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The influence of geomorphic unit spatial distribution on nitrogen retention and removal in a large river

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ABSTRACT

Fluvial geomorphic features drive nutrient dynamics in river systems that have only recently begun to be incorporated into conceptual and numerical models designed to predict nutrient yields and flux. The role of channel geomorphic units (pools, riffles, etc.) and their associated aquatic communities in determining nitrogen retention and removal in aquatic ecosystems is understudied. Here we study the effects of the spatial distribution of geomorphic features on within-channel nitrate dynamics. We developed an agent-based model that simulates biological and hydrological processes involved in nitrate retention and removal occurring in a river segment of the 6th order Cahaba River, AL (USA). We simulated nitrate retention and removal under three scenarios in which the total area of geomorphic units were held constant while their longitudinal distributions were manipulated under low and high nitrate supply levels (relative to biological demand). High nitrate supply simulations suppressed any effect caused by differing longitudinal sequence of geomorphic units/aquatic communities. In contrast, low nitrate supply simulations demonstrated differences in total potential nitrate retention and removal for the study segment based on the spatial distribution of geomorphic units/aquatic communities. Our findings suggest that the spatial arrangement of geomorphic units and their associated aquatic communities can be an important control on nitrogen dynamics in large rivers, demonstrating that fluvial geomorphic features merit consideration when nutrient retention and removal in rivers is examined. Thus, measures of channel geomorphology employed in water quality management, biogeochemical studies, and to evaluate the efficacy of restoration efforts on nutrient levels should be broadened to include characterization of the spatial configuration of geomorphic units and their associated aquatic communities.

1. Introduction

Few studies (Munn and Meyer, 1990; Martí and Sabater, 1996; Doyle et al., 2003) attempted to determine the effects of channel morphology on in-stream biogeochemical processes because of the challenges associated with isolating controlling factors and removing confounding variables. In this study, we applied a model simulation approach to help reduce the impact of confounding factors that would prohibit isolating channel geomorphology effects. In our simulations, discharge and material inputs to the model reach, organism type and functionality within the model study segment, and total geomorphic unit area (specifically, bedrock shoal and pool area) within the model study segment were unchanged during channel morphology manipulation. Therefore, we can presume that any detected ecosystem processing rate changes were the consequence of changes in channel morphology.

Channel geomorphology can directly affect nutrient dynamics via physical processes in a river, e.g., influencing phosphorus retention through modifying channel depth and velocity (Doyle et al., 2003). Channel geomorphology can also modify nitrogen dynamics indirectly by creating spatio-temporal variability of aquatic communities (e.g., macrophytes and phytoplankton) and their associated biological processes. The channel provides habitats and nutrients for aquatic communities and meanwhile aquatic communities affect nitrogen dynamics by assimilating nitrogen into their biomass (i.e., nutrient uptake) (Currie and Kalff, 1984; Hecky and Kilham, 1988; Davis, 1991). The influence of fluvial geomorphology to aquatic communities can be both static and dynamic. Static influences include the physical habitat structure that con-

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trols the abundance and composition of the biological communities (Montgomery, 1999). Dynamic influences include the disturbances and flow regimes associated with regional geomorphology (geomorphic provinces) and local geomorphic processes (Minshall, 1988; Ward, 1989; Montgomery, 1999). Although conceptual frameworks linking geomorphology and aquatic ecosystems at a broad scale exits, quantification of geomorphic influences on ecosystem process at any particular stream/river remains unclear and difficult.

In this study, we developed an agent-based model to simulate the river segment system. The agent-based model explicitly considers the components (i.e., the agents) of a systems, and emphasizes the interactions among these agents and the interactions between agents and their environment (Grimm, 1999; Grimm and Railsback, 2013). The agents can be individuals or a group of individuals that have similar features. The agent-based model has been extensively applied to environmental resource management, such as water, forest, and land use/land change management (Bousquet and Le Page, 2004). In this study, we defined agents as a discrete small amount of water containing nitrate. In stream studies, the agent-based model can capture dynamic hydrological transport of solute due to storm event or complex in-channel geomorphology change, can directly track the traveling time and uptake length of solute, and can track the fate and cycling of each solute, which is difficult for traditional modeling approaches.

We tested the hypothesis that the longitudinal distribution of different geomorphic units (sections of channel with channel morphologies determined by a range of flows and spatial variability in channel substrate resistance to hydraulic erosion; more specifically, pools and bedrock shoals) and their associated aquatic communities, including both community composition and biomass accrual, affect the spatial distribution of nutrient availability, as well as reach-scale nitrate retention and removal, in river channels because: (1) physical and biological processes upstream can affect downstream processes, and (2) the different aquatic communities dominating different geomorphic units use varying strategies to use nitrogen and vary in their response to nitrogen limitation and nitrogen saturation conditions. For example, upstream aquatic communities modify water nitrogen concentrations through uptake, which reduces the nitrogen availability for downstream biological processes. A downstream decline in nitrogen availability affects biological process rates and, ultimately, the density of downstream aquatic communities.

The overall goal of this study was to explore how much the spatial distribution of different in-channel aquatic communities, as represented by geomorphic units (pools, bedrock shoals, etc.), have potential to affect ecosystem functions in the growing season, including nitrate retention and removal. Specifically, we aimed to: (1) develop an agent-based model to simulate the hydrological and biological processes (i.e., growth of algae and macrophytes, and denitrification), nitrate retention and removal in a river segment; (2) quantify the nitrate retention and removal under different spatial distributions of geomorphic units/aquatic communities under different nitrate input levels; and (3) explore the condition related to nitrate supply level under which the impacts of spatial distribution of geomorphic units/aquatic communities on nitrate retention and removal would be reduced. The simulation model was parameterized based on a segment of the Cahaba River, AL (USA).

2. Materials and methods

2.1. Study site

The model development and parameterization was based on field data obtained from a 2.7 km segment of the Cahaba River near West Blocton, AL, located within the Cahaba River National Wildlife Refuge (Fig. 1). This portion of the Cahaba River flows through the Fall Line physiographic transition zone with an average annual discharge of 11 $m^3 s^{-1}$ (Fig. 1), and is characterized by alternating sections of bedrock shoals (discordant plane beds) and pools. The Cahaba River is a 6th order unregulated river (average annual discharge 70 $m^3 s^{-1}$), and its headwaters drain the metropolitan area of Birmingham, AL. The Cahaba River is considered an impaired river due to high nitrogen and phosphorus concentrations. Since 2000, the U.S. Environmental Protection Agency (EPA) and the Alabama Department of Environmental Management (ADEM) have endeavored to reduce nutrient runoff received by the Cahaba River from surrounding lands and wastewater treatment facilities. Phosphorus (33 μgPO_4-P L^{-1} on average) and nitrate (318 μgNO_3-N L^{-1} on average) concentrations in the river were monitored at a USGS gaging station (02424000) located at Centerville, AL, and data were obtained from USGS (2009, 2010).

2.2. Model framework

2.2.1. The agent-based model

We created an agent-based model to simulate the growth of phytoplankton and macrophytes, and the denitrification occurring in the rhizosphere of macrophytes during the growing season (May–August). Phytoplankton, macrophytes and denitrifiers in this study specifically referred to freshwater algae in the water column, aquatic plants attach on stable surface, and denitrifying bacteria in the benthic sediment. We mapped the geomorphology of the Cahaba River study segment and determined the main geomorphic units, pools and bedrock shoals, and the channel surface area occupied by each geomorphic unit. We used our geomorphic mapping in the model development to create longitudinally distributed geomorphic unit/aquatic community zones, subsequently referred to as "zones" that consisted of pools dominated by algae and bedrock shoals dominated by emergent aquatic macrophytes. The traveling time of solutes is particularly important to biological uptake and removal because it controls the solute availability to organisms within the zone (i.e., it affects the biological rate) and the time for organisms to take up or to remove the solute within a zone (i.e., it affects zone-wise nitrogen retention and removal fluxes). In this study, we determined the traveling time of each zone by dividing the longitudinal length of the zone by its average flow velocity.

In this model, a number of agents, each representing a discrete small amount of water containing nitrate (NO_3-N), were released at the upstream end of the study reach at each time step (Fig. 2). Agents entered the most upstream zone first and were individually assigned a traveling time based on the frequency distribution of traveling times for that zone. The traveling time of solutes was considered equivalent to the time that organisms have to react to the solutes. Agents were kept within the zone until their traveling time equaled their assigned traveling time. Organisms, such as macrophytes, phytoplankton, and denitrifiers, within the zone took up the agents for biomass production or energy yield via denitrification. If an agent represented a small amount of solute and this small amount was more than the organisms needed for biomass production at the current time step, and organisms would use this remaining amount first before starting to consume another agent in the next time step. If organisms did not take up an agent during the entire time the agent travelled in the zone, it exited the zone and entered the next adjacent, downstream zone. The agent-based model was coded in JAVA 8 (code available at https://github.com/laurencelin/Agent-based-Stream-Model).

2.2.2. Biological nutrient uptake

Based on the observed biomass data for macrophytes during growing season (growing from initial biomass before reaching car-