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Efficient diffusive routing computation for the National Water Model v3.0 using a topological relationship map

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OWP OFFICE OF WATER PREDICTION

INTRODUCTION

- The Muskingum-Cunge channel routing method of the current version of the National Water Model (NWM) is not suitable for capturing significant backwater effect.
- To better predict backwater flooding, the Office of Water Prediction has undertaken to add new hydraulic channel routing capabilities to the NWM v3.0.
- The MC uses terrain grid as its spatial domain and computes flow and depth upstream-to-downstream only while hydraulic channel routing methods use both upstream-to-downstream and downstream-to-upstream for satisfying boundary conditions.
- To make the bidirectional computation possible, a new channel routing framework that reads a channel network or sub-network as a whole in each direction is required.

METHOD

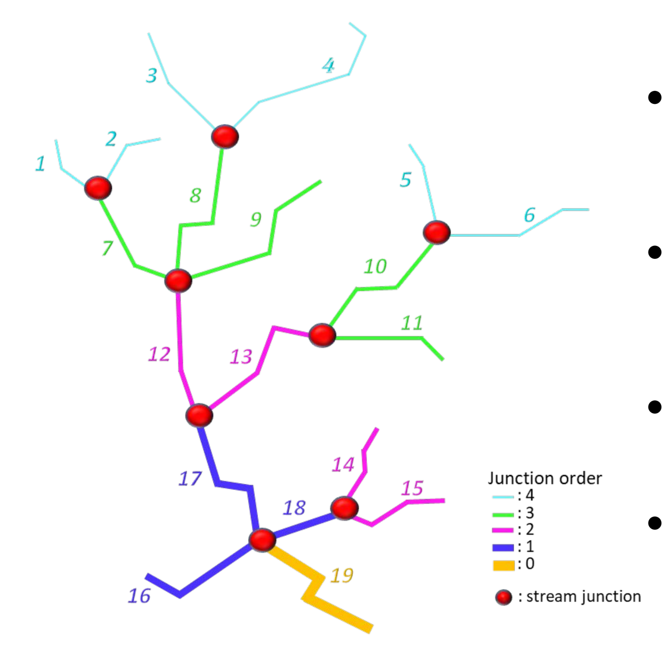


Figure 1. Channel network diagram

- We built a continental-scale flow routing framework that represents a channel network as a collection of directed acyclic graphs (DAG) (Halgren et al. 2020).
- In the DAG, stream junctions are topologically ordered so that an upstream junction has a higher order than the downstream junction as shown in Figure 1.
- Sub-networks of the same order value are independent of each other as they do not pass any water volume across.
- We use this ordering to sequentially solve flow and depth in diffusive routing as laid out in Table 1.

Table 1. Channel network connection lookup table for hydraulic channel routing

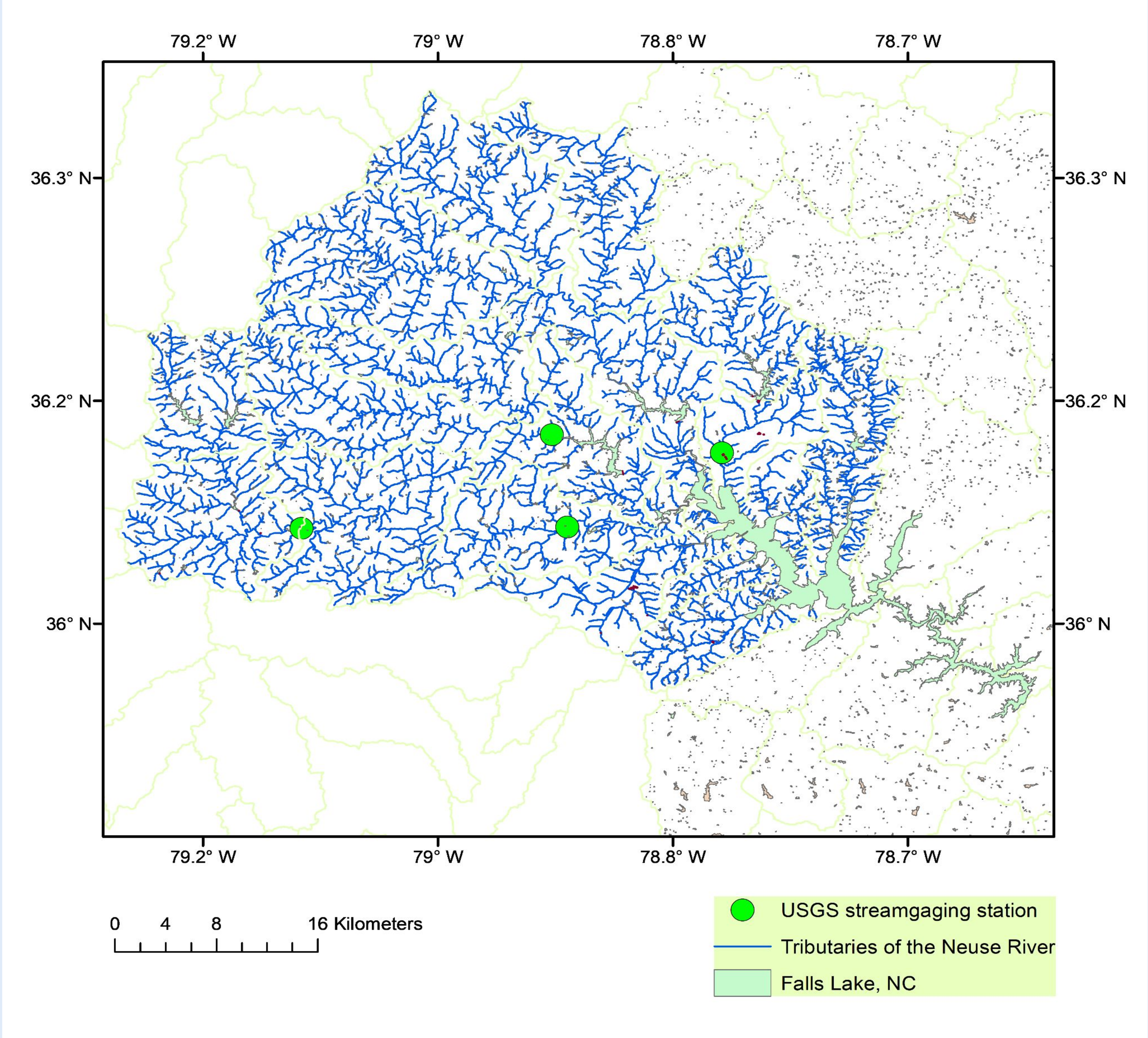
j*	Total nodes[a]	j of ds.[b] reach	Total us.[c] reach	j of us. reach	j of us. reach	j of us. reach
1	n_1	7	0			
2	n_2	7	0			
3	n_3	8	0			
4	n_4	8	0			
5	n_5	10	0			
6	n_6	10	0			
7	n_7	12	2	1	2	
8	n_8	12	2	3	4	
9	n_9	12	0			
10	n_{10}	13	2	5	6	
11	n_{11}	13	0			
12	n_{12}	17	3	7	8	9
13	n_{13}	17	2	10	11	
⋮	⋮	⋮	⋮	⋮	⋮	⋮

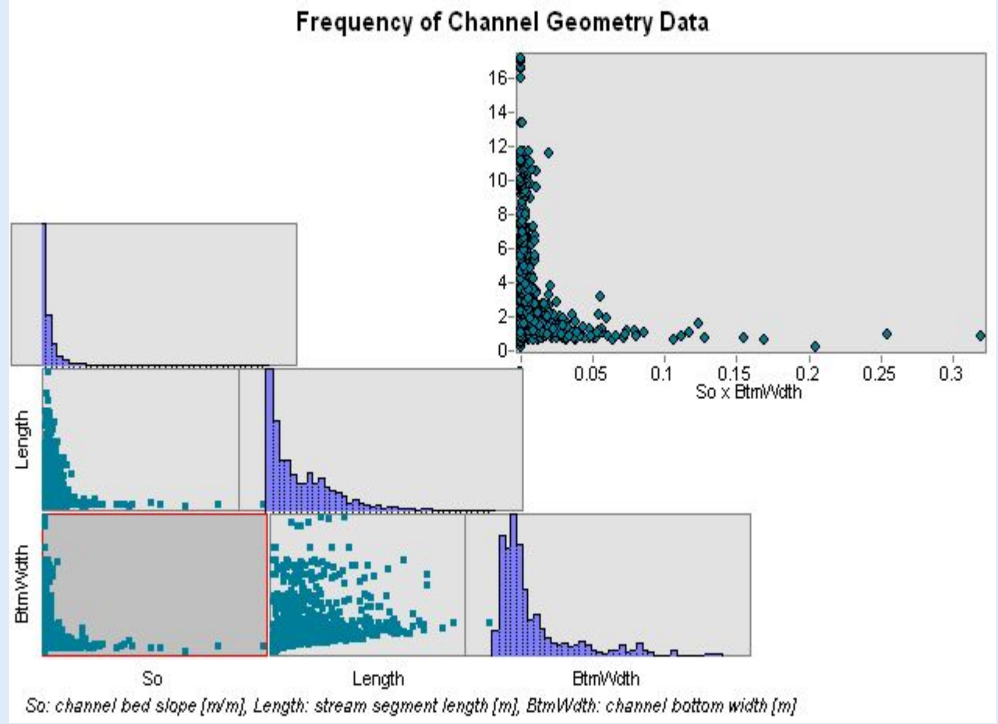
* Stream reach index marked on the network diagram is identical to the row index of this table as well as the computation sequence of diffusive routing.
[a] Diffusive wave routes water at each node and thus the number of nodes is always one more than the number of stream segments within a stream reach.
[b] Downstream. [c] Upstream.

- Each stream reach is numbered sequentially from 1, starting for reaches of the highest-to- lowest order as shown in Figure 1.
- Upstream-to-downstream and downstream-to-upstream connectivities are recorded in the form of such assigned integer reach numbers, as displayed in Table 1.
- This lookup table enables an efficient passing of input datasets, described in Figure 2.
- The row index value of the table locates a steam reach of the same value to be routed in the ascending order.

Channel network-based routing technique that enables continental-scale hydraulic routing has been developed

Test Domain for Diffusive Wave Routing:

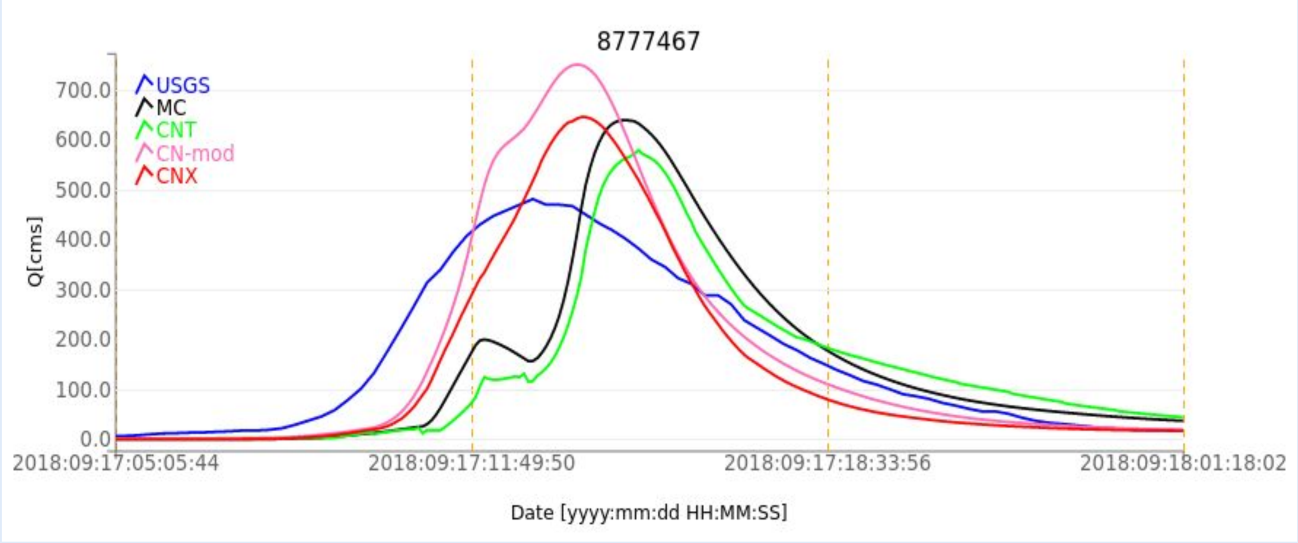


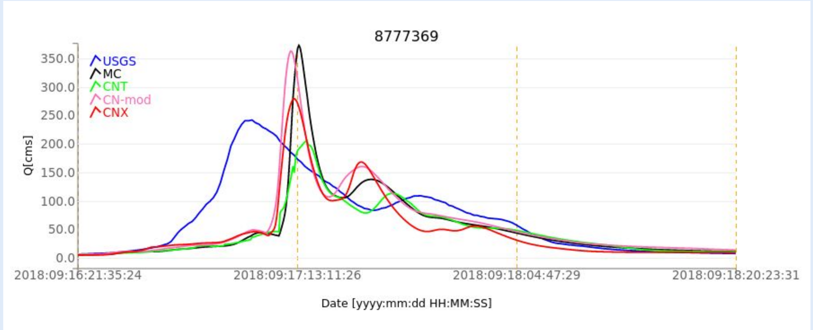


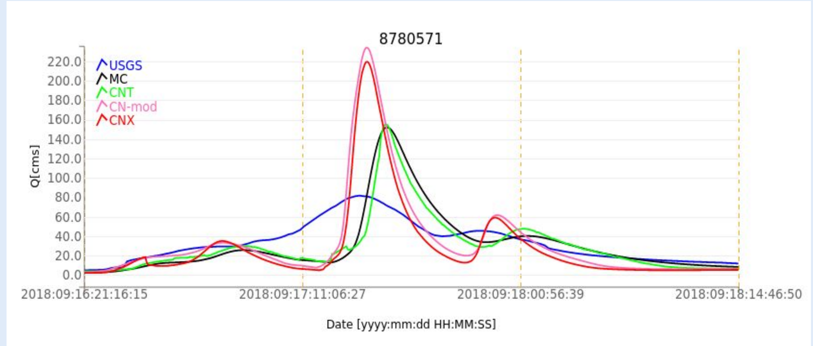
Map on the left shows the NHD channel network of a headwater basin (drainage area of 1,100 km^2) of Neuse River, NC with 1,075 stream segments. Average values of bed slope, segment length, and bottom width of synthetic channels with trapezoidal main and rectangular floodplain are 0.01 m/m, 1067.3 m, and 2.25 m. The minimum length of stream segment is 4 m.

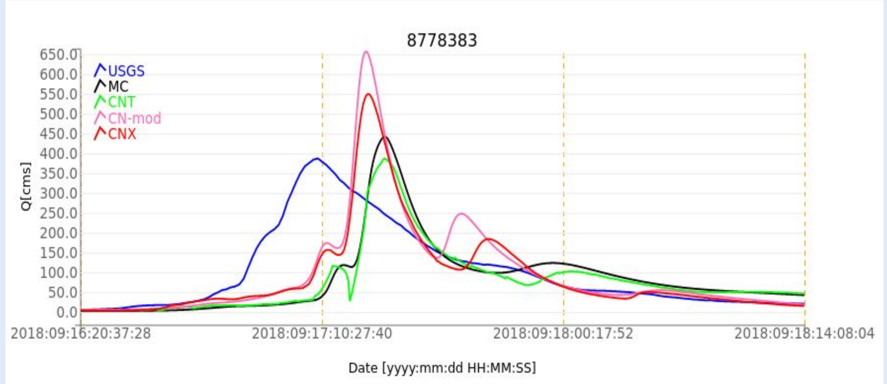
Summary Table and Hydrograph Plots:

	MC	CNT	CN-mod	CNX
Simulation time step [sec]	300	300	variable	300
Average value of Courant Number	0.56	0.54	0.02	0.75
Average Peak flow timing error [min]	+154	+169	+100	+100
Computation time in serial computing [sec]	21	159	30417	233





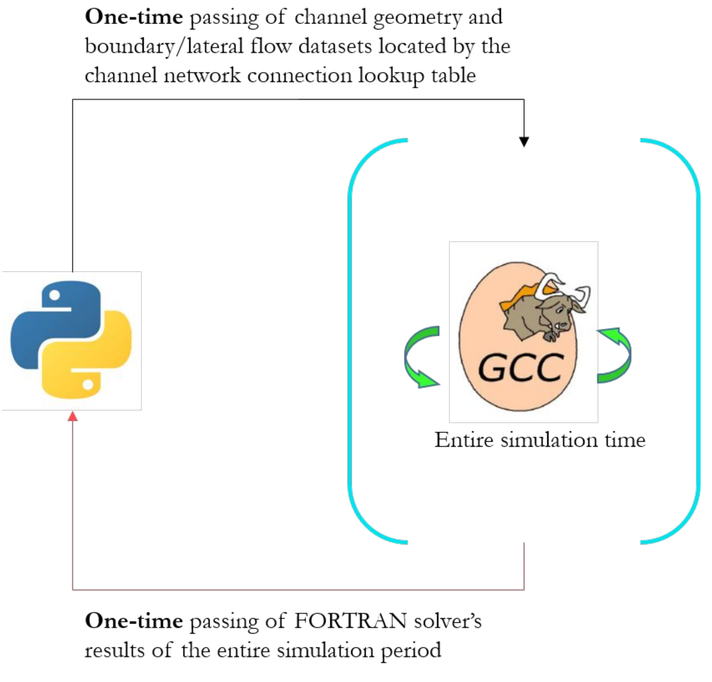




MC: Muskingum Cunge
CNT: diffusive wave by second order finite difference in time
CN-mod: diffusive wave with variable time step
CNX: diffusive wave with uniform space step

Test period for the four hydrograph plots is when Hurricane Florence hit this area in September, 2018. Error in predicting USGS observed streamflow by all four routing kernels is believed to be mainly caused by inaccurate estimates of lateral flow value.

METHOD (continued)



- This structure of I/O, depicted in Figure 2, save input-output time compared to redundant static input data passing at every simulation time step.
- It also boost the efficacy of numerical or mathematical code development by encapsulating the development solely under a particular high-performance computing language such as FORTRAN.

Figure 2. I/O between Python code base and FORTRAN diffusive wave solver

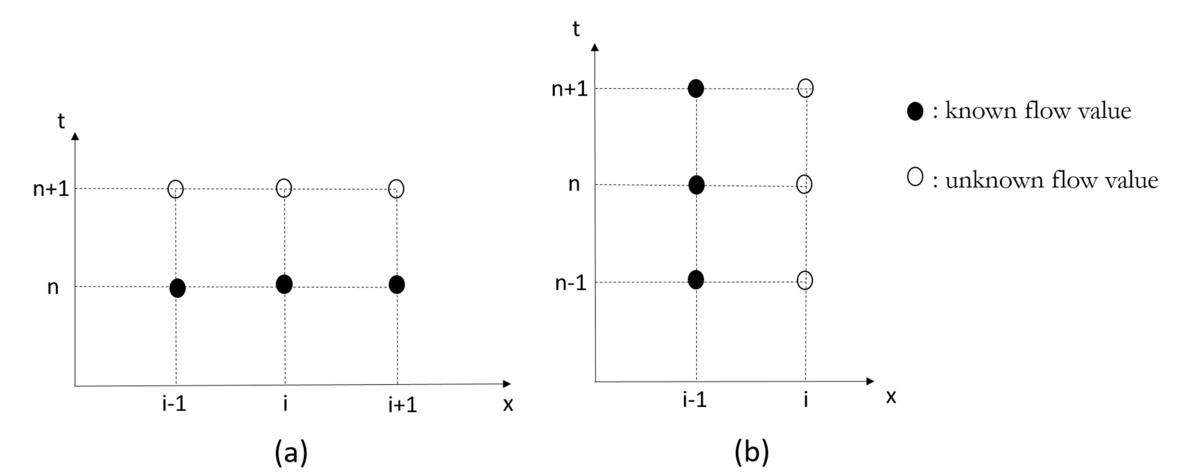


Figure 3. Discretization of diffusive routing kernels (CNT, CN-mod, and CNX). (a) for CN-mod and CNX. (b) for CNT.

- The CNT uses a modified form of the diffusive wave equation that is solved by the Crank-Nicolson (C-N) method (Moussa and Bocquillon 1996). The FORTRAN code of the CNT was developed by Meselhe Research Group, Tulane University.
  - Pros:
    - computes fastest among the three diffusive methods
    - runs on variable space steps
  - Cons:
    - sensitive mainly to simulation time step, limiting the available range of diffusivity and celerity
    - Less accurate than CN-mod and CNX mainly because of a modified form of the diffusive wave equation
- The CN-mod was developed by Meselhe Research Group, Tulane University by solving a total differential form of the diffusive wave equation using trapezoidal rule and Hermite interpolation.
  - Pros:
    - offers superior routing accuracy
    - runs on variable space steps
  - Cons:
    - computes slowest among the three methods by strict requirement of the Courant condition.
- The FORTRAN code of CNX (Moussa and Bocquillon 1996) was developed by the OWP, solving the diffusive wave equation on numerically created uniform space steps with the C-N method.
  - Pros:
    - offers accuracy close to CN-mod
    - computes with speed close to CNT
  - Cons:
    - Can't run on variable space steps (space interpolation is required)

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