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Identification of groundwater flowpaths and denitrification zones in a dynamic floodpain aquifer

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Abstract

The groundwater flow system in the thick sand and gravel aquifer of the wide forested floodplain along the Lower Wisconsin River was characterized using major ion and oxygen and deuterium stable isotope analyses to explain nitrate attenuation in the floodplain. Critical to the groundwater flow system are the 60–90 m bluffs, the Pleistocene river terrace, and the modern floodplain with ridge and swale microtopography. Upland nitrate concentrations reached 12 mg NO_3–N/L, but were largely below the detection limit in the downgradient floodplain wetlands. A transect of monitoring wells and multilevel samplers, with depths of up to 6 m, were installed to characterize spatial and temporal variability in the floodplain groundwater flowpaths. Results showed that the topography induces deep, intermediate, and shallow flow systems and that temporal variability causes mixing between water from different sources. Nitrate attenuation in this system is likely a combination of dilution, plant uptake and denitrification. The absence of dissolved oxygen and nitrate and presence of high soluble iron concentrations in the lower floodplain indicate an ample supply of electron donors for oxygen consumption, denitrification and subsequent iron reduction. The data indicate that conditions created by the topography and temporal variability of the system are suitable for denitrification to occur at depth.

1. Introduction

Wetlands provide critical ecosystem services across the landscape. Increasing and protecting these ecosystem services is considered a priority to address problems such as flooding damage, loss of biodiversity and excessive nutrients in waterways (Zedler, 2003). For example, excessive amounts of nitrate flowing from the Mississippi River into the Gulf of Mexico have created a well documented hypoxia zone (Goolsby et al., 1999) and efforts are ongoing to determine ways of reducing nitrate inputs into the Mississippi River. Riparian zones, both narrow buffer strips and broader floodplains, have been shown to attenuate nitrate in groundwater derived primarily from agricultural fertilizers as it moves from upland areas to streams and rivers (Gilliam, 1994; Hill, 1996; Vidon and Hill, 2004).

Nitrate attenuation occurs through denitrification, plant uptake and dilution. Numerous previous studies have been conducted to determine the mechanism for nitrate attenuation. These focused primarily on denitrification in groundwater systems with shallow

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confining layers that force groundwater flow into shallow riparian soils. For example, Maitre et al. (2003) studied the effectiveness of nitrate removal in a riparian 0.2–5 m thick sand and gravel aquifer that overlies a silt/clay till confining layer. They found denitrification activity highest in the surface horizons. Hedin et al. (1998) delineated groundwater flowpaths within 4 m of a first-order stream channel in Michigan and found that denitrification occurred primarily within this near-stream region, where upward flowing nitrate-rich water mixed with organic carbon-rich water from shallower flowpaths. In a study near a small stream in southern Ontario, Cey et al. (1999) observed decreases in nitrate concentrations beneath a break in slope, approximately 15 m from the stream. They attributed these decreases, in part, to downward flow of nitrate-laden groundwater induced by infiltration through an uncultivated buffer strip. The downward flowing, nitrate-laden water also experienced denitrification as it entered a reducing zone that coincides with a shallow clay layer. While most studies have focused on dissolved organic carbon as the primary electron donor in denitrification, Böhlke et al. (2002) found that FeS_2 was the major electron donor in a study of denitrification processes in a 10–15 m thick sand aquifer underlying a 50 m wide riparian zone.

Some studies have suggested that denitrification is less likely to occur in thicker aquifers perhaps due to limited carbon availability (Peterjohn and Correll, 1984). However, Hill (1996) also noted the need for further study of nitrate attenuation and denitrification in thicker aquifers, citing the relevance of three-dimensional flow effects and interaction between water from subsurface and surface water sources. Puckett et al. (2002) demonstrated that moderately deep groundwater flowpaths can allow nitrate laden groundwater to pass unaltered under riparian zones and discharge into streams. They emphasize that in aquifers without a shallow confining layer it is critical to investigate the hydrology and biogeochemistry of the riparian and upland aquifer to understand the potential for a riparian zone to remove nitrate from the groundwater. Vidon and Hill (2004) developed a conceptual model of the connection between landscape hydrogeologic characteristics and nitrate removal in the riparian zone based on eight stream riparian sites. They found that greater than 90% of nitrate removal occurred within the first 15 m of the riparian zone in sandy loam soils with shallow 1–2 m confining layers. In contrast, sites with sandy soils and confining layers at depths of 6 m had greater than 90% nitrate removal over 25–176 m. The study demonstrates the importance of topography, soil type, and depth of confining layers in determining nitrate removal efficiency.

Devito et al. (2000) demonstrated the importance of microtopography for biogeochemical cycles as a result of the small scale vertical hydrologic gradients created by microtopography. They found that the downward gradients created by microtopography were critical for moving organic carbon from overlying peat layers into interbedded sands. Similarly, Johnston et al. (2001) found the variability in riverine geomorphic structures and the resulting hydrologic zonation of the floodplain to be more significant for nutrient cycling in river wetlands than substrate differences. Cey et al. (1999) also noted that denitrification is often found to occur over very narrow zones, often in association with a break in slope, which induces changes in hydrological conditions needed for denitrification.

Understanding groundwater flowpaths and temporal and spatial variability and groundwater-surface water interactions are critical to exploring mechanisms for nitrate attenuation in thicker aquifers in broad floodplains (Hill et al., 2000). Sampling scale has a critical impact on establishing groundwater flowpaths (Hunt et al., 1998). In addition to traditional physical measurements of the water levels, stable isotopes and major ions composition of groundwater are proving to be particularly effective tools for establishing groundwater flow patterns and the extent of mixing between waters from different sources (Böhlke and Denver, 1995; Kehew et al., 1998; Mengis et al., 1999; Sidle et al., 2000).

This paper presents a detailed characterization of groundwater flowpaths and groundwater/surface water interactions in a forested floodplain wetland along a major tributary to the Mississippi River, the Wisconsin River, developed using stable isotope, water chemistry and physical data. This characterization highlights the importance of temporal variability in groundwater flowpaths and microtopography and allows for an explanation of nitrate attenuation at