A Scalable River Network Simulator for Extreme Scale Computers using the PETSc Library

Getnet Betrie
Hong Zhang, Barry Smith, and Eugene Yan
Argonne National Laboratory, USA

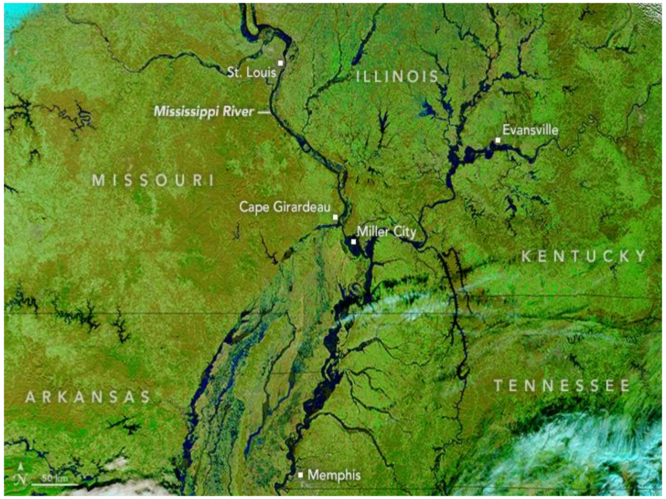
AGU Fall Meeting
Washington, D.C.
December 11, 2018

Outline

- Introduction
- PETSc/DMNetwork
- Numerical methods
- Test and scaling results
- Future work

Introduction

- Most flow routing models are not suitable river-basin scale and real-time applications
- Muskingum (kinematic) based parallel flow routing model developed
- Does not capture a wave propagation in the upstream direction
  - Backwater effect
  - Overestimate flood peak
  - $S_f \neq S_b$ in case of dam-break



Source: NASA (2016)

Dynamic

Diffusive

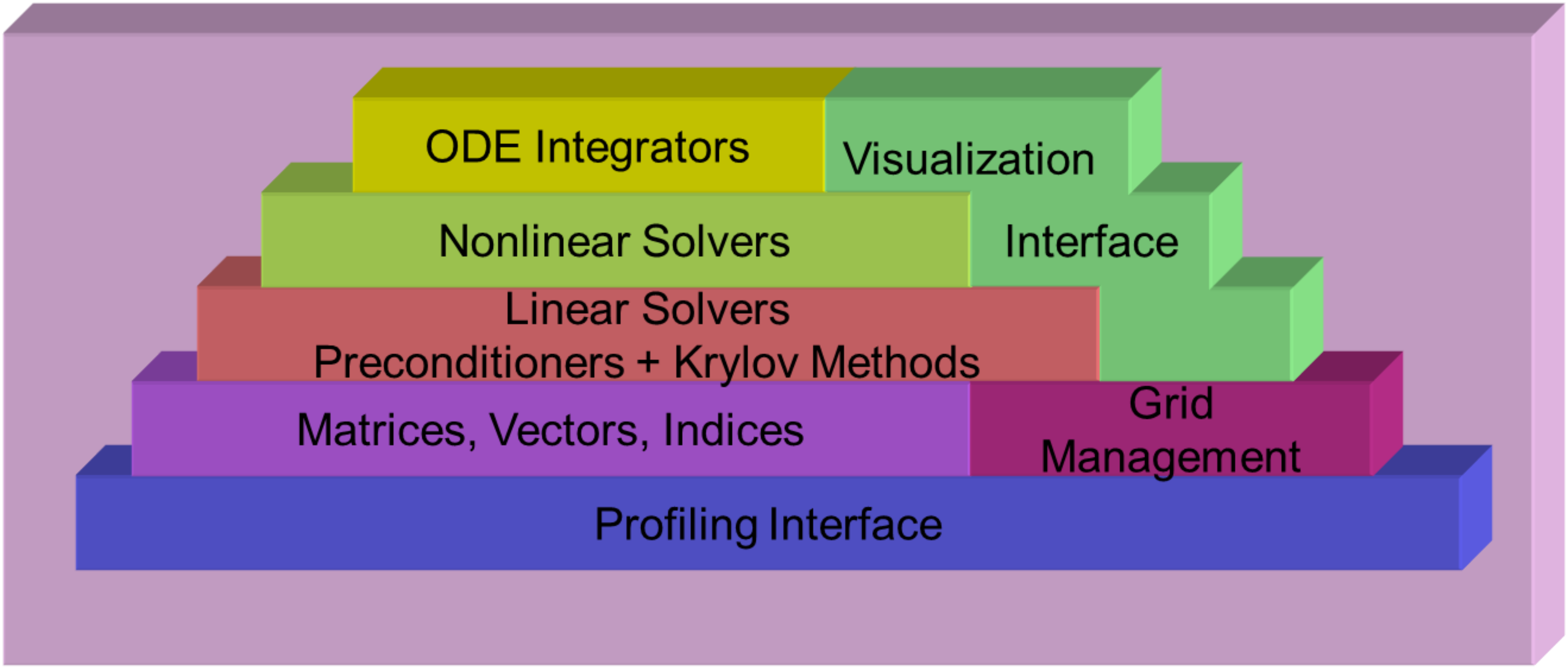
Kinematic

$$\frac{1}{g}\frac{\partial u}{\partial t} + \frac{u}{g}\frac{\partial u}{\partial x} + \frac{\partial h}{\partial x} + \left(S_f - S_b\right) = 0$$

- Scalable River Network Simulator (SRNS) developed to solve SW equations using PETSc/DMNetwork

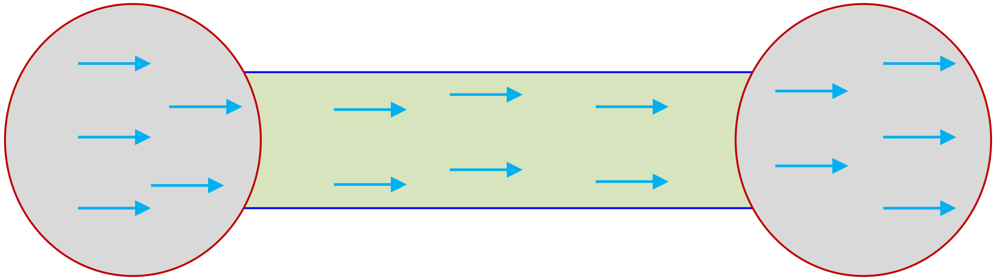
PETSc (Portable Extensible Toolkit for Scientific computation)

- High-performance software for the scalable (parallel) solution of scientific applications

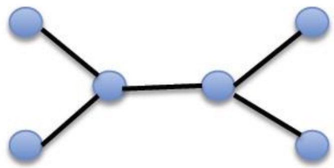


DMNetwork

- It is one of data management packages in PETSc
- Data and topology management for multiphysics PDE-based network problems
  - Circuits, power grid, gas networks, electrical and water distribution
- Design elements
  - Vertex: connection points in topology graph
  - Edge: a connection between vertices
  - Component: physics associated with vertex and edges

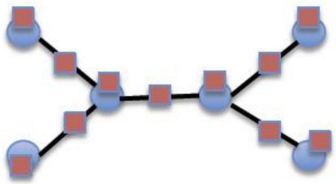


Steps for using DMNetwork



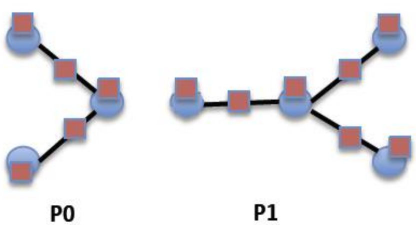
Set up graph →

DMNetworkLayoutSetup()



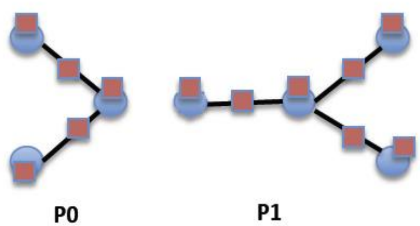
Add physics →

DMNetworkAddComponent()
DMNetworkAddNumVariables()



Partition →

DMNetworkDistribute()



Solve →

KSPSetDM/SNESSetDM/TSSetDM()
KSPSolve()/SNESSolve()/TSSolve()

One-dimensional Free Surface Flow Model

- Flow in a reach simulated

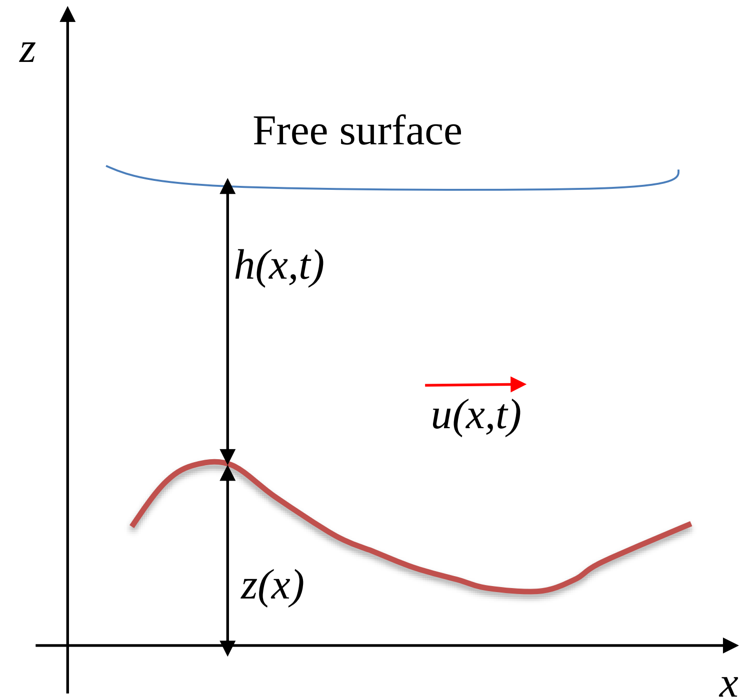
$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} = 0$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2 + \frac{1}{2}gh^2)}{\partial x} = gh(S_b - S_f)$$

- Flow in a junction

$$\sum q_i = 0, \forall i$$

$$h_i = h_j, \forall i \neq j$$



h is water depth

u is flow velocity

z bottom elevation

S_b is bed slope

S_f is friction term

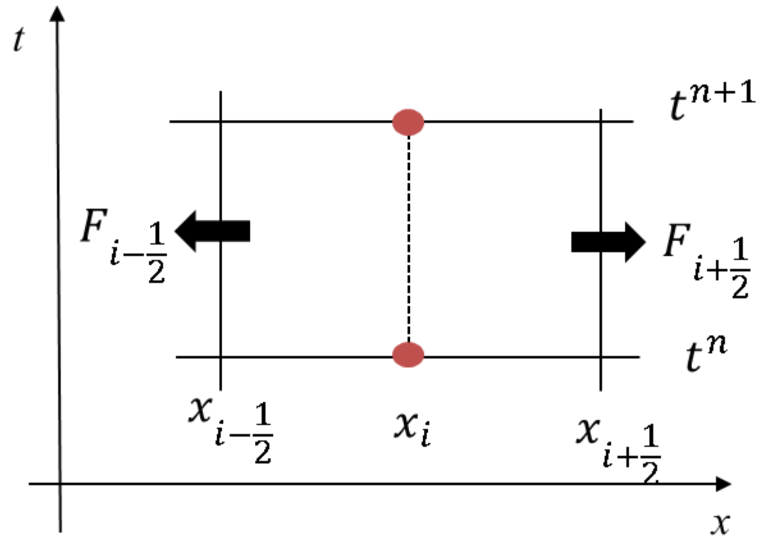
q_i is flow rate

Numerical Methods

- Finite volume method used

$$U_i^{n+1} = U_i^n - \frac{\Delta t}{\Delta x}\left[F_{i+\frac{1}{2}} - F_{i-\frac{1}{2}}\right]$$

$U_i = [h_i, q_i]$, $i = 1, \ldots, ncells$ on a reach



- Flux on cell interface is estimated
  - The Godunov method (first order)
  - Second order methods will be implemented

Numerical Methods Cont'd

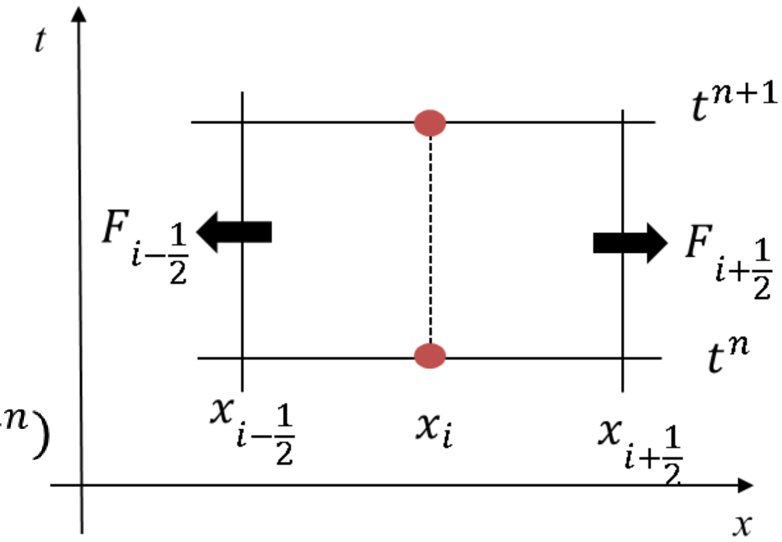
- Forward Euler used for time stepping

Step 1: Initialization at all grid cells

$$\frac{dU_i}{dt} = 0$$

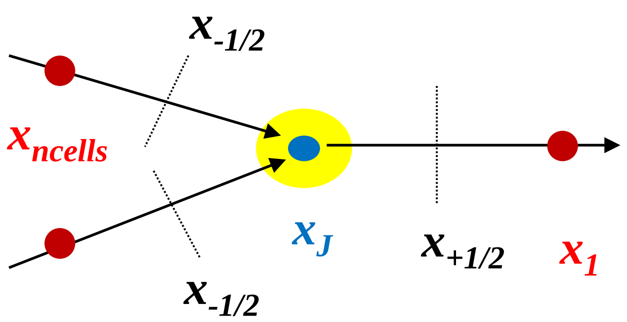
Step 2: Interior reach cells (*i=2 to ncell-1*)

$$\frac{dU_i}{dt} = -\frac{1}{\Delta x_i}\left[F_{i+\frac{1}{2}}(t^n) - F_{i-\frac{1}{2}}(t^n)\right] + S_i(t^n)$$



Step 3: Junction cell

$$\frac{dU_J}{dt} = -\frac{1}{\Delta x}\left[\sum F_{+\frac{1}{2}} - \sum F_{-\frac{1}{2}}\right]$$



Numerical Methods Cont'd

- Post-step processing at t^{n+1}

Step 1: Update ending cell points on a reach

$$h_1 = h_J^{US} \qquad h_{ncells} = h_J^{DS}$$

$$q_1 = \frac{q_J^{US}}{n_{out}} \qquad q_{ncells} = \frac{q_J^{US}}{n_{in}}$$

n_{out} : *number of out going reaches at* x_J^{US}

n_{in} : *number of incoming reaches at* x_J^{DS}

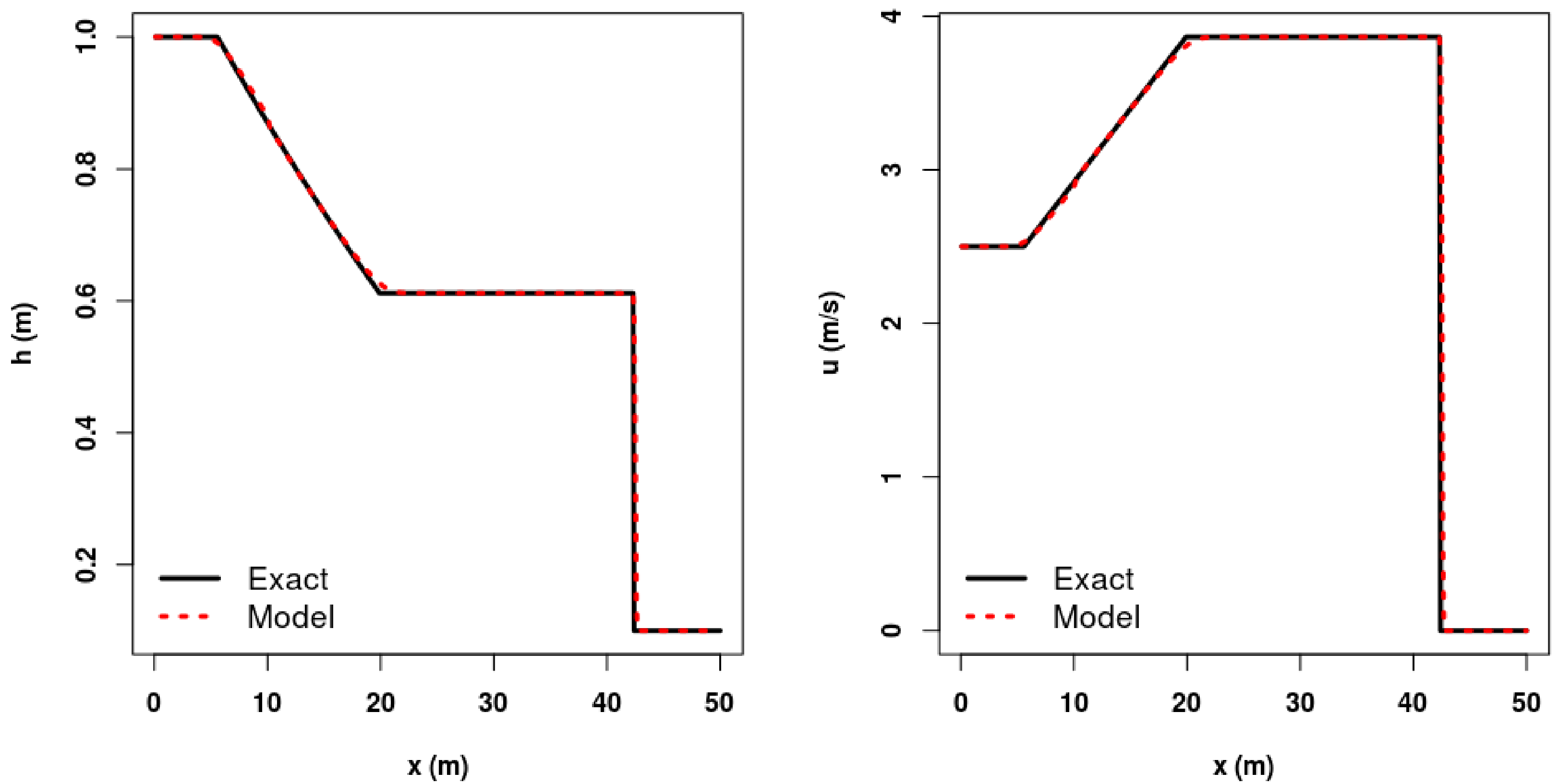
Step 2: Update boundary vertex points

- Reservoir
- Demand
- Inflow
- Others

Benchmark Test 1: Dam-break Problems (Toro, 2001)

$$h(x) = \begin{cases} h_L = 1 & 0 < x \le 10 \\ h_R = 0.1 & 10 < x \le 50 \end{cases} \qquad u(x) = \begin{cases} u_L = 2.5 & 0 < x \le 10 \\ u_R = 0.0 & 10 < x \le 50 \end{cases}$$

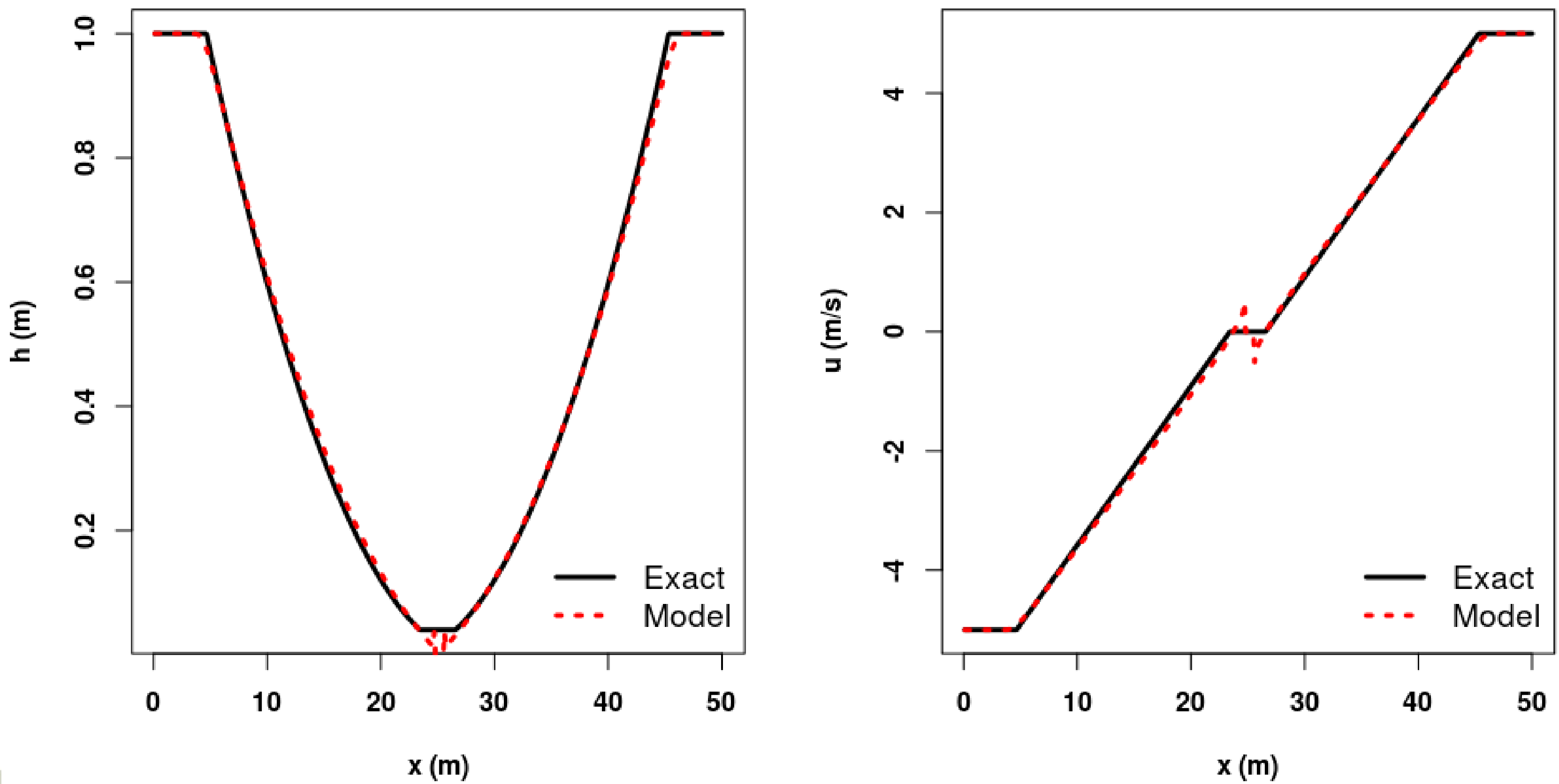
Simulated left rarefaction and right shock waves



Benchmark Test 2 : Dam-break Problems (Toro, 2001)

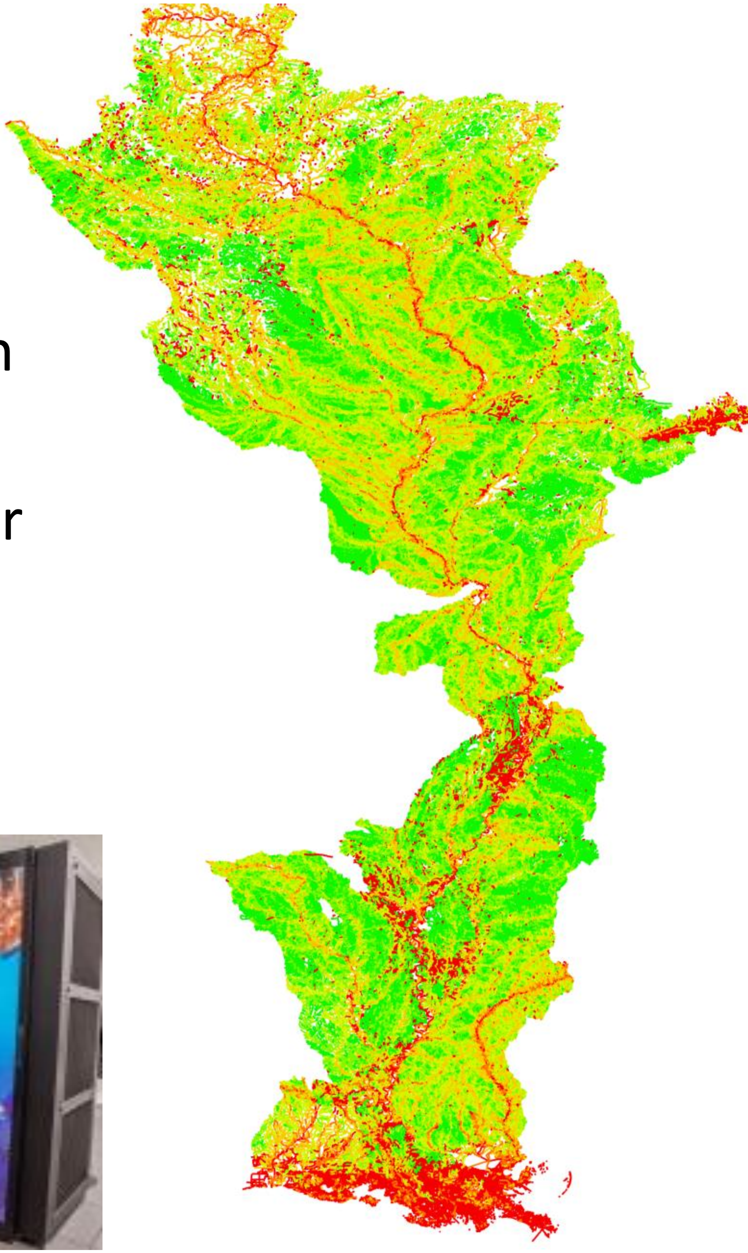
$$h(x) = \begin{cases} h_L = 1 & 0 < x \leq 25 \\ h_R = 1 & 25 < x \leq 50 \end{cases} \qquad \mathrm{u}(x) = \begin{cases} u_L = -5 & 0 < x \leq 25 \\ u_R = 5 & 25 < x \leq 50 \end{cases}$$

Simulated left and right rarefactions waves which generate nearly dry bed



Scaling Study

- The Mississippi River simulated for scaling test
- Represents 1/8th of the total reaches in the conterminous U.S.
- NHDPlus dataset used to setup the river network
- Simulation conducted on Theta at ANL



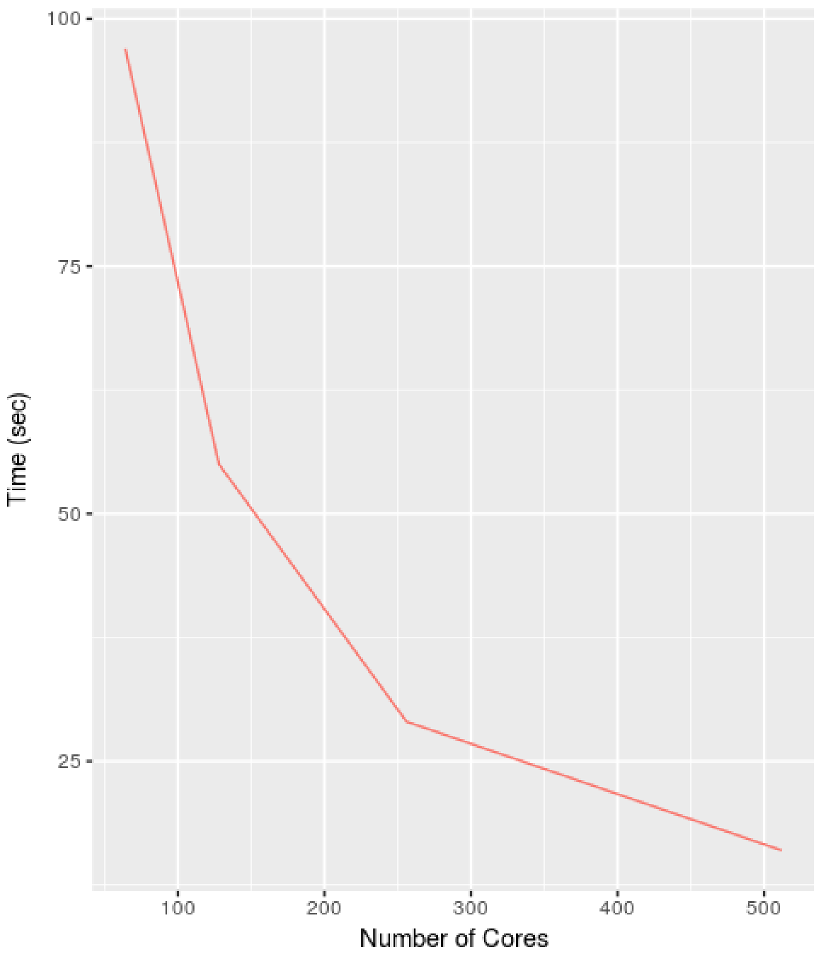
11.69 petaflops system

4,392 (node) x 64 (cores)

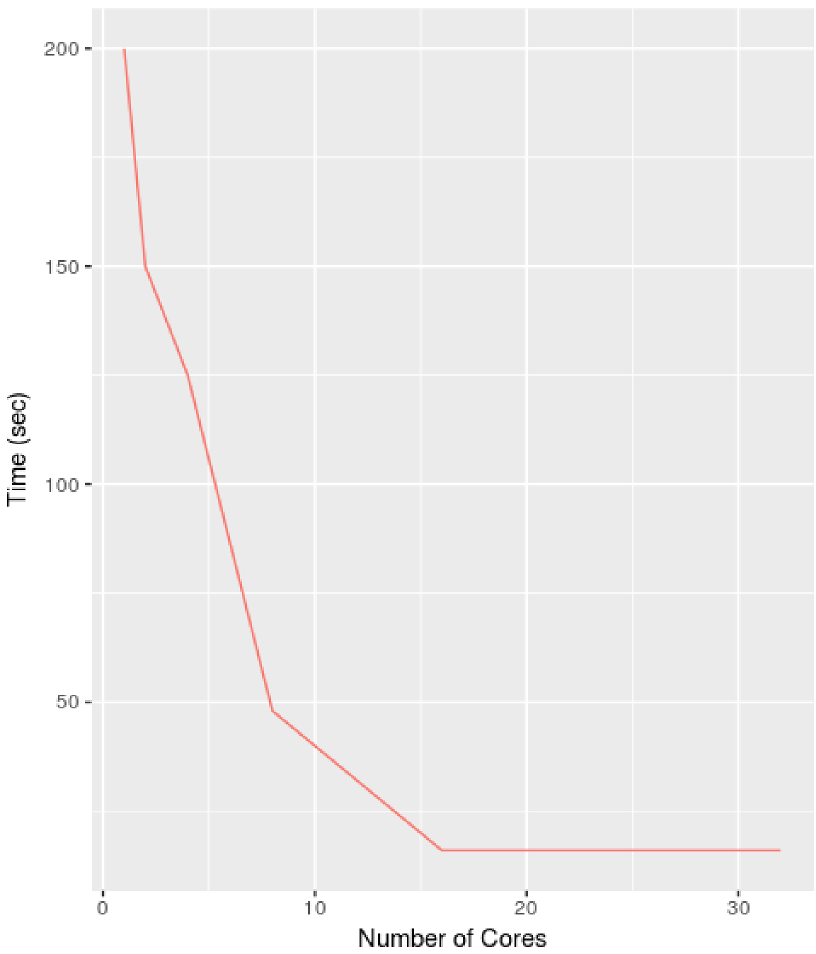
Total cores = 281,088

Scaling Results

SRNS: 28,894,804 unknowns

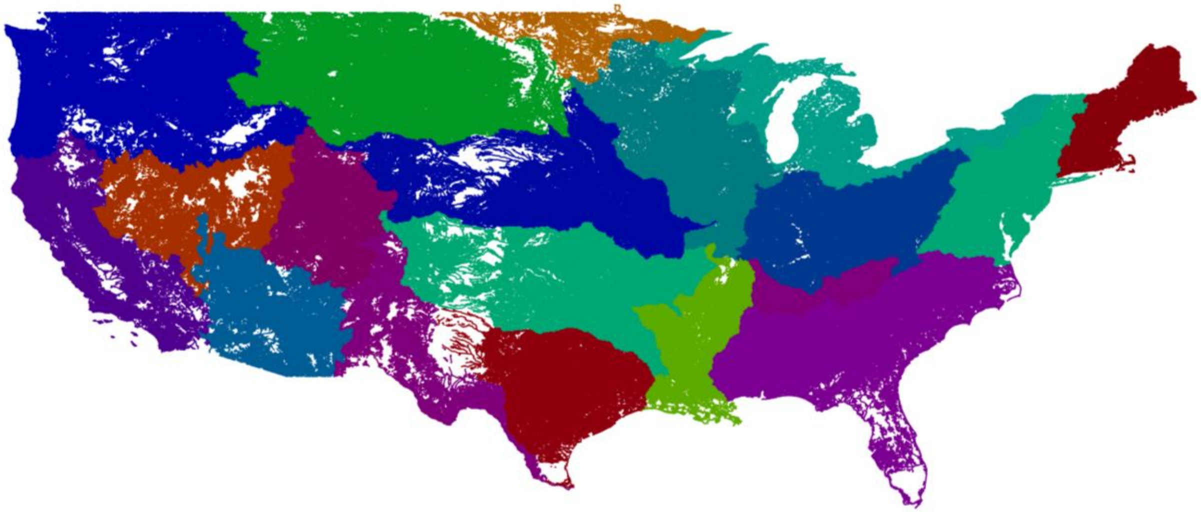


RAPID (David et al. 2011): Upper Mississippi simulation



Future work

- Implement second order methods to compute flux
- Conduct additional tests to verify the improved implementation
- Simulate the river networks for the conterminous U.S. using subnetwork option provided by DMNetwork
- Couple it with Earth System Models



Thank you!

Contact: gbetrie@anl.gov