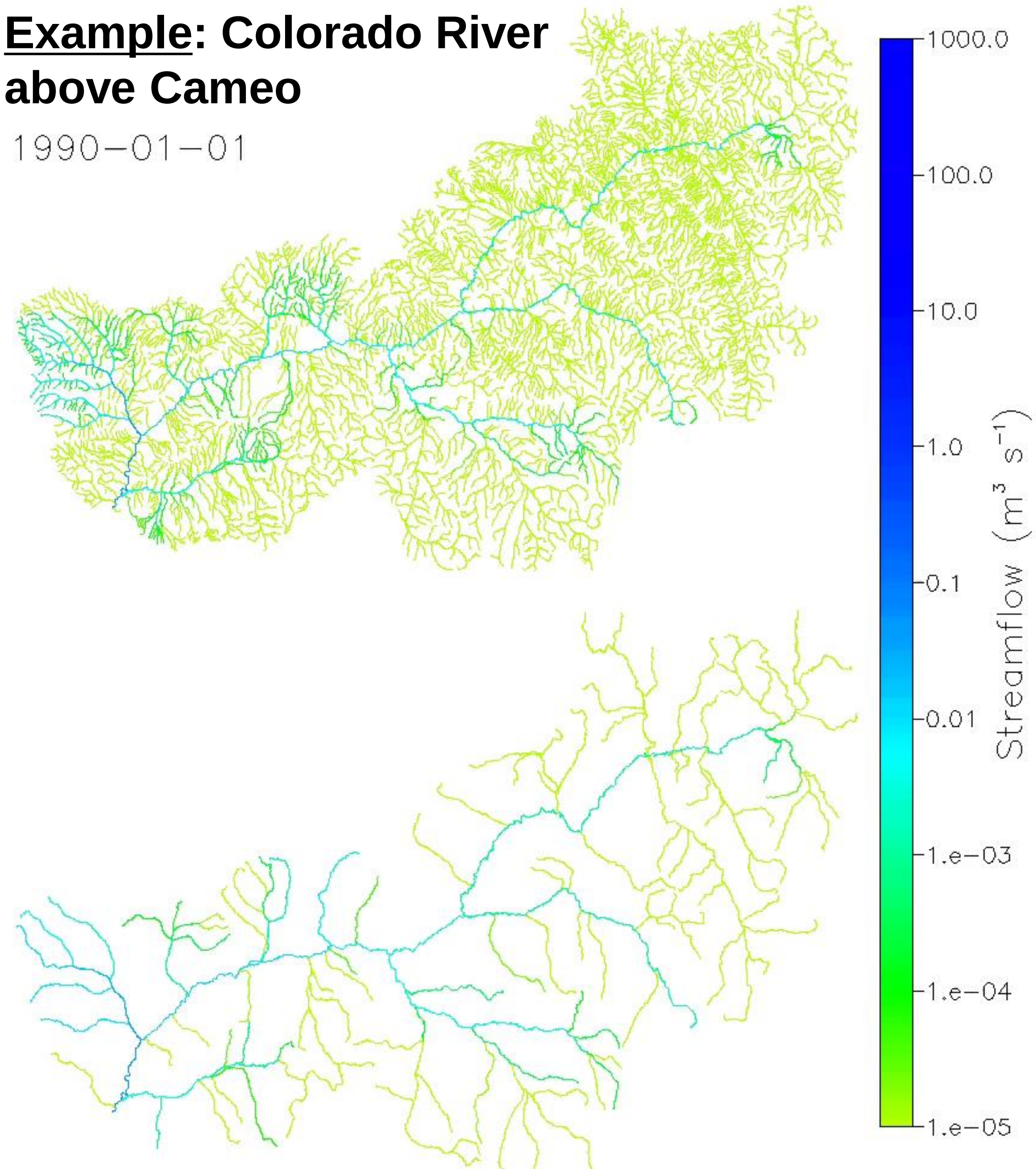
Can aggregate basins at a given Pfafstetter level, and route using the same underlying network

- *Aggregation is basin-specific, so have greater resolution in specific areas (adaptive in time, e.g., as a storm passes through)*
- *Supports "computationally frugal" model instantiations (for ensemble forecasting, parameter estimation trials, etc.)*



<u>Example</u>: Colorado River above Cameo



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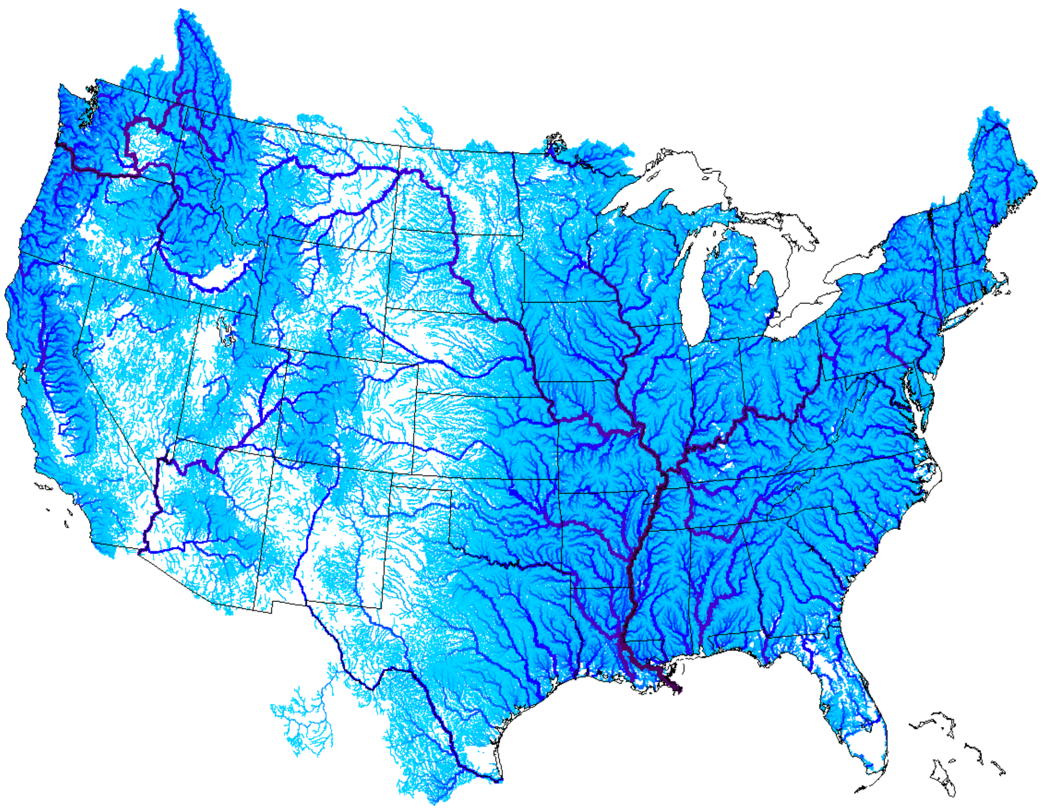
CONUS domain routing with NHD++

SUMMA/mizuRoute simulations of mean annual runoff for the NHD++ network

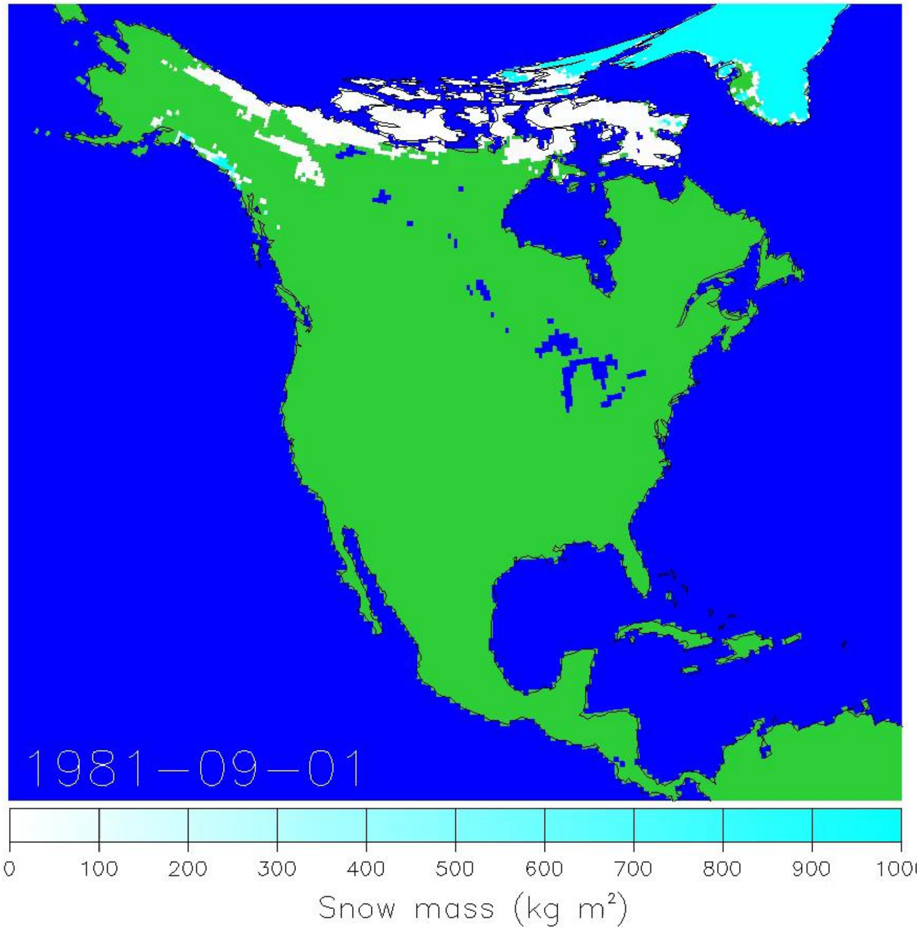


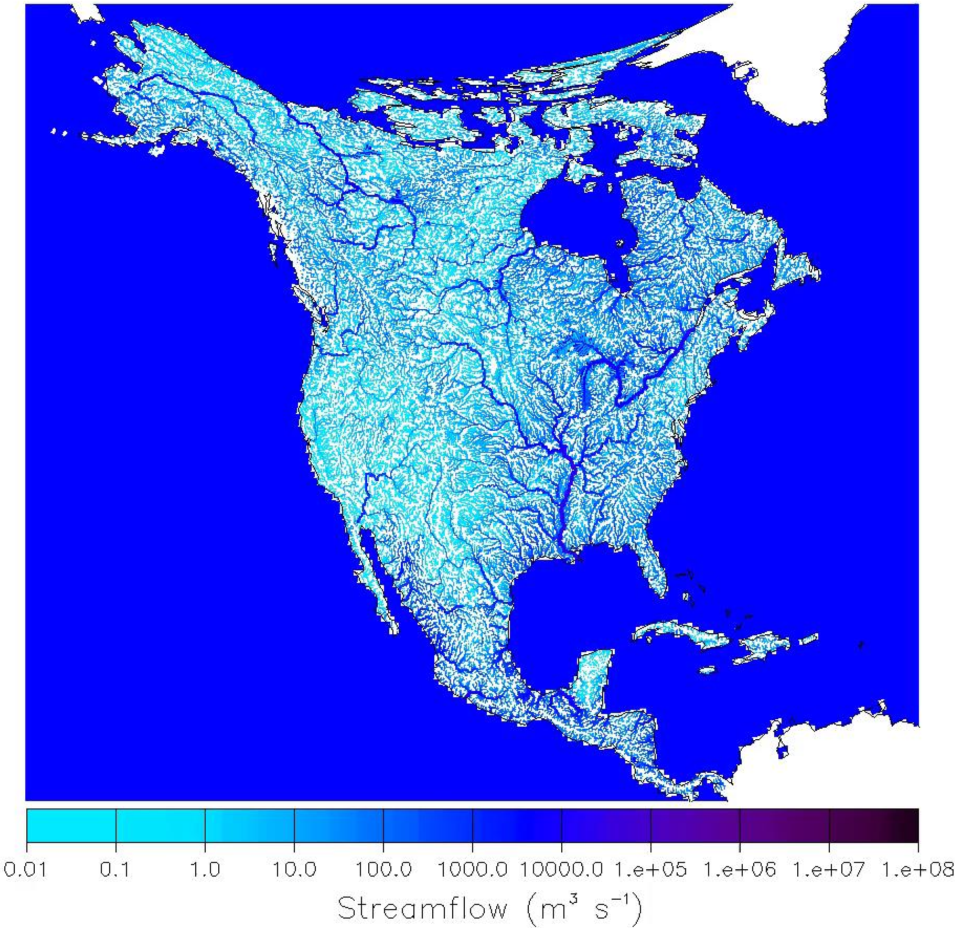
- mizuRoute configured for the NHD++ network (~2.7M streams)
- Major overhaul of mizuRoute to navigate the NHD++ network and generate information on reach characteristics to support multiple routing models
- Implemented a topological numbering scheme (Pfafstetter coding system) to
  - Simplify filtering of the river network
  - Enable efficient network-based domain decomposition procedures
  - Enable hydrologic prediction across scales

Problems: Heterogeneous network; broken links
Advantages: Widespread community use; efforts to improve the network

Continental-domain routing

- Hydrologic Derivatives for Modeling and Applications (HDMA)
  - Digital river network developed by Kris Verdin for the catchment land model
  - Uses Pfafstetter coding system
  - Global dataset





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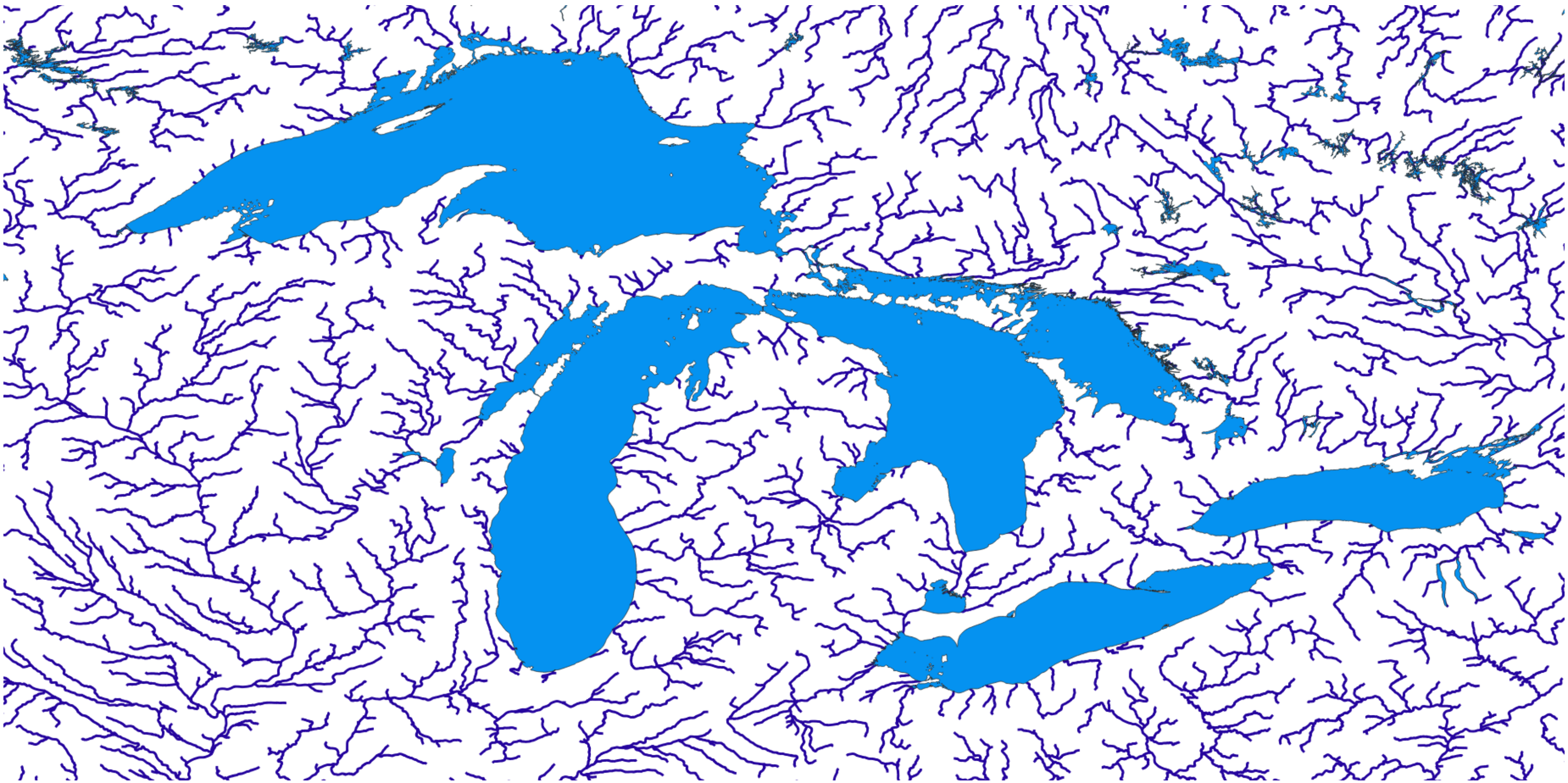
Lakes/reservoirs

- Work underway to incorporate hydroLakes in mizuRoute
  - Intersecting stream segments with hydroLakes
  - Extracting mizuRoute lake attributes from hydroLakes
  - Initial simulations over the Great Lakes (obtained evaluation data)



Working in progress

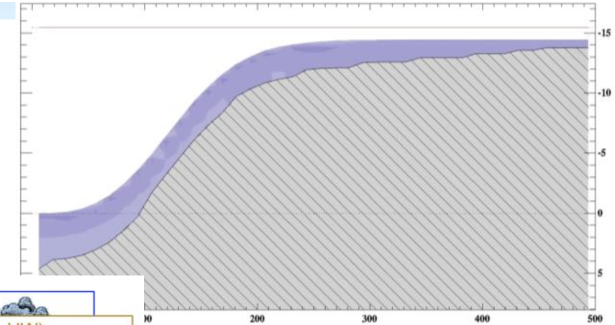
- mizuRoute parallelization development
  - Complete Pfafstetter parallelization with MPI
- NHD+ aggregations
  - Complete NHD+ aggregations over the CONUS
  - Evaluate/improve aggregated NHD+ simulations
  - Evaluate scaling issues
- hydroLakes
  - Complete stream/lake intersections
  - Initial testing of lake simulations in mizuRoute
- Coupling
  - Refactor of mizuRoute driver
  - Upgrade to ESMF “re-gridders”
  - Integrate CTSM energy balance with mizuRoute water balance


Thanks!

Extra slides

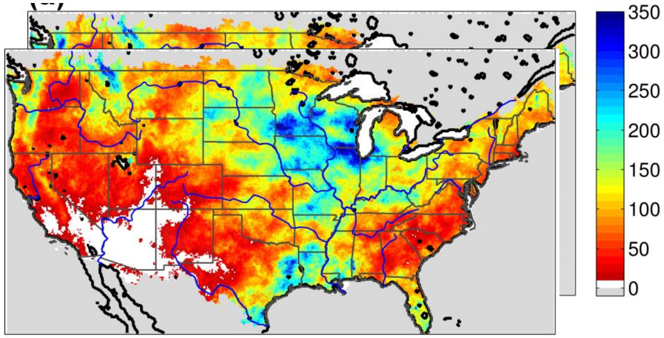
CTSM hydrology

Sub-grid hillslopes



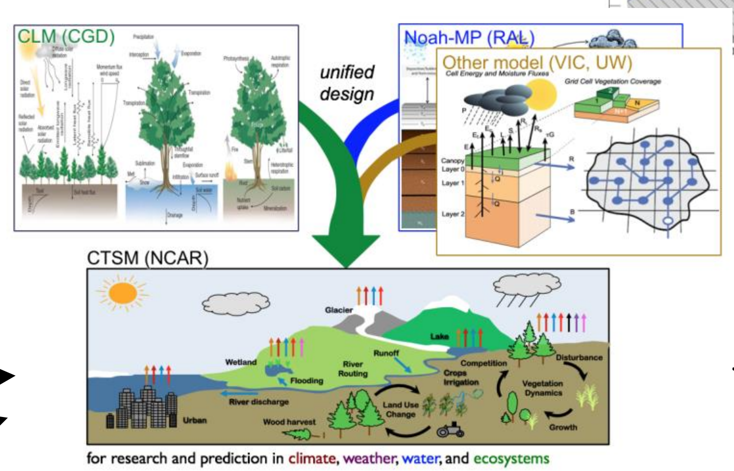
Swenson et al., in prep

Ensemble forcing (GMET)

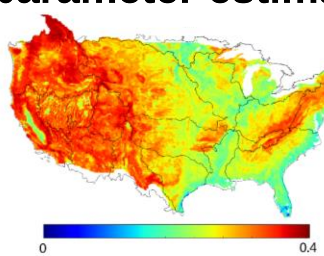


Clark and Slater, 2006; Newman et al., 2015

CTSM

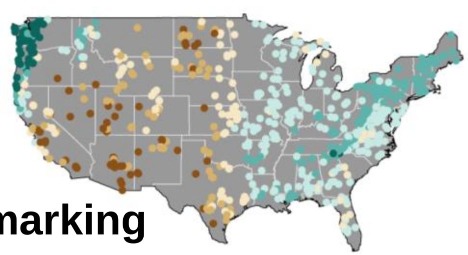


Large-domain parameter estimation



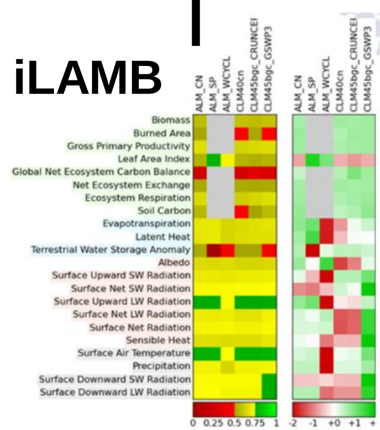
Mizukami et al., 2017

Model benchmarking



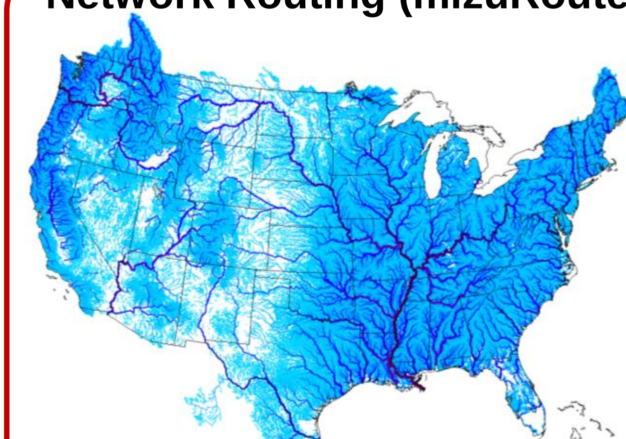
Addor et al., 2017; Newman et al., 2017

iLAMB



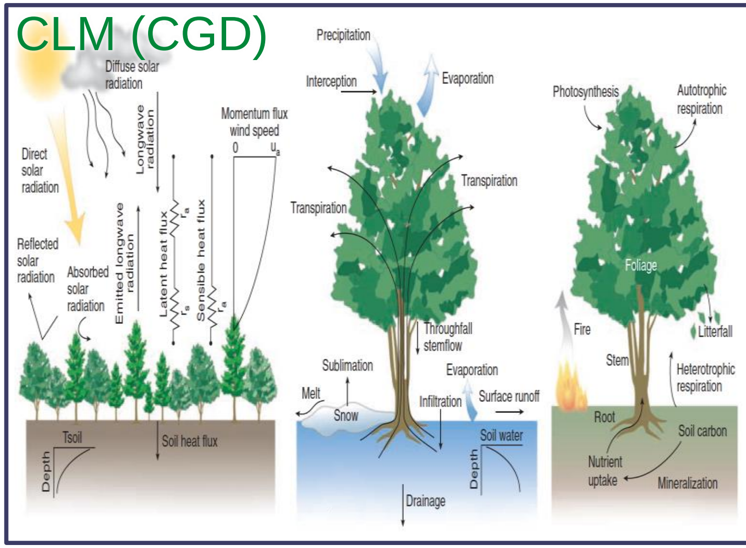
Hoffman et al., 2017

Network Routing (mizuRoute)

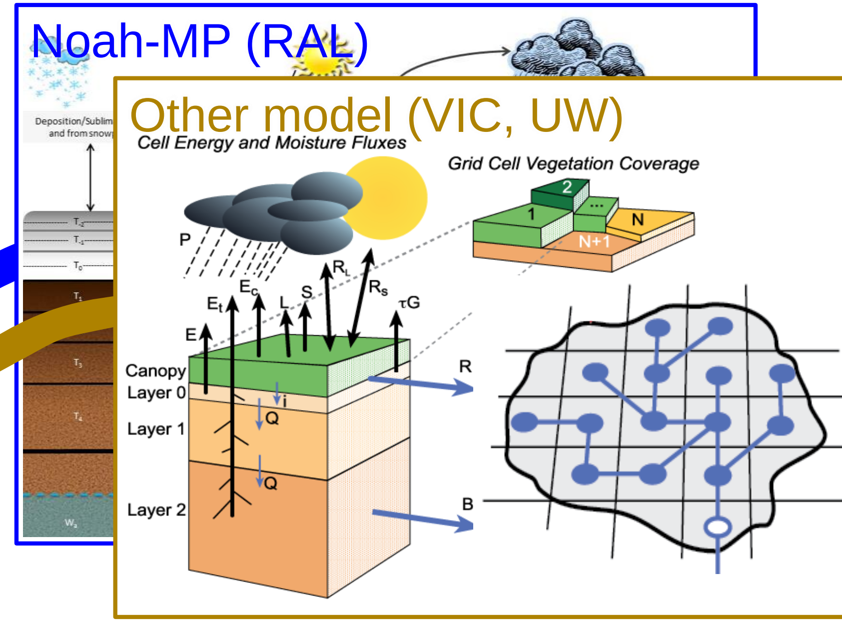


Clark et al., 2008; Mizukami et al., 2016

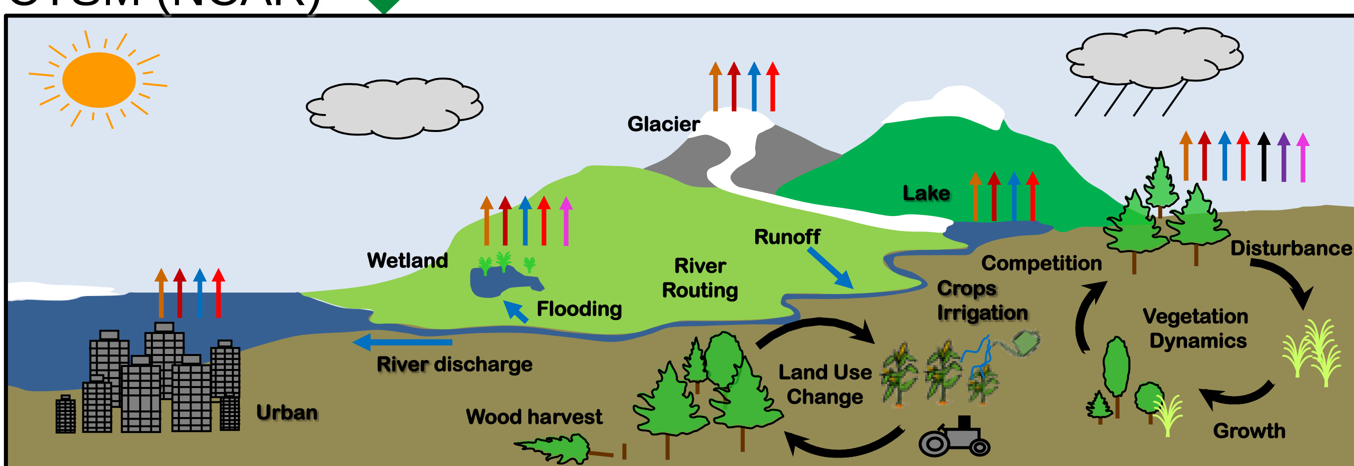
The Community Terrestrial Systems Model



unified design



CTSM (NCAR)



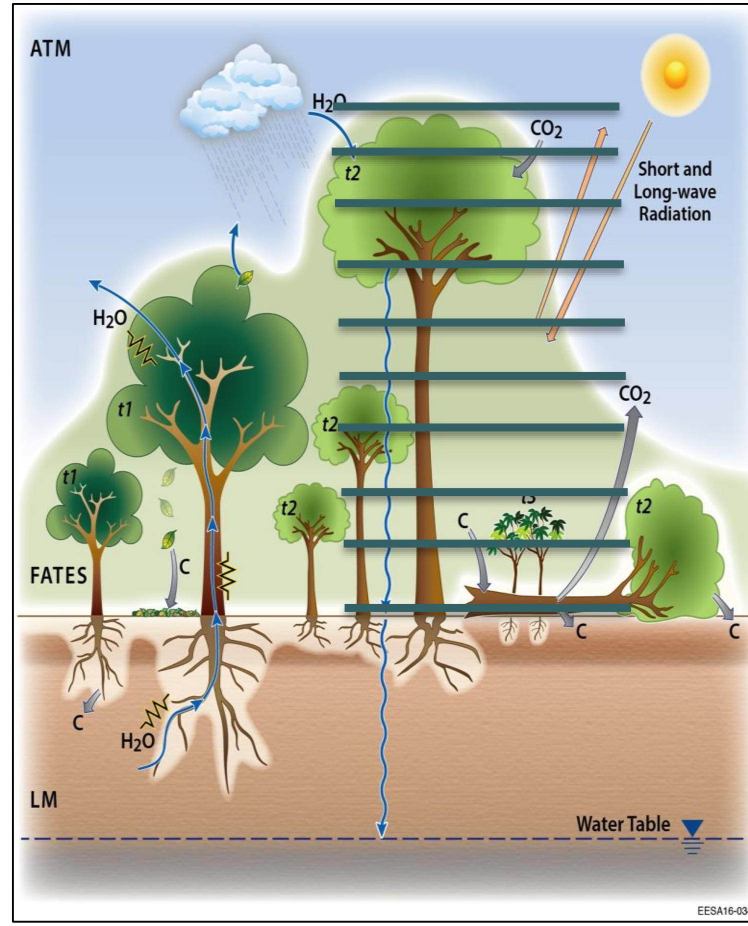
A community effort to unify and simplify the terrestrial components of an Earth System prediction framework.

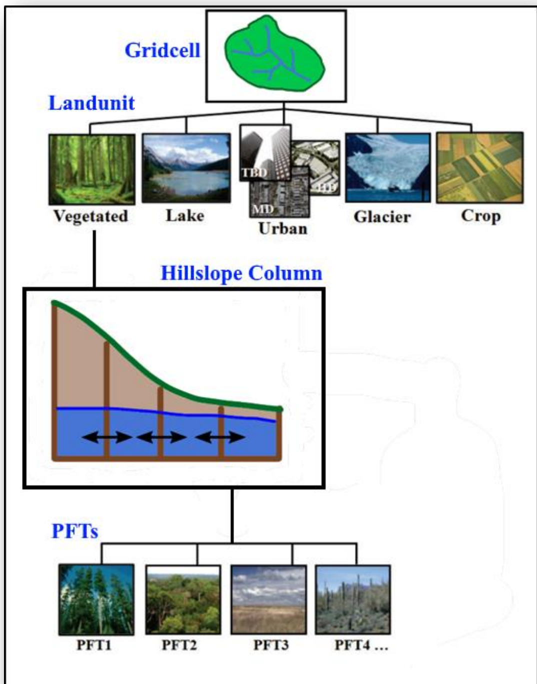
for research and prediction in climate, weather, water, and ecosystems

CTSM development

- Ecosystem vulnerability and impacts on carbon cycle and ecosystem services
- Sources of predictability from land processes
- Impacts of land use and land-use change on climate, carbon, water, and extremes
- Water and food security in context of climate change, climate variability, and extreme weather

Ecosystem Demography / Multi-layer canopy





Lateral fluxes of water

Water and land management

Application 2: Parallelization (OMP)

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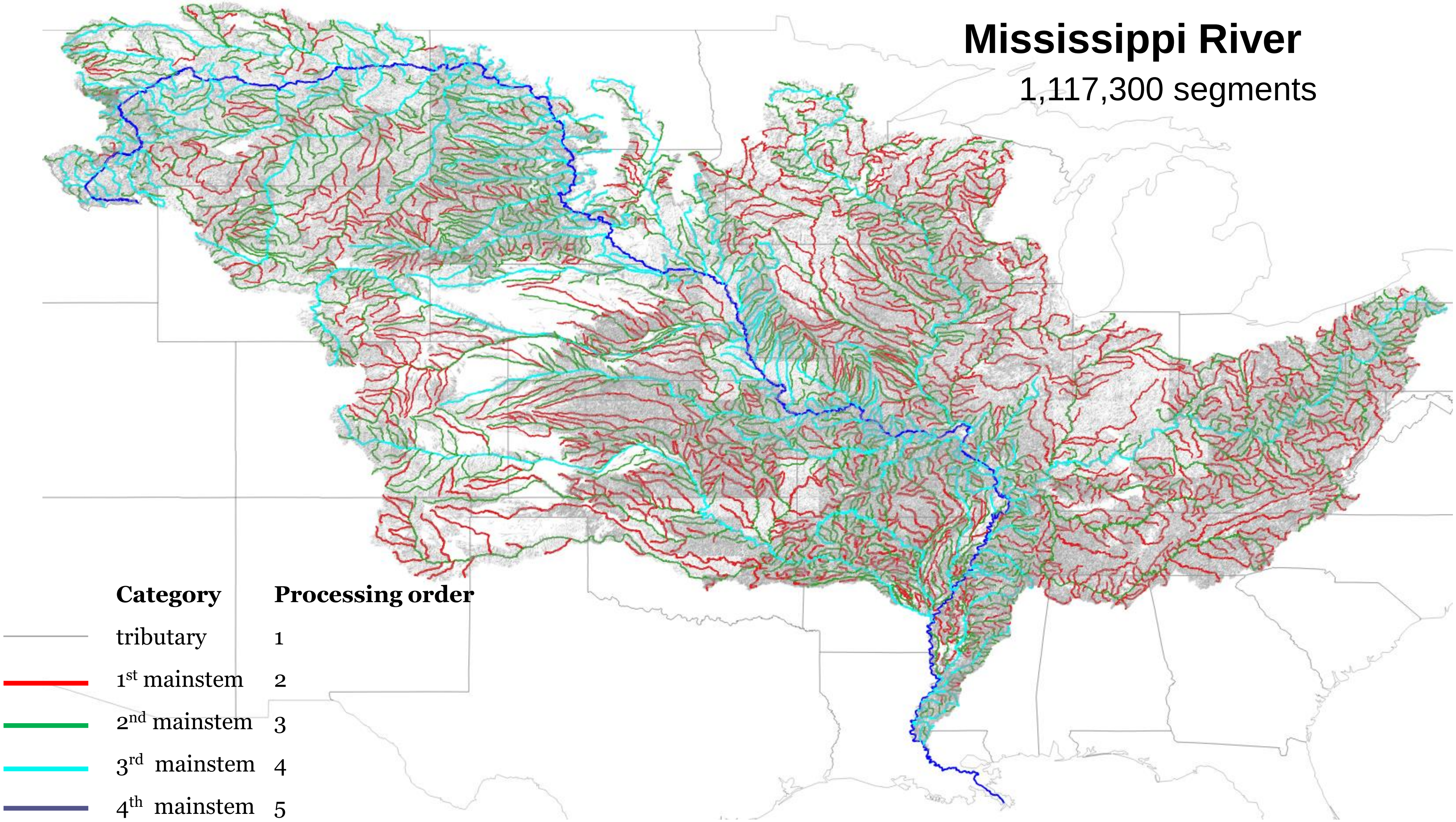
Pfafstetter numbering system helps classify stream segments into "mainstem" and "tributary" that can be processed independently

Parallel processing with OpenMP



Application 2: Parallelization (OMP)

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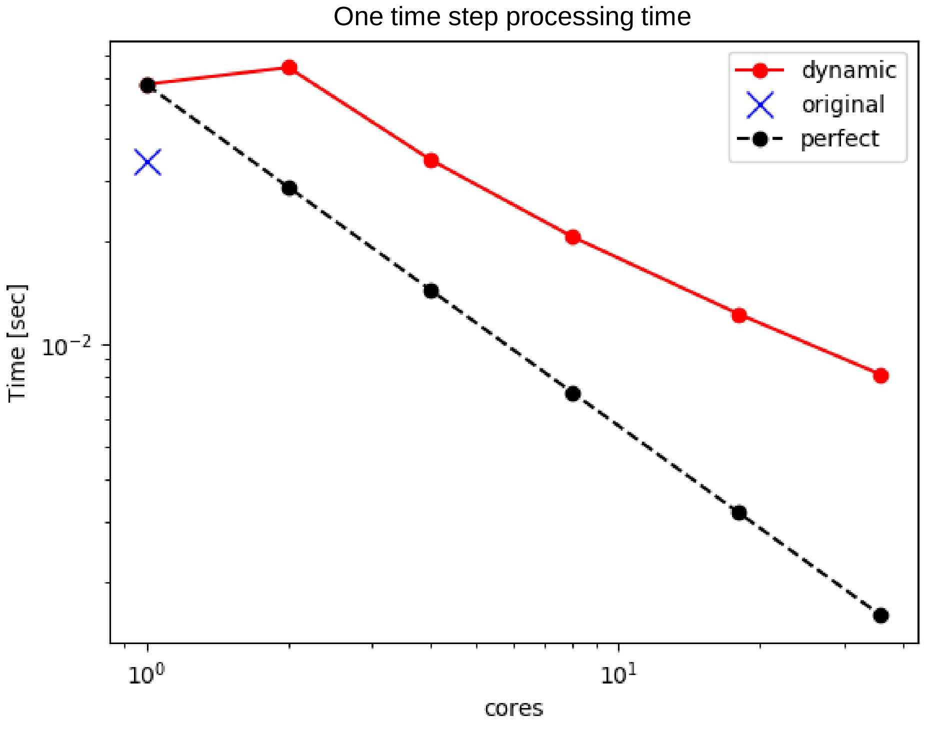
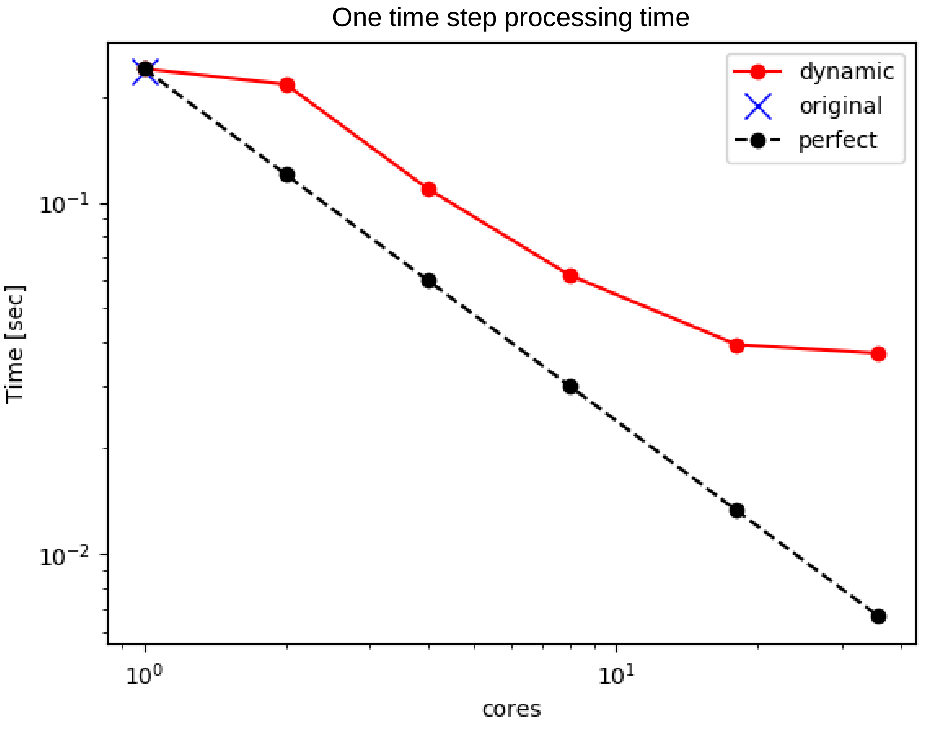
OpenMP Scaling

Unit hydrograph routing



Kinematic wave routing

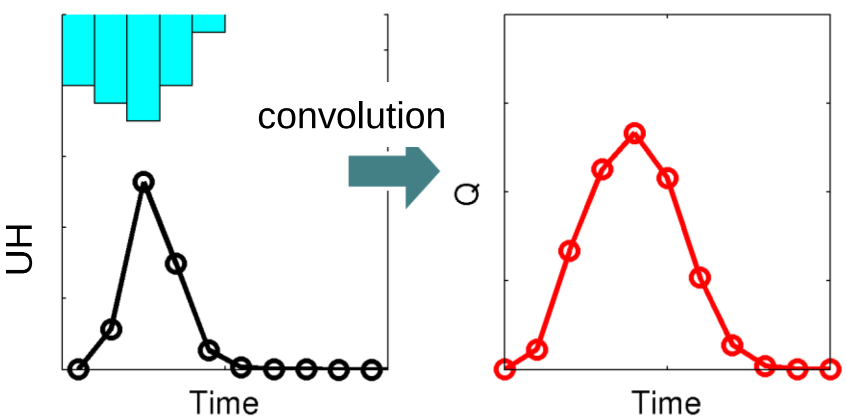


UH channel routing

Obtain streamflow at ③

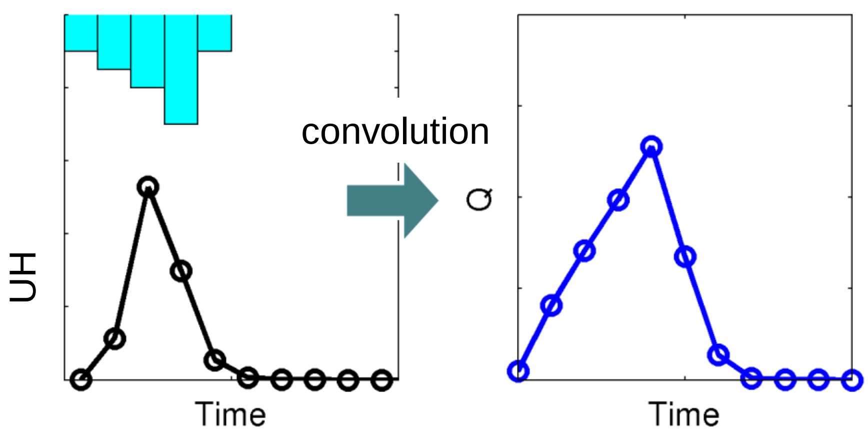
Route flow at ① through s2 + s3

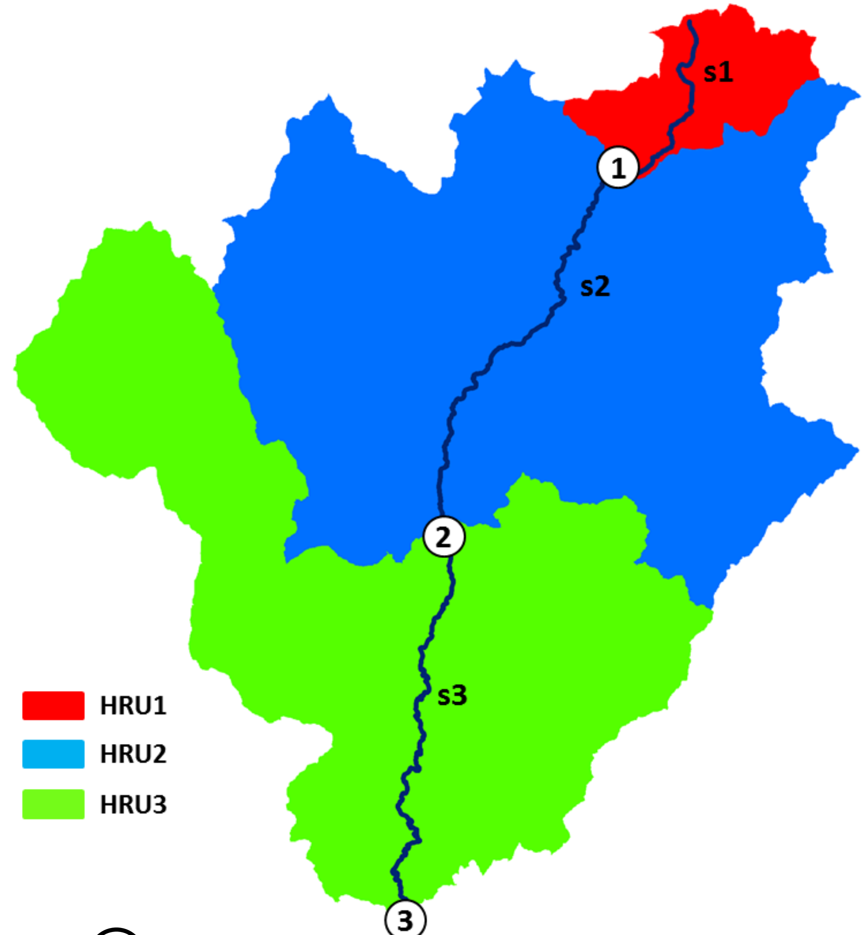
Runoff [L T-2]



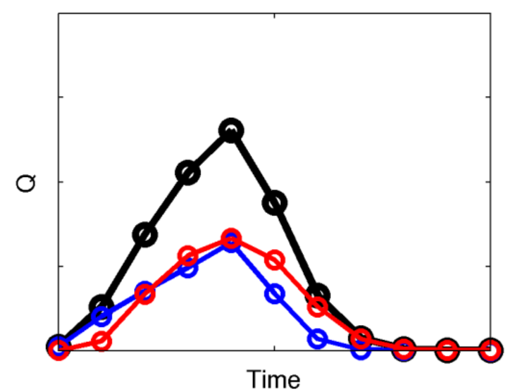
Route flow at ② through s3

Runoff [L T-2]





Q at ③



raph): the
lting from one
over HRU
time step

seg length [L]

rity [L T^{-1}]

D = diffusivity [L T^{-2}]