Identifying biogeochemical processes beneath stormwater infiltration ponds in support of a new best management practice for groundwater protection

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Abstract When applying a stormwater infiltration pond best management practice (BMP) for protecting the quality of underlying groundwater, a common constituent of concern is nitrate. Two stormwater infiltration ponds, the SO and HT ponds, in central Florida, USA, were monitored. A temporal succession of biogeochemical processes was identified beneath the SO pond, including oxygen reduction, denitrification, manganese and iron reduction, and methanogenesis. In contrast, aerobic conditions persisted beneath the HT pond, resulting in nitrate leaching into groundwater. Biogeochemical differences likely are related to soil textural and hydraulic properties that control surface/subsurface oxygen exchange. A new infiltration BMP was developed and a full-scale application was implemented for the HT pond. Preliminary results indicate reductions in nitrate concentration exceeding 50% in soil water and shallow groundwater beneath the HT pond.

Key words biogeochemistry; natural attenuation; groundwater protection; stormwater infiltration; best management practice

INTRODUCTION

As the demand for fresh water increases throughout the world to meet both public supply and irrigation needs, stormwater is increasingly being managed as a resource by operation of stormwater infiltration ponds to help offset possible declines in aquifer water levels. When applying an infiltration best management practice (BMP), a balance must be maintained between augmenting the quantity while protecting the quality of groundwater. A common constituent of concern is nitrate, due to its worldwide prevalence and well documented environmental and human health impacts.

EXISTING INFILTRATION POND MANAGEMENT

A typical infiltration BMP involves excavation of a basin above the water table,

without modification of the underlying soil, where stormwater runoff is directed for surface water pollution control and flood control purposes. Because stormwater exits the pond by only infiltration or evaporation, impacts to groundwater can be substantial.

Site Monitoring and Hydrogeologic Conditions

Two stormwater infiltration ponds in central Florida, USA, were monitored during 2007-2009 to identify subsurface biogeochemical processes. Chemical and hydrologic data were collected including: major element, nutrient, organic carbon, and trace metal chemistry; dissolved gases; stable oxygen and hydrogen isotopes of water, and oxygen and nitrogen isotopes of nitrate and nitrogen gas (N_2); soil mineralogy and chemistry; nitrite reductase gene density by real-time polymerase chain reaction (PCR); and relevant hydraulic/physical measures (rainfall, pond stage and groundwater level, soil moisture and temperature). Water samples were collected from ponded stormwater, suction lysimeters (0.5, 0.9, and 1.4 m depths), and shallow wells near the water table.

Both stormwater ponds are located in watersheds that have transitioned from rural to residential land use during 1973-1990 and have remained residential to present day. The South Oak (SO) pond is 1600 m^2 in bottom area with a watershed of 29 ha; the Hunter's Trace (HT) pond is 2800 m^2 in bottom area with a watershed of 23 ha. Hydrogeologic conditions at each pond are quite different. Soils at the SO pond generally are finer textured than the HT pond (Fig. 1a). The water table typically was less than 1 m deep at the SO pond and less than 3 m deep at the HT pond. Textural differences contributed to the large differences in the soil moisture retention curves (Fig. 1b). The greater moisture retention characteristics of the SO soil support the wet to nearly saturated soil that existed beneath the pond even during prolonged dry periods. Whereas the relatively coarse textured soil at the HT pond dried rapidly after infiltration events. For 46-155 mm rainfall events, infiltration rates were 14-29 mm/d at the SO pond, while at the HT pond infiltration rates were 170-260 mm/d.
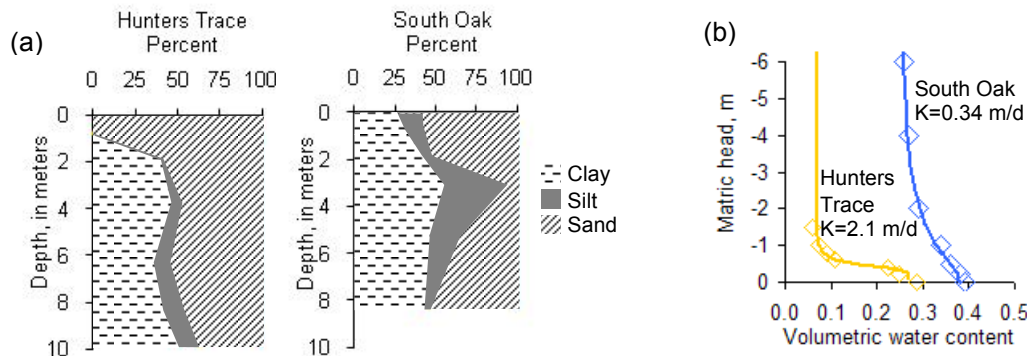

Figure 1. Soil properties at the infiltration ponds: (a) textural variations with depth; (b) soil moisture retention curves reported by Naujock (2008) for undisturbed cores collected from 0.3 m depth (K, saturated hydraulic conductivity).

Biogeochemical Processes

A temporal succession of biogeochemical processes was identified beneath the SO pond, including oxygen reduction, denitrification, manganese and iron reduction, and methanogenesis. Dissolved oxygen (DO) concentrations beneath the SO pond indicate a cyclic variation between oxic and anoxic conditions, with oxic conditions occurring shortly after major runoff events (Fig. 2). For example, during July-November 2008

the pond remained flooded continuously (up to 2.1 m deep) due to heavy summer rainfall. Increasing alkalinity and CO_2 concentrations suggest that dissolved organic carbon (DOC) was being mineralized during the wet season, thus likely serving as an important electron donor for all biogeochemical processes. DOC concentrations were 4.1-13 mg/L at depths above 2.6 m. Soil analyses indicate increases from spring to fall 2008 in organic carbon in the pore water at depths above 2.3 m compared to decreases in the soil solids, suggesting mass transfer of organic carbon from solid to aqueous phases consistent with DOC increases (Fig. 2). After oxygen and nitrate were depleted in the shallow groundwater by July 2008, manganese and iron (Fe) concentrations steadily increased (Fig. 2). Soil analyses indicate Fe oxides contents as high as 20,000 mg/kg that may serve as the source of dissolved Fe. Methane (CH_4) concentrations start to increase in August 2008, peak in November, and finally drop after the pond was dry again in December (Fig. 2). Elevated CH_4 concentrations likely are the result of methanogenesis; slight decreases in both alkalinity and CO_2 at the peak CH_4 concentration suggest use of the CO_2 reduction pathway.
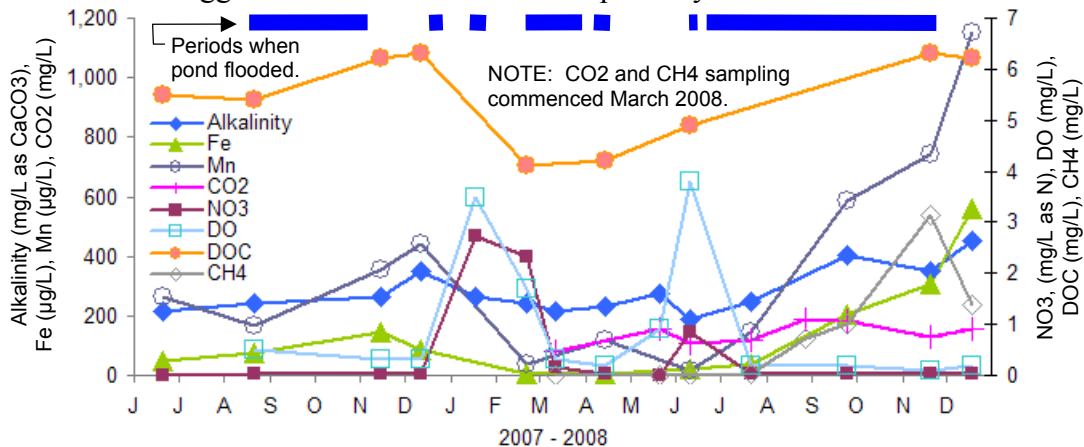

Figure 2. Water quality in the shallow groundwater (2.6 m deep well) beneath the South Oak pond. Fe, iron; Mn, manganese; CO2, carbon dioxide; NO3, nitrate; DO, dissolved oxygen; DOC, dissolved organic carbon; CH4, methane.

In contrast, aerobic conditions persisted beneath the HT pond, resulting in DOC depletion and nitrate leaching into the water-table aquifer. Nitrate concentrations were 0.07-7.2 mg/L in soil water (lysimeters) and 1.4-3.3 mg/L in groundwater. DOC in soil water decreased with depth (8.5-2.9 mg/L), decreasing further in groundwater (0.5-1.0 mg/L). Aerobic conditions precluded the reduction of other electron acceptors.

Nitrate Transport and Fate

The differing subsurface oxygen conditions and ensuing biogeochemical processes had a strong influence on the transport and fate of nitrogen at each pond site. For example, at the SO pond concomitant peaks in DO and nitrate concentrations likely indicate short periods of nitrification (Fig. 2). In June 2008, a nitrate concentration of 3.3 mg/L was measured in the lysimeter at a depth of 1.4 m and 0.84 mg/L from the 2.6 m deep well; however, nitrate concentrations remained below 0.016 mg/L (laboratory method reporting limit) for the remainder of 2008 in the 2.6 m deep well (Fig. 2). The biogeochemical conditions at the SO pond result in low nitrate concentrations as a result of denitrification. Evidence of denitrification is further supported by excess N_2

concentrations as high as 3 mg/L; isotopically heavy $\delta^{15}N$ and $\delta^{18}O$ of nitrate (25 and 15‰, respectively) and light $\delta^{15}N$ of N_2 (1‰) (Kendall and Aravena, 2000); and PCR results indicating elevated nitrite reductase gene densities at depths above 1.4 m. At the HT pond site, advection-dominated transport of nitrate prevails due to the persistent aerobic conditions and permeable soils. Biogeochemical differences between the two pond sites likely are related to soil textural and hydraulic properties that control surface/subsurface oxygen exchange. In particular, a fine textured soil that remains wet during prolonged dry periods will promote anoxic conditions because (1) the diffusion coefficient of oxygen through water is 10^4-10^5 times less than through air, and (2) the gas diffusion coefficient in soil is proportional to the square of the volumetric gas content (Jin and Jury, 1996). Thus the large moisture content (saturation exceeding 70%) of SO soils likely inhibits transport of oxygen into the subsurface (Fig. 1b).

NEW INFILTRATION BEST MANAGEMENT PRACTICE

A new infiltration BMP was developed based on the natural biogeochemical processes identified at the existing ponds. The new BMP entails excavation of native soil in the bottom of a fore bay area of an existing pond; emplacement of a 0.3 m thick amended soil layer; and construction of a berm forming separate pollution control and flood control basins. The amended soil layer is a 1:1:5 mixture (by volume) of native soil, tire crumb (to increase sorption capacity (Hossain *et al.*, 2009)), and clayey sand (to increase soil moisture retention). The full-scale BMP was implemented at the HT pond in 2009 and water-quality and hydrologic monitoring are being conducted in 2009-2010. Preliminary results from sampling 5 weeks after construction after two large runoff events indicate 50-80% reductions in nitrate from pre-construction median concentrations in soil water and at the water table. During this time, nitrogen was predominately in the nitrate form, with non-detectable ammonia and nitrite (less than 0.02 and 0.002 mg/L, respectively) and either constant or decreasing organic nitrogen, suggesting mass loss of dissolved nitrogen. Nitrate decreases may be due to dilution, sorption, reduced nitrification, denitrification, or some combination of these processes.

Implementation of the new infiltration BMP is expected to be a viable alternative for improving and protecting groundwater quality. Additional nutrient data from the remaining sampling events and examination of major element, isotope, dissolved gas, soil chemistry, PCR, and soil gas sampling results should provide greater insight into the biogeochemical processes controlling nitrate fate and the environmental and cost effectiveness of the new BMP.

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