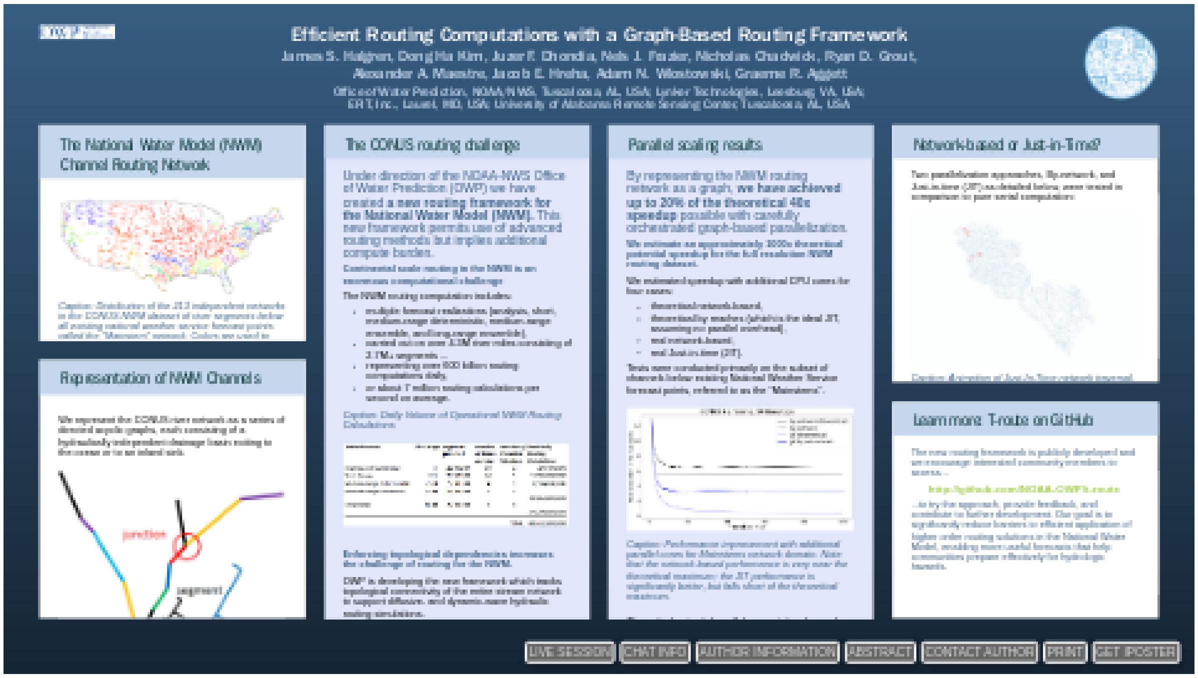
Efficient Routing Computations with a Graph-Based Routing Framework



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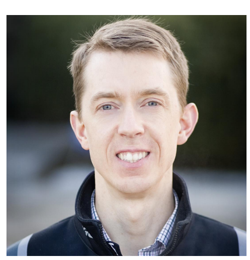

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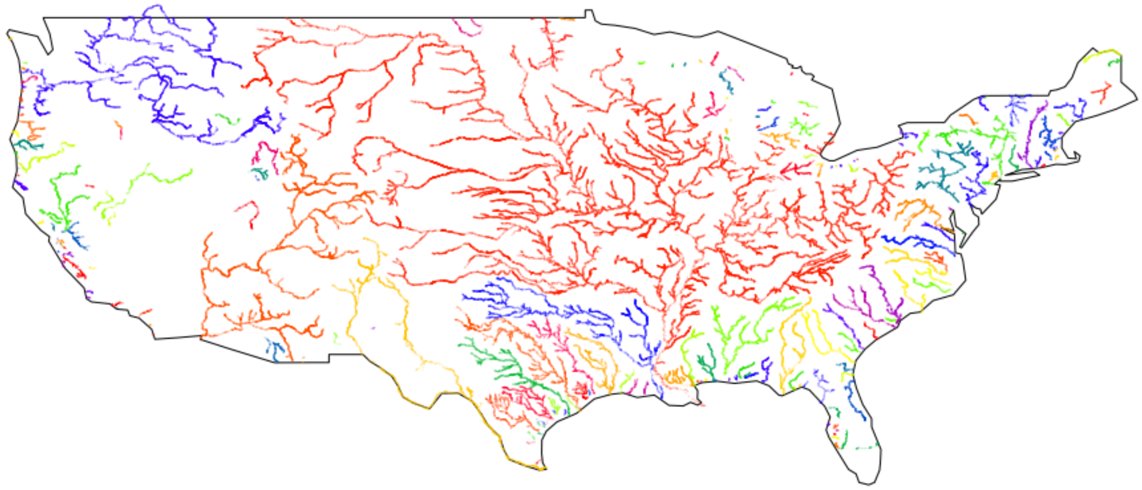
THE NATIONAL WATER MODEL (NWM) CHANNEL ROUTING NETWORK



Caption: Distribution of the 213 independent networks in the CONUS NWM dataset of river segments below all existing national weather service forecast points called the "Mainstem" network. Colors are used to indicate independent networks, each draining to unique tailwater segments at the CONUS boundary.

Using the NHD+ V2.0 Medium Resolution data set, the CONUS river network is composed of:

- 4.3M stream/river miles
- 2,729,077 individual segments
- 2,102,010 reaches
- 1,029,217 junctions, and
- 14,713 independent drainage basins (disjoint networks).

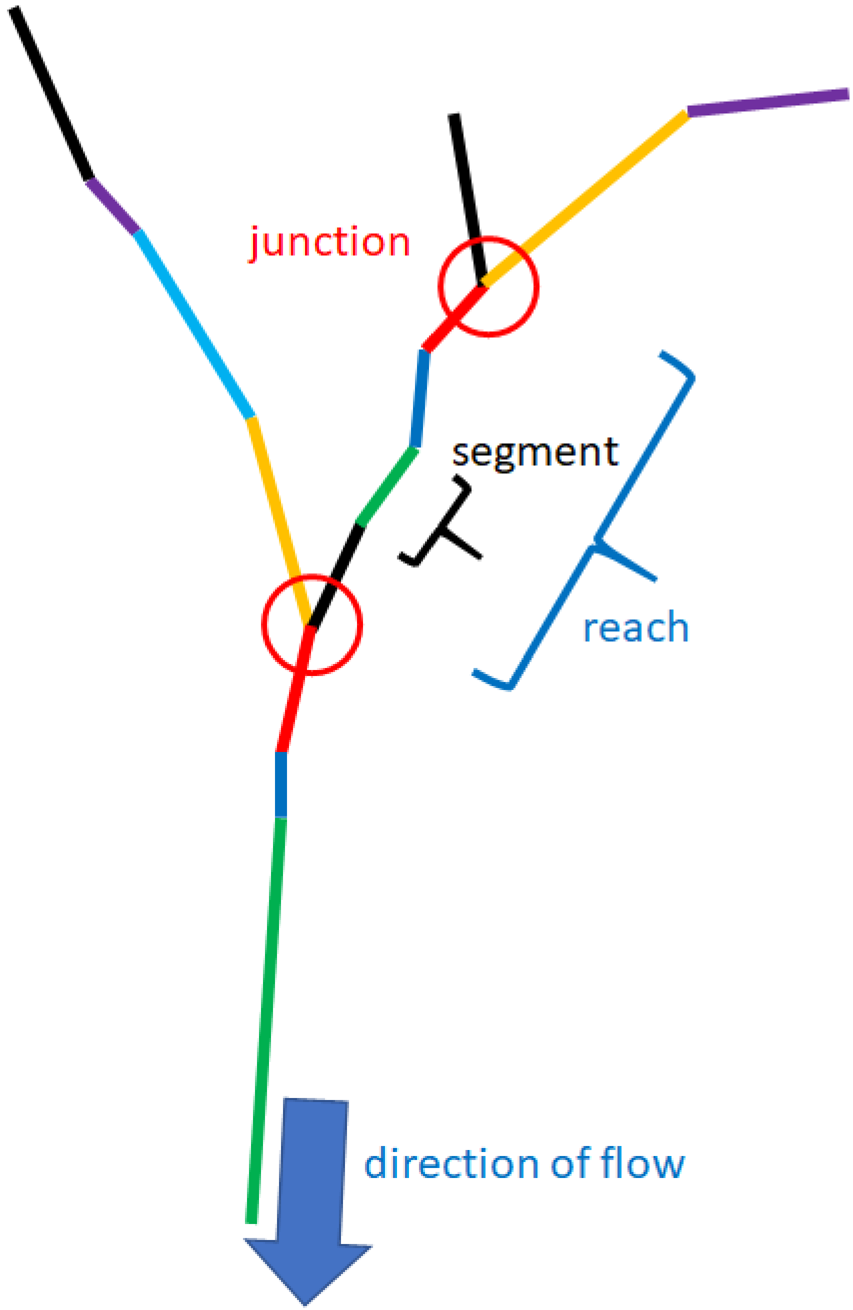
Terminal segments, which represent river outlets emptying into the ocean or an inland sink, define independent river networks within the larger NWM routing dataset. There are more than 5,000 terminal segments of order 1, meaning that they define an independent network consisting of a single reach with no tributaries emptying directly into the ocean. Only the Mississippi outlet reaches order 10

Strahler order of network outlet	Number of independent networks	*Cumulative Independent networks*	Segments of given order	*Cumulative segments*
Order 10	1	*1*	441	*441*
Order 9	2	*3*	3,334	*3,775*
Order 8	4	*7*	7,495	*11,270*
Order 7	31	*38*	20,956	*32,226*
Order 6	87	*125*	48,275	*80,501*
Order 5	230	*355*	91,386	*171,887*
Order 4	987	*1,342*	170,417	*342,304*
Order 3	1972	*3,314*	315,289	*657,593*
Order 2	5788	*9,102*	598,992	*1,256,585*
Order 1	5611	*14,713*	1,472,492	*2,729,077*

Caption: Tabulation of orders represented in the 14k+ independent networks of the NWM channel dataset network. Distribution of the 213 independent networks in the CONUS NWM dataset of river segments below all existing national weather service forecast points.

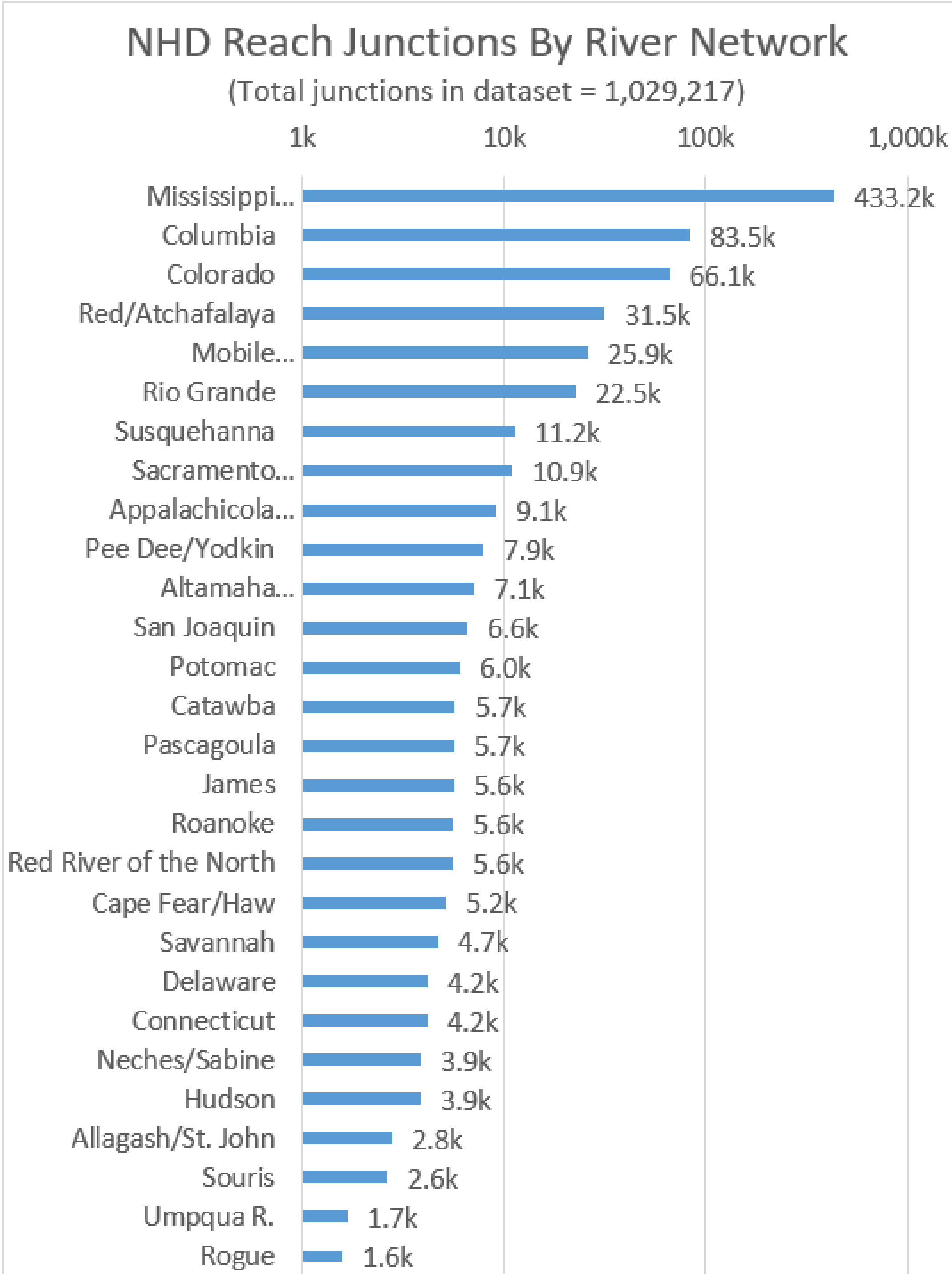
REPRESENTATION OF NWM CHANNELS

We represent the CONUS river network as a series of directed acyclic graphs, each consisting of a hydraulically independent drainage basin exiting to the ocean or to an inland sink.



Caption: *Elementary components of the CONUS river network graph. The smallest elements, denoted by discrete colors, are individual stream segments. Linear combinations of segments between junctions form reaches. Junctions exist at the confluence of two or more reaches.*

Network complexity, expressed as a number of junctions, is a useful measure of the level of dependence of the graph, and gives an idea of the computational burden for each independent network.



Caption: *Size distribution of river networks with greater than 2k junctions in the CONUS NWM dataset.*

THE CONUS ROUTING CHALLENGE

Under direction of the NOAA-NWS Office of Water Prediction (OWP) we have created **a new routing framework for the National Water Model (NWM).** This new framework permits use of advanced routing methods but implies additional compute burden.

Continental scale routing in the NWM is an enormous computational challenge

The NWM routing computation includes:

- multiple forecast realizations (analysis, short, medium-range deterministic, medium-range ensemble, and long-range ensemble),
- carried out on over 4.3M river miles consisting of 2.7M+ segments ...
- representing over 600 billion routing computations daily,
- or about 7 million routing calculations per second on average.

Caption: Daily Volume of Operational NWM Routing Calculations

NWM Forecast	***Time Steps***	***Segments (approx.)***	***Number of Times per day***	***Number of Ensemble Members***	***Total Daily Routing Calculations***
Analysis and Assimilation	3	2,700,000	24	1	194,400,000
Short Range	216	2,700,000	24	1	13,996,800,000
Medium Range deterministic	2880	2,700,000	4	1	31,104,000,000
Medium Range ensembles	2448	2,700,000	4	7	185,068,800,000
Long Range	8640	2,700,000	4	4	373,248,000,000
				TOTAL	603,612,000,000

Enforcing topological dependencies increases the challenge of routing for the NWM.

OWP is developing the new framework which tracks topological connectivity of the entire stream network to support diffusive- and dynamic-wave hydraulic routing simulations.

Tracking the topological connectivity and enforcing dependence of the calculations permits use of the routing methods, but also means that some calculations must wait for others to be completed instead of being completely embarrassingly parallel within each timestep. The current method uses simplifying assumptions, incompatible with higher-order routing solutions, to allow for simplified, fully parallel routing execution within each timestep.

Our challenge was to introduce this topological dependency in the NWM routing framework while still managing the required hourly calculation volume.

Here, we present our routing framework and a computing scheme to drive rapid parallel computation while maintaining the topological dependence of the routing network.

PARALLEL SCALING RESULTS

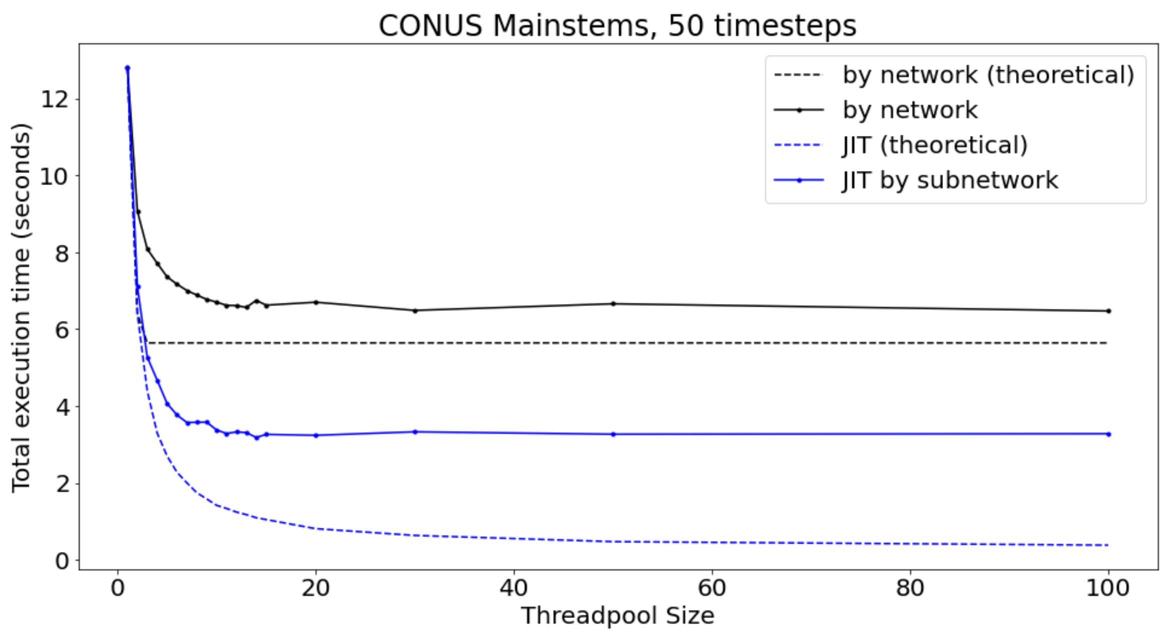
By representing the NWM routing network as a graph, **we have achieved up to 20% of the theoretical 40x speedup** possible with carefully orchestrated graph-based parallelization.

We estimate an approximately 1000x theoretical potential speedup for the full resolution NWM routing dataset.

We estimated speedup with additional CPU cores for four cases:

- theoretical network-based,
- theoretical by reaches (which is the ideal JIT, assuming no parallel overhead),
- real network-based,
- real Just-in-time (JIT).

Tests were conducted primarily on the subset of channels below existing National Weather Service forecast points, referred to as the "Mainstems".



Caption: Performance improvement with additional parallel cores for Mainstems network domain. Note that the network-based performance is very near the theoretical maximum; the JIT performance is significantly better, but falls short of the theoretical maximum.

Theoretical potential parallel computational speedup is calculated as the ratio of the total segment count to the parallel method limiting size.

Network-based parallel execution limited by total segment count of largest network.

- Estimated 2x speedup in both Mainstems and Full Resolution datasets (Mississippi basin accounts for roughly half of the total segment count.)
- Experimental results yielded close to the theoretical maximum.

JIT method speedup limited by largest network depth, i.e., length of path from the furthest headwater to the outlet.

- Depth of Mainstems network mississippi basin is 73 reaches compared to 27k reaches overall so JIT theoretical maximum improvement is 27k / 73 (i.e., ~40x)
- Experimental results yield about 10% efficiency (i.e. ~4x speedup). Careful re-distribution of subnetworks to threads has yielded a 20% efficiency in a smoke test (i.e. 8x speedup).

- Theoretical potential performance improvement grows with network size -- the depth of the Mississippi Basin in the Full resolution dataset is 2218 reaches compared to 2.1M reaches overall so JIT theoretical maximum improvement is 2.1M / 2218 (i.e., ~1000x).

The actual speedup will be affected by numerous computational realities including: i/o overhead, parallel thread or process pool spin-up time, array access efficiency (i.e. cache misses), etc.

NETWORK-BASED OR JUST-IN-TIME?

Two parallelization approaches, By-network, and Just-in-time (JIT) as detailed below, were tested in comparison to pure serial computation:

Caption: Animation of Just-In-Time network traversal, with calculations on separate portions of the tree coalescing to finish simultaneously at the outlet. At any moment in the animation, red sparks highlight reaches of a common reverse network order that may be computed in parallel.

Serial computation

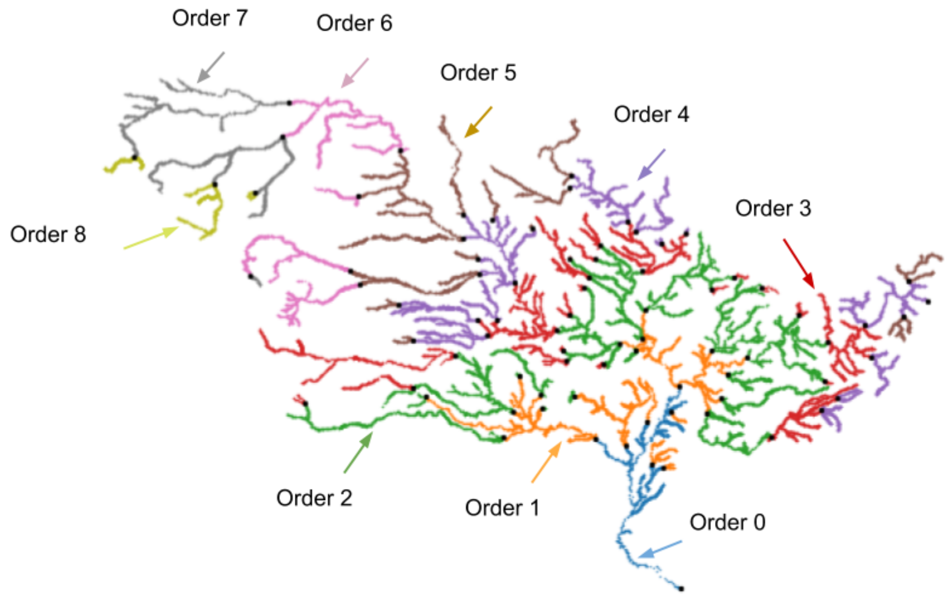
- Starting upstream, proceeding downstream,
- One network at a time.
- Computationally inefficient, but a useful benchmark.

Independent network parallelization

- Divide computation according to separate networks, e.g., the Colorado River, Mississippi, etc. are computed independently.
- Performance limited by the size of the largest basin, i.e., the Mississippi.

Just-In-Time parallelization

- Calculate first the headwater reaches of edges of the longest network...
- Followed by all reaches below headwaters, etc.
- Orchestrating the computation so each dependency is computed just before it is needed downstream (hence "Just-in-time") provides best theoretical potential speedup.
- Practical efficiencies are obtained by grouping the reaches into cascading orders of subnetworks.



Caption: Grouping the reaches into subnetworks balances the practical impact of many parallel calls. An optimal subnetwork size is small enough to permit sufficient parallelism and large enough to ensure that parallel overhead is not burdensome. Colors denote subnetworks of common reverse network order. Higher order subnetworks are computed prior to lower order subnetworks in order to maintain topological dependencies.

LEARN MORE: T-ROUTE ON GITHUB

The new routing framework is publicly developed and we encourage interested community members to access...

http://github.com/NOAA-OWP/t-route (http://github.com/NOAA-OWP/t-route)

...to try the approach, provide feedback, and contribute to further development. Our goal is to significantly reduce barriers to efficient application of higher order routing solutions in the National Water Model, enabling more useful forecasts that help communities prepare effectively for hydrologic hazards.

AUTHOR INFORMATION

The authors are part of the development team for the National Water Model at the Office of Water Predcition for NOAA's National Weather Service. We wish to gratefully acknowledge the excellent work of the OWP and NCAR teams (and others) who have prepared the National Water Model as it stands today. Author affililiations are as follows: James S. Halgren[1,2], Dong Ha Kim[1,2], Juzer F. Dhondia[1,4], Nels J. Frazier[1,3], Nicholas Chadwick,[1,3], Ryan D. Grout[1,2], Alexander A. Maestre[1,4], Jacob E. Hreha[1,2], Adam N. Wlostowski[1,2], Graeme R. Aggett[2]

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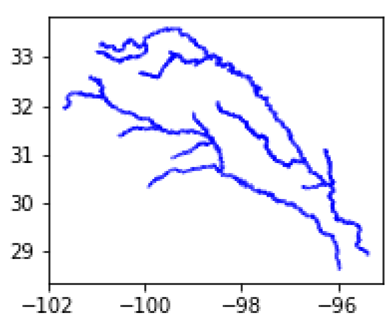
ABSTRACT

To resolve non-uniform and unsteady flows in the National Water Model (NWM), the Office of Water Prediction is developing additional routing engines to power simulations with the dynamic and diffusive approximations of the St Venant equations. This gives rise to two major computational challenges. First, the presence of both upstream and downstream boundary conditions requires tracking topological connectivity of the entire network within the computation. Second, all solution methods, whether explicit or implicit, become computationally expensive when scaled to continental domains. To be viable for operational modeling as an element of the National Water Model, the computational framework for dynamic routing must address these challenges.

We present a continental-scale flow routing framework that represents the flow network as a collection of directed acyclic graphs where edges point in the direction of downstream flow. We use information from this graph representation to efficiently drive a parallelized computation of flow from headwaters downstream to the tailwaters. This approach has achieved modest performance gains in terms of overall compute time and resources for the routing cases we have tested. The framework is publicly developed and we encourage interested community members to use our approach and provide feedback.

Initial results show that we can simulate 5 days of continental scale flow routing below all existing national weather service forecast points in approximately 10 minutes using only 4 processors. Also, the new framework permits computation using upstream dependencies in all timesteps, which is not possible in the present NWM routing framework. We will continue our work with the goal of significantly reducing barriers to efficient application of higher order routing solutions in the National Water Model, enabling more useful forecasts that help communities prepare for hydrologic hazards.



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