Modeling Riparian Hollow Controls on Nitrogen Cycling in Snowmelt Dominated Catchments

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Abstract

A multi-scale understanding of processes controlling the nitrogen budget is essential for predicting how nitrogen loads will be affected by climate-induced disturbances. Recent studies in snowmelt-dominated catchments have documented changes in nitrogen retention over time, such as declines in watershed exports of nitrogen, though there is a limited understanding of the controlling processes driving these trends. Working in the mountainous headwater East River Colorado watershed, our study aims to refine this process-based understanding by exploring the effects of riparian hollows as nitrogen cycling hotspots. The objectives of this study are to (1) quantify the influence of riparian hollows on nitrogen retention in snowmelt-dominated catchments, (2) understand how disturbances (i.e. early snowmelt, long summer droughts) and heterogeneities affect the nitrogen-retention capacity of riparian hollows, and (3) quantify the relative contribution of riparian hollows to the watershed nitrogen budget using high-resolution LIDAR watershed data. We used a multi-component flow and reactive transport model, MIN3P, to simulate the biogeochemical kinetics of riparian hollows, using data from the East River watershed to parameterize, constrain, and validate the model. Several hydrological, biogeochemical, and geological perturbations were then imposed across simulations to assess the effects of abrupt and gradual perturbations on riparian hollow hydrobiogeochemical dynamics. Topographic position and wetness indices were used to scale the net yearly storage and flux terms from riparian hollows, and reveal the significant impacts hollows can have on aggregated watershed biogeochemistry. Initial model results suggest that riparian hollows serve as significant nitrogen sinks, and that earlier snowmelt and extended dry season considerably limit denitrifying processes. Our work linking remote sensing and empirical scaling techniques to numerical biogeochemical simulations is an important first-step in assessing nitrogen-retaining features relative to the watershed nitrogen budget.

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ABSTRACT

A multi-scale understanding of processes controlling the nitrogen budget is essential for predicting how nitrogen loads will be affected by climate-induced disturbances. Recent studies in snowmelt-dominated catchments have documented changes in nitrogen retention over time, such as declines in watershed exports of nitrogen [1], though there is a limited understanding of the controlling processes driving these trends [2]. Working in the mountainous headwater East River Colorado watershed, our study aims to refine this process-based understanding by exploring the effects of riparian hollows as nitrogen cycling hotspots [3]. The objectives of this study are to (1) quantify the influence of riparian hollows on nitrogen retention in snowmelt-dominated catchments and (2) understand how disturbances (i.e. early snowmelt, long summer droughts) and heterogeneities affect the nitrogen-retention capacity of riparian hollows. We used a multi-component flow and reactive transport model, MIN3P [4], to simulate the biogeochemical kinetics of riparian hollows, using data from the East River watershed to parameterize, constrain, and validate the model. Several hydrological and biogeochemical perturbations were then imposed across simulations to assess the effects of abrupt and gradual perturbations on riparian hollow hydrobiogeochemical dynamics. Initial model results suggest that riparian hollows serve as significant nitrogen sinks only under certain hydrological and geochemical conditions, with earlier snowmelt and extended dry seasons considerably limiting denitrifying processes.

2. BACKGROUND, HYPOTHESIS & APPROACH

Motivation: Disturbances to the watershed nitrogen balance will likely be exacerbated by a changing climate. To predict and respond to more extreme imbalances, it is necessary to understand the multi-scale mechanisms controlling these trends.

Hypothesis: Riparian hollows function as important nitrogen cycling hotspots due to retained moisture under surface ponding conditions.

Objectives:
1) Quantify the nitrogen-retention capacity of riparian hollows, assessing the significance relative to the watershed nitrogen budget.
2) Understand how climate-induced perturbations affect the nitrogen-retention capacity of riparian hollows.

Approach:
1) Develop a flow and reactive transport model reflecting the biogeochemical dynamics of riparian hollows, using data from the East River (Figure 1) to constrain the model.
2) Impose and assess hydrological and geochemical perturbations across several simulations to delineate controls on nitrogen storage within riparian hollows.

Figure 1: Span of the East River.

3. MODEL DEVELOPMENT

3.1 Model Domain

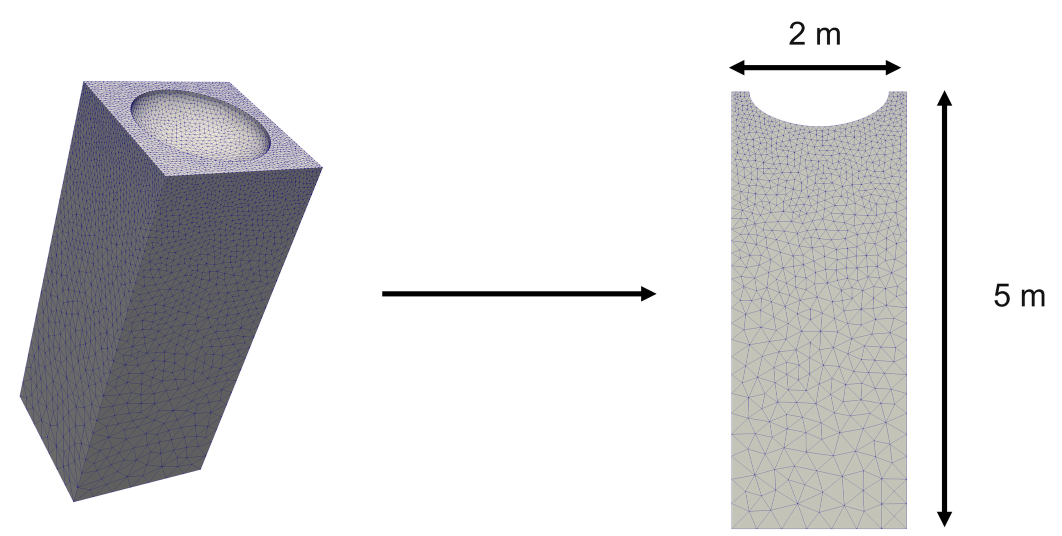

Figure 2: Three-dimensional schematic of riparian hollow and two-dimensional cross section used as model domain.

3.2 Reaction Network

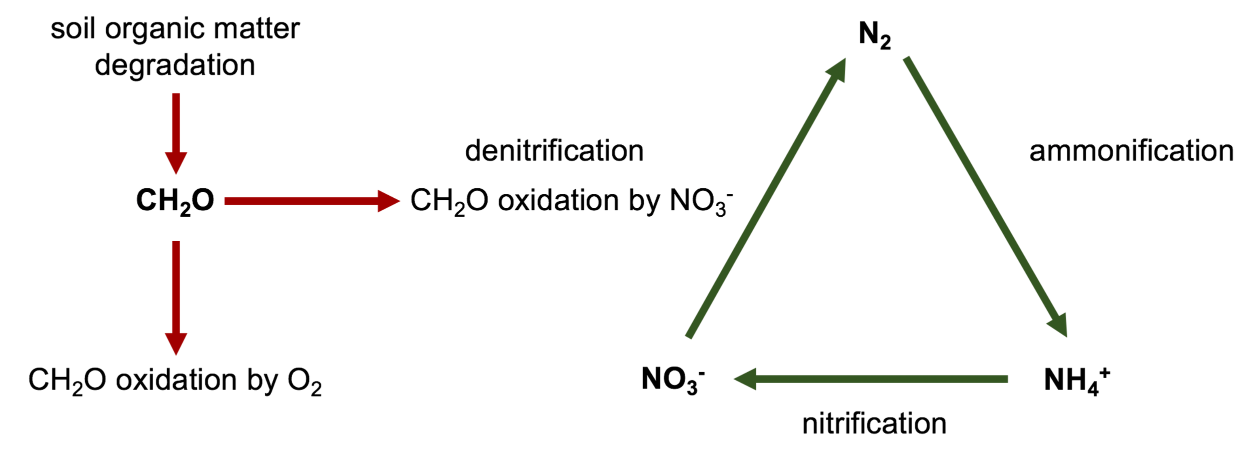

Figure 3: Modeled reaction network with nitrogen cycle reactions shown in green and carbon transformations shown in red.

3.3 Hydrological Boundary Conditions

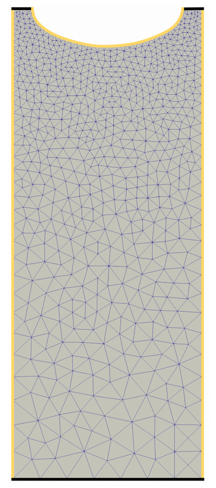

Figure 4: Hydrological boundary conditions with specified head boundaries shown in yellow and no-flow boundaries shown in black.

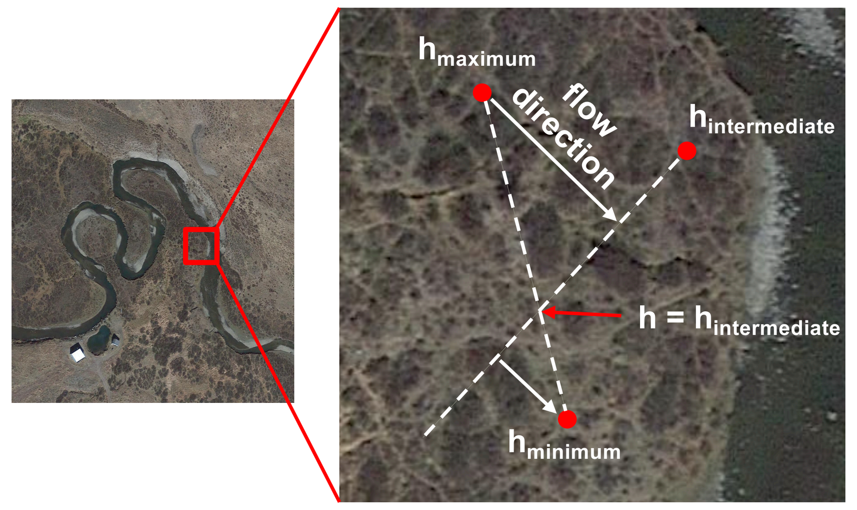

Figure 5: Time-series head data across three wells were used to calculate the flow direction and gradient using the 'three-point method' shown above. These head and gradient data were used for the specified head boundary conditions.

3.4 Hydrological and Geochemical Perturbations

Hydrological: surface water duration (Figure 6), depth to groundwater, gradient
Geochemical: pH, CH_2O, NO_3, NH_4, N_2

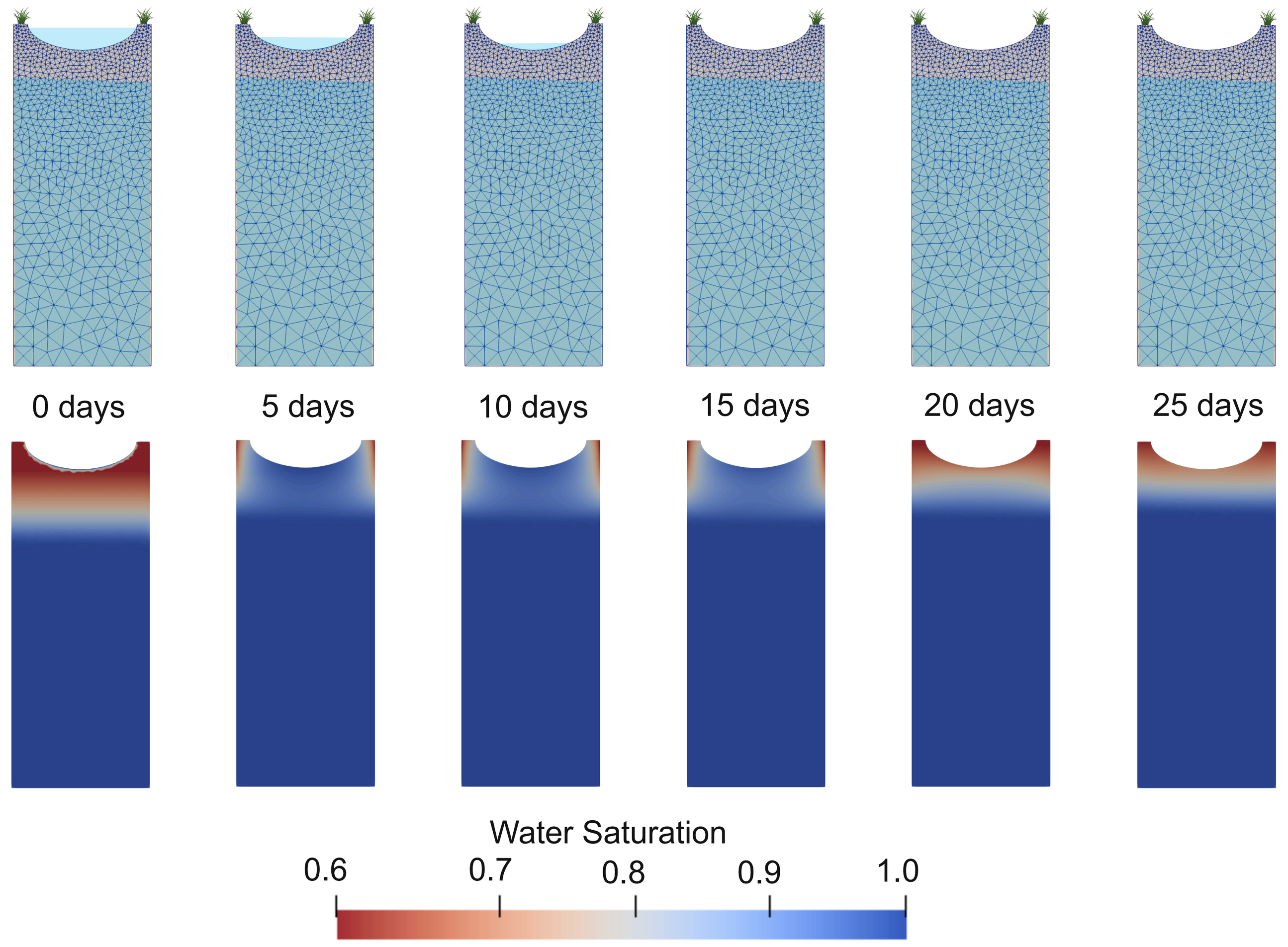

Figure 6: Top row) Conceptual time-series schematic of shallow water table with a surface water duration of 15 days. Bottom row) Corresponding saturation model in MIN3P.

4. RESULTS

4.1 Time-Series Flow Direction and Gradient Analysis

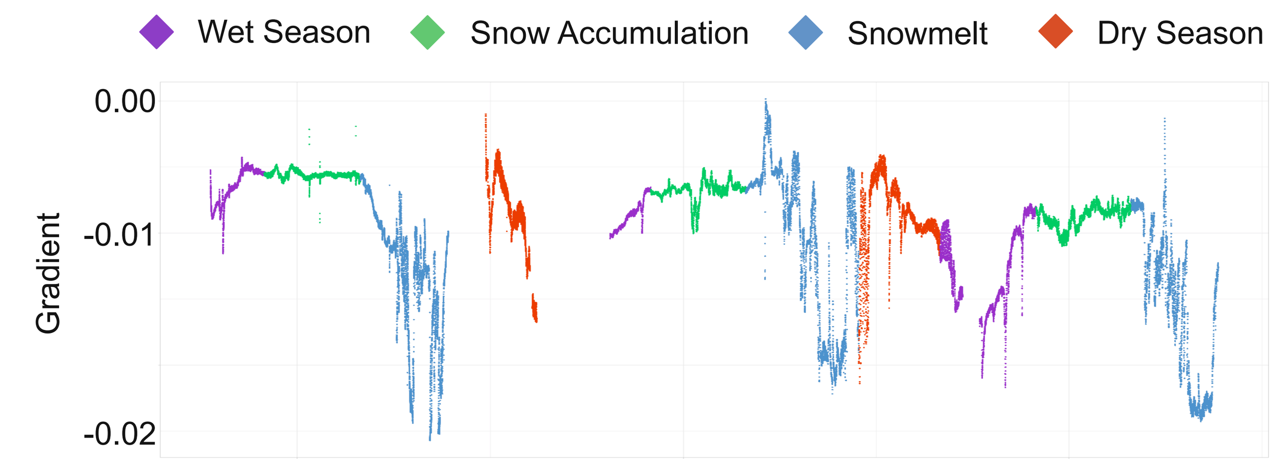

Figure 7: Gradient time-series showing strong seasonal patterns, with gradient increasing by an order of magnitude during snowmelt seasons.

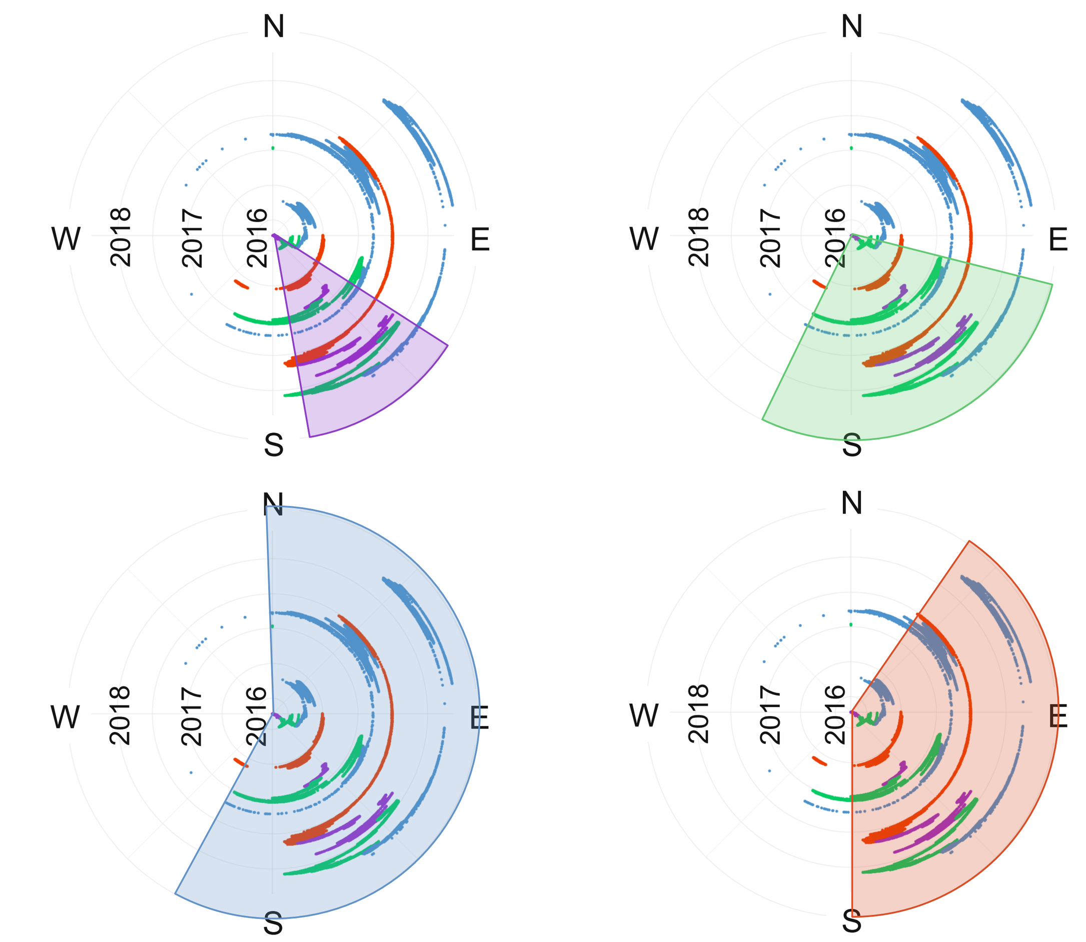

Figure 8: Flow direction time-series showing seasonally dependent variations, with small variations during wet seasons and significant variations during snowmelt seasons.

4.2 Hydrological and Geochemical Controls on N Retention

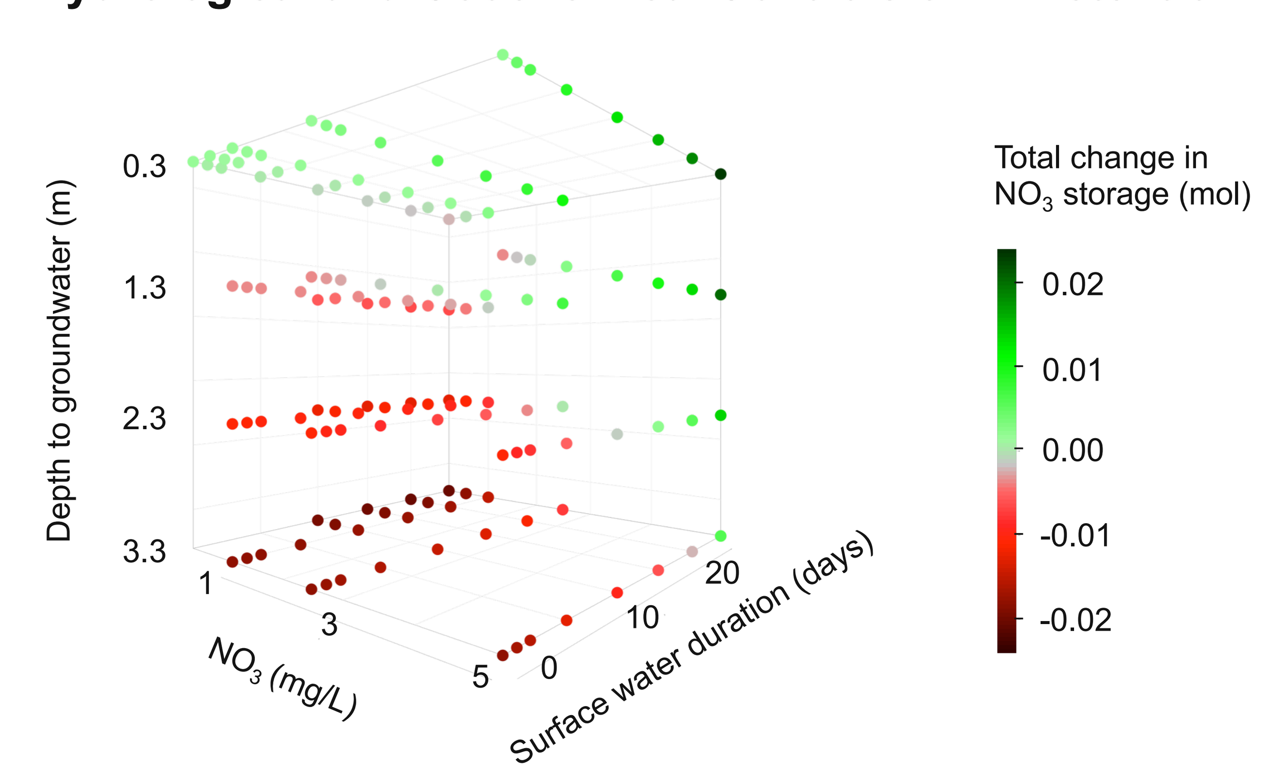

Figure 9: Summary of simulations showing effects of surface water NO_3 concentration, surface water duration, and depth to groundwater on the nitrogen retention capacity of riparian hollows; each point represents one twenty-five-day simulation.

5. DISCUSSION

5.1 Groundwater Inputs

Seasonal gradient fluxes and seasonally dependent flow directions suggest dynamic primary sources of intra-meander groundwater. Variations between lateral hydrologic inputs (i.e. from adjacent hillslopes) and longitudinal hydrologic inputs (i.e. from upstream) may have significant implications for the biogeochemical inputs of riparian hollows (Figure 10).

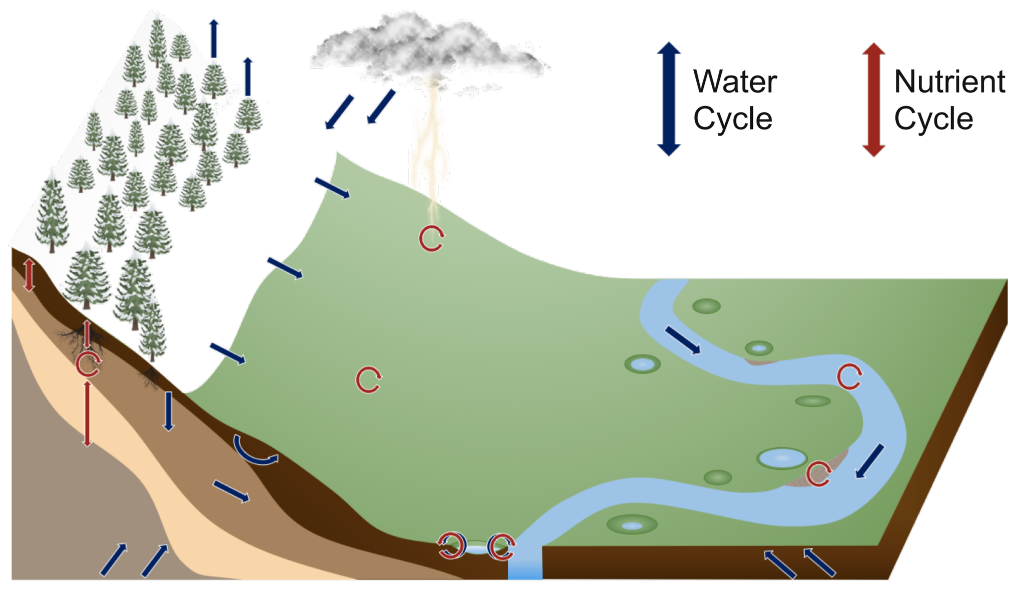

Figure 10: Illustration of dynamic hydrological and geochemical processes affecting biogeochemical inputs of riparian hollows.

5.2 Initial Model Results

Analysis of two-hundred hydrobiogeochemical simulations reveals that surface water nitrate concentration, surface water presence duration, and groundwater depth are important controls on the nitrogen-retention capacity of riparian hollows.

5.3 Future Research

To more accurately simulate the hydrobiogeochemical dynamics of riparian hollows, the following components will be implemented in future reactive transport simulations:
1) Coupled iron oxidation and denitrification
2) Sulfate reduction-oxidation
3) Density-dependent flow and heat transport
4) Interconnectivity of riparian hollows

Additionally, the following hydrologic and geochemical perturbations will be imposed to further explore primary controls on nitrogen retention in riparian hollows:
1) Intermittent surface ponding
2) Varying depths of surface water inundation
3) Greater water table fluctuations
4) Varying aqueous species concentrations in both groundwater and surface water

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