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Groundwater flow path dynamics and nitrogen transport potential in the riparian zone of an agricultural headwater catchment ☆

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SUMMARY

Shallow groundwater dynamics play a critical role in determining the chemistry and movement of nitrogen (N) in the riparian zone. In this study, we characterized N concentration variability and hydrologic transport pathways in shallow groundwater draining areas of a riparian area with and without emergent groundwater seeps. The study was conducted in FD36, an agricultural headwater catchment in the Ridge and Valley physiographic region of central Pennsylvania, USA. Three seep and adjacent non-seep areas were each instrumented with a field of 40 piezometers installed in a grid pattern (1.5-m spacing) at both 20- and 60-cm depths. Piezometers were monitored seasonally for approximately two years (October 2010–May 2012). Results showed that hydraulic head within seep areas was variable and some regions exhibited upward vertical hydraulic gradients of 0.18–0.27. Non-seep areas were characterized by uniform hydraulic head levels and were relatively hydrostatic. Nitrate-N (NO_3-N) concentrations in seep areas were significantly greater than those in the non-seep areas at two of the three study sites. A two-component mixing model using chloride as a conservative tracer indicated that shallow groundwater in seep areas was primarily (53–75%) comprised of water from a shallow fractured aquifer, which had elevated NO_3-N concentrations (5.7 mg L^{-1}). Shallow groundwater in non-seep areas, however, was comprised (58–82%) of perched water on top of the fragipan that was likely recharged locally in the riparian zone and had low NO_3-N concentrations (0.6 mg L^{-1}). Higher NO_3-N concentrations, variable hydraulic head, and groundwater emergence onto the land surface in seep areas provided evidence for preferential flow paths as an important conduit for water and N movement in these areas of the riparian zone. We conclude that the potential for N delivery to the stream in FD36 was much greater from seep areas compared to non-seep areas. Targeted management of seeps should be a priority in efforts to reduce NO_3-N levels in riparian zones within headwater agricultural catchments.

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1. Introduction

Nitrogen (N) is one of the most common agricultural contaminants in groundwater and surface water around the world (Galloway and Cowling, 2002). Due to its high solubility, N is easily transported in water from agricultural fields to nearby waterways (Simmons et al., 1992). Excess N loading of groundwater and surface water is of concern because it can create conditions that lead to negative water quality outcomes (Correll, 1998). For example, eutrophication caused by excessive inputs of nutrients, such as N, is the most common impairment of surface waters in the U.S. (USEPA, 2008). Insufficient progress toward N reduction goals and continued poor water quality in many surface water bodies emphasizes the need to develop management plans that address N pollution from agricultural landscapes.

Riparian corridors are often considered to be effective sites for remediation of agricultural N (Peterjohn and Correll, 1984), especially those located along first-order streams (Peterson et al., 2001). Indeed, a meta-analysis by Mayer et al. (2007) demonstrated the influence of riparian zones on the supply, transport,

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and fate of N in headwater catchments. The authors found that in 88 peer-reviewed papers on riparian zone effectiveness, riparian zones decreased NO_3-N concentrations in surface water and groundwater by an average of 68%. Guidelines for N mitigation measures in riparian zones have typically focused on factors such as width and vegetation composition (Mayer et al., 2007), but less consideration has been given to hydrologic factors that affect N transport in the riparian zone (Hill, 1996; Angier and McCarty, 2008). Since water is a key medium for N movement, hydrological processes and properties of the riparian zone have an impact on N transport and delivery to streams. For example, the transmissivity of riparian zone sediments can influence N dynamics, as groundwater residence time within the subsurface affects N behavior (Ocampo et al., 2006). Differences in flow paths can also affect groundwater (Calver, 1990) and contaminant delivery patterns (Angier et al., 2001).

Early concepts of riparian zone hydrology in agricultural headwater catchments often assumed uniform, lateral groundwater movement from an upland field, through the riparian zone, and ultimately to a stream (Jordan et al., 1993; Bosch et al., 1994). These conceptual models suggest a scenario in which there is sufficient contact time between groundwater and the soil matrix to facilitate N removal. While many riparian zones have sediment layers with high N removal potential (Groffman et al., 1992), the presence of environmental conditions suitable for N removal (e.g., soils high in organic carbon, anaerobic settings, N demand by vegetation) alone may be insufficient to remove N from groundwater if flow paths deviate from uniform lateral flow. Recent research suggests that much of the riparian groundwater may travel underneath the riparian zone and discharge upward to streams (Bohlke and Denver, 1995) or travel through preferential subsurface flow paths, even in the presence of an aquiclude (e.g., fragipan) occurring at shallow depth (Hill et al., 2000; Angier et al., 2005). These flow pathways can result in N-laden groundwater that effectively bypasses the remediation capacity of the riparian zone (McGlynn and McDonnell, 2003; Vidon et al., 2010).

One example of preferential flow in the riparian zone is the presence of groundwater-sustained wetlands, slope wetlands, springs, or emergent groundwater seeps (hereafter referred to as seeps). These groundwater discharge zones often serve as a primary source of streamflow in headwater catchments (O'Driscoll and DeWalle, 2010). Several characteristics of seeps, such as visible zones of groundwater emergence and the rapid discharge of groundwater, suggest that in these areas preferential flow may play a substantial role in determining the quantity and chemistry of water in the riparian zone. Evidence of this was reported in a study by Devito et al. (2000), in which groundwater upwelling areas showed consistently elevated nitrate-N (NO_3-N) concentrations (20 mg L^{-1}) relative to neighboring inactive areas with low (<1 mg L^{-1}) NO_3-N concentrations. Similarly, preferential flow paths have been shown to play a major role in NO_3-N leaching in agricultural landscapes (Di and Cameron, 2002). Thus, information on riparian zone hydrology is needed to better explain temporal and spatial variations in N across the riparian zone.

We report here the results of a study examining spatial and temporal patterns of groundwater and N transport at three paired study sites within the riparian zone of FD36, a small agricultural headwater catchment in central Pennsylvania, USA. Each study site included an area with an emergent groundwater seep and an adjacent area without a seep (i.e., non-seep) in order to contrast hydrological and biogeochemical processes within different areas of the riparian zone. The objectives of this study were to (1) investigate shallow groundwater dynamics and identify key hydrologic flow pathways within both seep and non-seep areas of the riparian zone; (2) determine the relationship between subsurface hydrologic characteristics and N concentrations within seep and non-seep areas; and (3) examine the N transport potential from both areas of the riparian zone.

2. Materials and methods

2.1. Site location and characteristics

FD36 (40 ha) is a headwater catchment within the non-glaciated, folded and faulted, Appalachian Ridge and Valley physiographic region (Fig. 1). Located approximately 40 km north of Harrisburg, Pennsylvania, USA, FD36 is one of 15 sub-catchments that form WE-38, a primary research site of the USDA-Agricultural Research Service since 1968 (Bryant et al., 2011). The climate is temperate and humid with annual precipitation averaging 1080 mm yr^{-1} and mean annual air temperatures of 8–10 °C (Gburek and Sharpley, 1998; Buda et al., 2011). Since 1996, stream discharge has been monitored every 5 min at four locations with recording H-flumes. Previous research in FD36 has shown that groundwater provides the majority (60–80%) of the annual streamflow (Pionke et al., 1996) and that surface and subsurface flow systems are predominately self-contained at the catchment scale (Gburek and Folmar, 1999a,b).

The dominant land use in FD36 is agriculture (56%) with woodlots (30%) and grassland (13%) comprising the remainder of the catchment. Fields upslope of the riparian zone are planted in three- to four-year sequences of corn, small grains, hay, and soybeans.

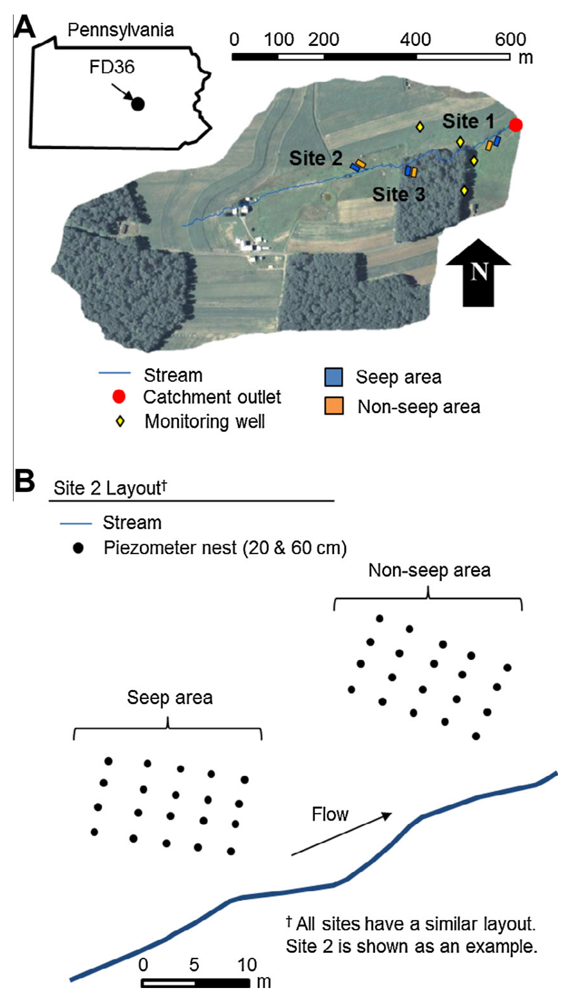

Fig. 1. (A) Aerial photo of FD36, an agricultural headwater catchment located in central Pennsylvania, USA, with three study sites marked. (B) Instrumentation at study site 2. Site 2 is shown, but all three study areas had identical instrumentation.