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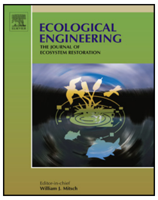

Effects of inset floodplains and hyporheic exchange induced by in-stream structures on nitrate removal in a headwater stream

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ABSTRACT

Stream restoration efforts in the United States are increasingly aimed towards water quality improvement, yet little process-based guidance exists to compare pollutant removals from different restoration techniques for variable site conditions. Excess nitrate (NO_3^-) is a frequent pollutant of concern due to eutrophication in downstream waterbodies such as the Chesapeake Bay. We used MIKE SHE to simulate hydraulics and NO_3^- removal in a 90 m restored reach of Stroubles Creek, a second-order stream in Blacksburg, Virginia. Site specific geomorphic, hydrologic, and hydraulic data were used to calibrate the model. We evaluated in-stream structures that induce hyporheic zone denitrification during baseflow and inset floodplains that remove NO_3^- during storm flows. We varied hydraulic conditions (winter baseflow, summer baseflow, storm flow), biogeochemical parameters (literature hyporheic zone denitrification rates and newly available inset floodplain removal rates) and boundary conditions (upstream NO_3^- concentration), sediment conditions (hydraulic conductivity), and stream restoration design parameters (inset floodplain length). Our results indicate that NO_3^- removal rates within the 90 m reach were minimal. Structure-induced hyporheic zone denitrification did not exceed 3.1% of mass flowing in from the upstream channel, was achieved only during favorable background groundwater hydraulic conditions (i.e. summer baseflow), and was transport-limited such that non-trivial removal rates were achieved only when the streambed hydraulic conductivity (K) was at least 10^{-4} m/s. Inset floodplain nitrogen removal was limited by floodplain residence time and NO_3^- removal rate, and did not exceed 1% of inflowing mass. Summing these removals for both restoration practices over the course of the year based on the frequency of storm and summer baseflow conditions yielded ~2.1% annual removal. Achieving 30% NO_3^- removal required increasing the length of stream reach restored to 0.9 km–819 km (depending on hydraulic conductivity) and 3.8–46 km (depending on inset floodplain length and nitrogen removal rate) for in-stream structures during baseflow and inset floodplains during storm flow, respectively. In one of the first comparisons of process-based modeling to the Chesapeake Bay Program stream restoration guidance, we found that the guidance overestimated hyporheic NO_3^- removal for our modeled reach, but correctly estimated inset floodplain removal. Overall, our results indicate that in-stream structures and inset floodplains can improve water quality, but overall required level of effort may be high to achieve desired results.

1. Introduction

1.1. Excess nitrogen and stream restoration

Excess nitrogen (N) loading is caused by anthropogenic activity, especially nitrate (NO_3^-) fertilizer runoff from agriculture (Royer et al., 2006). Downstream movement of N is then accelerated by channel incision and simplification from reduced storm infiltration in the contributing watershed (Henshaw and Booth, 2000), which reduces residences times and hence potential for natural attenuation. As a result, a high amount of N reaches coastal waters, causing problems associated with eutrophication (Howarth et al., 2002). In the Chesapeake Bay, nutrient loading has caused hypoxia and algal blooms (Kemp et al., 2005) and has negatively affected the ecosystem (Langland et al., 2000), leading to the monumental Chesapeake Bay Total Maximum Daily Load (TMDL) for N, phosphorous (P) and sediment (USEPA, 2010).

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Stream restoration aims to return stream corridors toward a preferable former condition, adapt them to a new environment, and/or control the factors adversely affecting the river (Brookes and Shields, 1996; Downs and Gregory, 2004; Wohl et al., 2005, 2015; Landers, 2010; Palmer et al., 2014). Many stream restoration practices are considered for mitigating water quality impacts, including channel realignment, riparian planting, in-stream structure installation, and floodplain reconnection (Roni et al., 2002; Ensign and Doyle, 2005; Kaushal et al., 2008; Opperman et al., 2009; Hester and Gooseff, 2010; Mason et al., 2012; Azinheira et al., 2014; Johnson et al., 2015; Jones et al., 2015). Yet water quality improvement is a relatively new goal compared to more traditional objectives such as bank stabilization, ecosystem enhancement or riparian zone management (Bernhardt et al., 2005), and little guidance is available to guide stream restoration design for purposes of improving N removal from the channel (Craig et al., 2008; Veraart et al., 2014; Johnson et al., 2015).

The Chesapeake Bay Program recently issued protocols that quantify the water quality benefits of stream restoration schemes and offer mitigation credits for strategies that prevent sediment erosion during storm flows, promote hyporheic zone nutrient processing, reconnect stream channels to their floodplains, and/or capture nutrient/sediment-laden runoff in upland dry channels (Berg et al., 2014). These protocols are a substantial advance in that they are the first to give varying water quality credit depending on which broad category of stream restoration practice is implemented. Yet the protocols do not acknowledge variability of water quality results within each category based on different specific practices (e.g., in-stream structures versus meanders), or in different specific settings (e.g., watershed position, geologic substrate), and are based on a small list of field studies (Jordan, 2007; Kaushal et al., 2008; Striz and Mayer, 2008). Expanding the range of information regarding the potential for stream restoration practices to impact water quality thus will be beneficial.

1.2. Hydraulic connection and residence time in storage zones

Stream restoration strategies enhance water quality by promoting the conditions that cause natural pollutant attenuation. When N removal is sought, these conditions are characterized by long contact times between N-impacted water and sediments or soils with high denitrification potential (Roley et al., 2012b). These conditions are typically achieved by exchange with off-channel storage zones where water moves more slowly than in the channel. In-stream structures achieve these conditions by inducing backwater upstream of the structure, which drives pollutants temporarily into streambed sediments (i.e. hyporheic zone, Hester and Doyle, 2008; Hester and Gooseff, 2010). Given favorable microbial and redox conditions (i.e. an anoxic environment with sufficient labile organic carbon), NO_3^- may be removed by denitrification in the subsurface before upwelling downstream of the structure (Kasahara and Hill, 2006; Lautz and Fanelli, 2008; Zarnetske et al., 2011). Inset floodplains (i.e. floodplain benches installed lower than top of bank) achieve N removal by promoting contact between N-laden water and plants and organic material as water moves across the inset floodplains at relatively low velocities (Roley et al., 2012a,b; Azinheira et al., 2014). This is also achieved by bankfull floodplains by a similar principle (Kaushal et al., 2008; Jones et al., 2015).

The efficacy of such N removal is controlled by the connectivity between the main channel and the reactive storage zone(s), the residence time distribution in the storage zone(s), and the strength of the removal mechanism (i.e. reaction or removal rate) (Stewart et al., 2011), such that ultimately one of these factors will limit the rate of N removal. Identification of this limiting factor on a strategy-specific and even site-specific basis will help to quantify the cost of achieving meaningful water quality improvements through stream restoration.

1.3. Objectives of study

The purpose of this study was to investigate the effectiveness of inset floodplains and in-stream structures at removing NO_3^- from a 90 m restored reach of Stroubles Creek in Blacksburg, Virginia. We used MIKE SHE to estimate removal as the percent of upstream NO_3^- that is removed via hyporheic zone denitrification during baseflow and inset floodplain NO_3^- removal during storm flow. Our specific objectives were to 1) determine the relative importance of various controls (e.g., sediment hydraulic conductivity, denitrification rates, stream restoration design parameters) on reach-scale steady-state NO_3^- removal using a rigorous process-based approach, 2) estimate net removal over the course of a year subject to natural seasonal variations in hydraulic boundary conditions, 3) determine the length of restored reach required for water quality improvement to become substantial, and 4) compare our modeled NO_3^- removal to those predicted by the Chesapeake Bay Program protocols in Berg et al. (2014).

2. Methods

2.1. Model governing equations

We used MIKE SHE (Graham and Butts, 2005; DHI, 2011) to model surface water and groundwater hydraulics, and dissolved solute transport with reaction in a stream reach, including surface water-groundwater interaction. We extended a previously developed MIKE SHE model of surface water-groundwater hydraulics and conservative tracer transport (Azinheira et al., 2014) in a stream reach located near Blacksburg, Virginia. MIKE SHE uses a fully implicit three-dimensional finite difference algorithm to solve the groundwater flow equation and an explicit algorithm to solve the two-dimensional diffusive wave approximation of the Saint Venant equation for surface water (Graham and Butts, 2005). Additional detail on the equations of the hydraulic model can be found in Azinheira et al. (2014).

The water quality component of MIKE SHE simulates solute transport using the advection-dispersion equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}(cv_i) + \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) + R_c + \left(\frac{\partial C}{\partial t}\right)_{reactions} \tag{1}$$

where C is the concentration of the dissolved solute in the model cell (g/m^3), t is time (s), $x_{i,j}$ is the distance along the respective Cartesian coordinate axis (m), v_i is the velocity vector determined during the hydraulics simulation (m/s), D_{ij} is the dispersion tensor (m^2/s), and R_c is the sum of the sources and sinks (g/m^3-s). MIKE SHE uses the three-dimensional (i,j = 1,2,3) advection-dispersion equation for solute transport in groundwater and the two-dimensional advection-dispersion equation (i,j = 1,2) for solute transport in surface water.

MIKE SHE also allows chemical reaction processes that remove solute from saturated groundwater and/or surface water. We simulated denitrification in the hyporheic zone and N removal in the inset floodplains by assuming first-order decay of NO_3^-, which can vary in space:

$$\left(\frac{\partial C}{\partial t}\right)_{reactions} = -kC \tag{2}$$

where k is the first-order decay rate (s^{-1}). MIKE SHE solves the advection-dispersion equation using the QUICKEST method (Leonard, 1979), an explicit scheme that applies upstream and