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Impact of intra-meander hyporheic flow on nitrogen cycling

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Abstract

Redox gradients within hyporheic zones significantly impact the biogeochemical cycling of carbon and nitrogen. To investigate the effect of these redox gradients on nitrogen transformation in the subsurface, we integrated a genome-informed complex reaction network into PFLTRAN, which is an open source, massively parallel, three-dimensional, reactive flow and transport code. This study was conducted in the lower East River catchment in southwestern Colorado. The lower East River has multiple river meanders extending over a distance of 11 km in rolling to mountainous region of the East Taylor watershed. We carried out reactive flow and transport simulations within two stream meanders to describe the biogeochemical zonation that evolves due to upwelling of nutrient rich groundwater and downwelling of oxygen rich stream. The specific objectives were to examine (1) the effect of hyporheic flow on biogeochemical zonation and (2) how meanders affect local nitrogen fluxes and transformation. Simulation results demonstrate that hyporheic flow paths within intra-meander regions lead to lateral redox zonation, which significantly impact nitrogen export into the stream system. Also, meander-driven hyporheic flow paths enhance denitrification rates because of the extended hyporheic region.

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Peer-review under responsibility of the organizing committee of WRI-15

Keywords: Hyporheic zone; biogeochemical cycling; residence time

1. Introduction

Hyporheic zones are hotspots of biogeochemical activity due to upwelling of nutrient rich groundwater and downwelling of oxygen rich water from the river streams. These hotspots lead to distinct redox gradients within the hyporheic zones. Redox gradients in sediment rich hyporheic zones significantly impact nitrogen cycling, which is a key to the functioning of ecosystems¹. Moreover, hyporheic exchanges show varying levels of denitrification potential based on hydro-geomorphological characteristics that act to remove riverine nitrogen¹. Therefore, it is important to understand how various processes interact to form distinct biogeochemical gradients and

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subsequently impact nitrogen transformation in the hyporheic zone.

The prediction of biogeochemical gradients in the hyporheic zone depends on reaction rates and the extent of hyporheic exchanges resulting from environmental forcing and boundary conditions. To better characterize nitrogen transformation in the hyporheic zone, we developed and integrated a complex reaction network in PFLOTRAN². PFLOTRAN is an open source and massively parallel code, which is capable of performing high-resolution 3-D simulations of flow and reactive transport. The specific objectives of this study are to examine (1) the effect of hyporheic flow on biogeochemical zonation and (2) how meanders affect local nitrogen fluxes and transformation.

2. Study Site and Modeling approach

We conducted this study in the lower East River system in the East Taylor Watershed in western Colorado. The study site is a high elevation catchment, rolling-to-mountainous topography with multiple river meanders extending over a distance of 11 km (Figure 1A). We chose the modeling domain as 400 m by 330 m near Rocky Mountain Biological Laboratory (RMBL). Digital Elevation Models (DEM) of 10 m resolution were acquired from the USGS and processed to burn in river locations in the modeling domain. DEM of 10 m resolution failed to capture the high-resolution geomorphological features (e.g., meanders). Therefore, we used the high-resolution drainage network available from the National Hydrography Dataset (NHD) to delineate meanders at exact locations (Figure 1B).

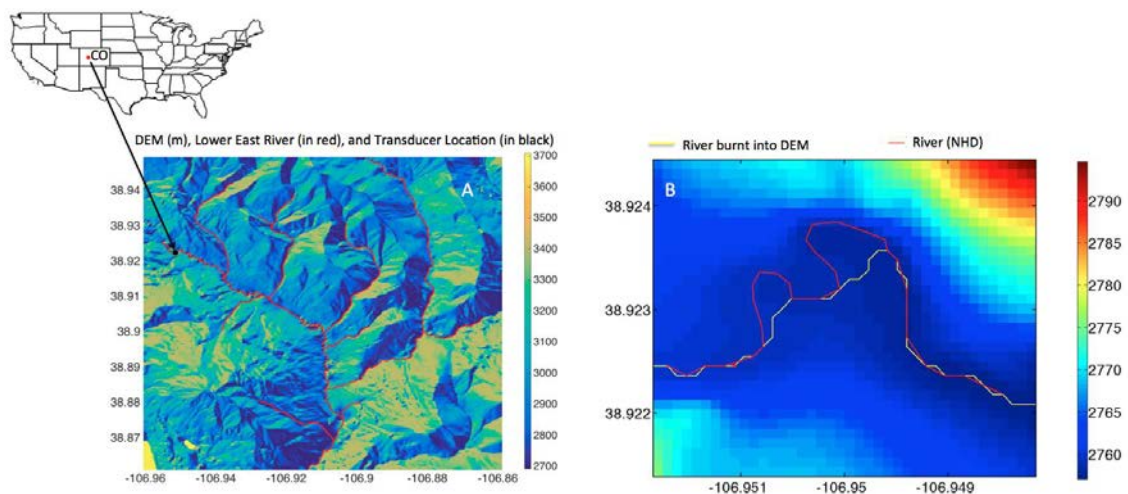


Fig. 1. (A) Lower East River catchment characterized by mountainous to rolling topography with multiple meanders; (B) DEM with 10 m resolution (solid yellow line) failed to capture meanders; however DEM and NHD dataset (solid red line) were able to mark exact locations of meanders. The study area is part of the Berkeley Lab's Watershed Function Scientific Focus Area and located in the East Taylor Watershed in western Colorado (CO).

The Darcy-Richards equation was used to model water flow under saturated and unsaturated conditions, respectively. The relationship between capillary pressure and saturation was described by van Genuchten parameters. The Mualem formulation was used to relate relative permeability and van Genuchten saturation functions. The three-dimensional model domain of the lower East River meanders is 330 m (X) by 400 m (Y) by 48 m (Z) (Figure 2). The model domain was uniformly discretized with 10 m horizontal (X and Y) resolution and 0.25 m vertical (Z) resolution using structured grids in PFLOTRAN. The minimum and maximum time steps were 10 s and 1800 s, respectively. The bottom boundary was assigned as no flow, whereas river cells and physical boundaries on sides were assigned as constant head and hydrostatic, respectively (Figure 2B).

Boundary water and groundwater chemistries were acquired from field measurements. The model was spun up to twice the residence time of groundwater for the flow and minerals to reach quasi-steady state. Subsequently, we performed various simulations (e.g., with meanders – DEM and NHD data; without meanders – only 10 m res

DEM) to investigate the impacts of hyporheic zones on nitrogen cycling. To describe biogeochemical fluxes, we integrated a complex reaction network into PFLOTRAN. The complex reaction network included abiotic reactions along with heterotrophic and chemolithoautotrophic pathways and was adopted from³. The key geochemical processes included in this study were aqueous speciation, mineral precipitation/dissolution reactions, and microbially mediated redox reactions. The primary species in the modeled reaction network included H^+ , HCO_3^- , Al^{+3} , Ca^{+2} , Cl^- , Fe^{+3} , Fe^{+2} , K^+ , Mg^{+2} , $NH_3(aq)$, NO_3^- , NO_2^- , Na^+ , $N_2(aq)$, $O_2(aq)$, HS^- , SO_4^{-2} , $SiO_2(aq)$, and acetate. Various minerals such as calcite, siderite, goethite and pyrite were included in the reaction network. The precipitation and dissolution of these minerals were modeled using kinetic rate laws. Microbially mediated pathways were simulated using single Michaelis-Menten kinetics, and the sequence of terminal electron acceptors (TEAs) was implemented using inhibition terms that impede lower energy-yielding redox reactions when higher energy-yielding electron acceptors are present^{4,5}.

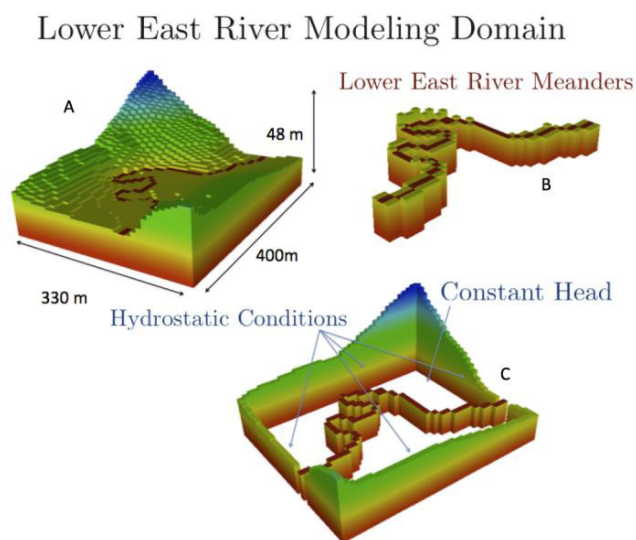


Fig. 2. (A) Modeling domain in the lower East River; (B) Two meanders inside the modeling domain; (C) boundary conditions on river cells and physical boundaries

3. Results

Figure 3 shows the transformation of nitrate within the East River meander system. Nitrate enters the hyporheic zone from the river stream. Nitrate showed lateral and vertical transport as a result of its high solubility (Figure 3A). Our results demonstrate that dissolved oxygen (DO) decreased significantly with depth in the organic carbon rich sediments. Nitrate was also reduced into a variety of reduced nitrogen species. Also, dissolved inorganic carbon and reduced nitrogen were exported back to the stream on the downstream side of the meander.

Finally, our approach also presents a novel technique for modeling hydrogeomorphic influences on nitrogen cycling for two meanders. We used the coarse resolution DEM combined with the high resolution NHD dataset. Our approach demonstrates the impact of meanders on nitrogen transformation due to the hyporheic exchanges. The extent of the hyporheic zone was found to be smaller when the NHD dataset was not used (Figure 3B). There was a slight difference in nitrogen concentration between the two scenarios i.e., with and without the NHD dataset. A small difference in the concentration can be large when upscaled to the river scale having 100s of meanders. Therefore, it is desirable to include meanders in the simulations when modeling the entire catchment. However, it is worth mentioning that these simulations were computationally expensive (~200,000 CPU hours for 1 year) even at the scale of two meanders. Therefore, it may not be realistic to use the high resolution DEM (e.g., sub meter) for modeling the entire catchment regardless of high-resolution DEM's capability to delineate extensive

geomorphological features. However, using NHD data and DEM together provides an excellent approach to enable simulating hydrological and biogeochemical processes at the large scale without increasing the degrees of freedom considerably.

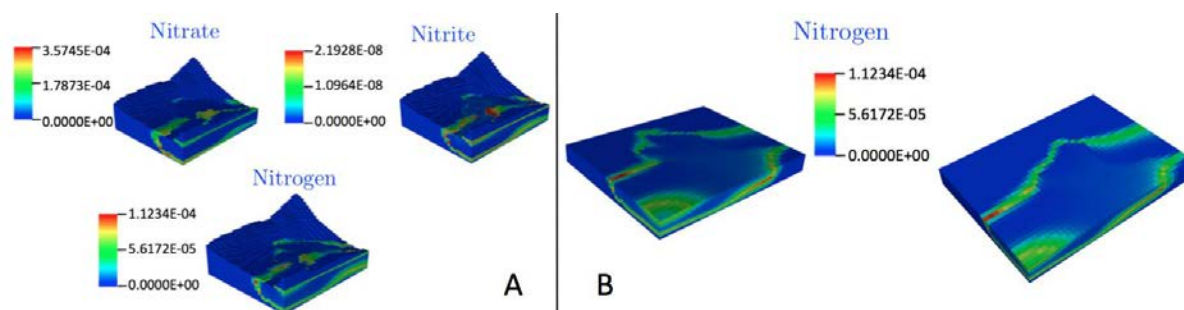


Fig. 3. (A) Nitrogen transformation in the hyporheic zone of two meanders of the lower East River; (B) The extent of the hyporheic zone (on the right) is smaller when the high resolution NHD dataset is not used. Horizontal slices of modeling domain just below the riverbed show how N_2 is transported back to the river stream and highlight imprints of meanders.

4. Conclusions

At the lower East River site, the intra-meander hyporheic flow paths and biogeochemical reactions lead to lateral redox zonation, which considerably impact the nitrogen fluxes into the stream system. Furthermore, the meander driven hyporheic exchanges increase denitrification rates because of relatively longer residence times in the organic carbon-rich sediments. High-resolution data such as NHD provide an efficient strategy to correctly delineate meanders. Using NHD dataset with the coarse resolution DEM can be advantageous in modeling the large-scale catchments with high-resolution geomorphic features without resorting to increasing degrees of freedom (DOFs).

Acknowledgements

This material is based upon work supported as part of the Genomes to Watershed Scientific Focus Area and Interoperable Design of Extreme-scale Application Software (IDEAS) at Lawrence Berkeley National Laboratory funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under Award Number DE-AC02-05CH11231.

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