Effectiveness of riparian buffers in controlling ground-water discharge of nitrate to streams in selected hydrogeologic settings of the North Carolina Coastal Plain

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Abstract Water-quality and hydrologic information were collected along ground-water flow paths from two well-drained and two poorly drained Coastal Plain settings in North Carolina to evaluate the relative effectiveness of riparian buffers in reducing discharge of nitrate to streams. At one well-drained site with a 100 m buffer, little or no effect was detected on surface-water quality by discharging ground water because extensive woody vegetation in the buffer was able to take up not only most nitrate, but also most ground water before discharging to the stream during the growing season (March–October). At the second well-drained site, ground water discharging to the stream from the side with a buffer contained about 2 mg/L of nitrate-nitrogen after passing through the bed of the stream compared to 6 mg/L in ground water discharging from the side with no buffer. In the poorly drained settings, nitrate in ground water decreased from about 6 mg/L in the recharge area to less than 0.02 mg/L downgradient from the riparian buffer. Ground water discharging from the side with no buffer contained 0.83 mg/L. Riparian buffers appear effective in reducing nitrate in ground water discharging to Coastal Plain streams.
Keywords Denitrification; ground water; hydrogeology; nitrate; riparian buffer

Introduction

The North Carolina Coastal Plain is a major agricultural area on the East Coast of the United States that supports crops, such as corn and soybeans, and large-scale livestock operations. Agriculture has been identified as a probable source of water-quality problems in streams and estuaries. Fertilizer and animal-waste applications to fields result in increased concentrations of nitrate in surface runoff and ground water. Because typically more than half of streamflow in the Coastal Plain of North Carolina (Figure 1) comes from ground water (McMahon and Lloyd, 1995), nitrate-contaminated ground water can contribute to the nitrogen load in streams. Elevated nutrient concentrations can cause eutrophication in streams and estuaries (Spruill *et al.*, 1998). Riparian buffers have been adopted as a management tool for reducing nutrients moving from agricultural fields to streams (Gilliam *et al.*, 1997). Riparian buffers as defined in this paper are forested strips along a streambank that can range from a few to several hundred metres wide. Buffers are present along many streams in eastern North Carolina, particularly along streams where the soil is too poorly drained to cultivate (Jacobs and Gilliam, 1985).

In the spring of 1997 a committee of university and government scientists evaluated best-management practices suitable for North Carolina, and recommended riparian buffers as a means of decreasing nitrate concentrations and other nutrients in subsurface and surface runoff from cultivated fields in the middle and upper Coastal Plain of the Neuse River Basin in North Carolina (Gilliam *et al.*, 1997). The basis of this recommendation is supported by many studies (e.g. Lowrance *et al.*, 1984; Peterjohn and Correll, 1984; Jacobs and Gilliam, 1985) that demonstrate the effectiveness of buffers in decreasing nitrate concentrations in ground water. Based on a statistical comparison of 15 sites with buffers to 15 sites without buffers in the Coastal Plain of North Carolina, Spruill (2000) found riparian buffers generally effective in reducing nitrate in discharging ground water. However,

because riparian buffers do not always decrease nitrate concentrations in ground water, questions persist regarding their effectiveness in specific environments. High concentrations of nitrate-nitrogen (> 3 to 4 mg/L) have been documented in ground water flowing beneath riparian buffers. Speiran (1996) reported nitrate-nitrogen concentrations greater than 5 mg/L in ground water beneath a riparian zone with coarse-grained low-carbon sediments in the Virginia Coastal Plain. Hamilton *et al.* (1993) reported high nitrate-nitrogen concentrations (8.5 mg/L) at 24 m below land surface in an aquifer receiving recharge from agricultural fields located far upgradient. Much of this deep ground water flows beneath riparian buffers before discharging to streams.

Based on research on buffers, such as that cited above, the question was posed as to whether characteristics of environmental landscapes can be identified that allow an evaluation of where and how well buffers are effective in reducing nitrate in ground water before discharging to surface water. The US Geological Survey (USGS) and the North Carolina Department of Environment and Natural Resources (NCDENR) initiated a 2-year study in 1997 to determine effectiveness of riparian buffers in two common, but different, hydrogeologic settings in the Coastal Plain of North Carolina. Water-quality and hydrologic information were collected along ground-water flow paths from two well-drained and two poorly drained Coastal Plain settings of North Carolina to evaluate the effectiveness of riparian buffers in reducing discharge of nitrate to streams. Specifically, the function of forested riparian buffers was evaluated with respect to nitrate reduction in ground water in two different hydrogeologic settings having different soil and drainage characteristics. The purpose of this paper is to present major findings from that study.

Description of study sites

Three flow-path study sites were selected in the Neuse River Basin and one in the Tar-Pamlico River Basin in the North Carolina Coastal Plain (Figure 1). Each site in the Neuse River Basin represents only one flow path from the recharge area to the discharge area near the stream – only one side of the stream is represented at these sites. The site in the Tar-Pamlico River Basin (Site 2) represents two flow paths, one with a buffer and one without a buffer on each side of the stream. Corn and soybeans are the primary crops grown at all four sites. Site 1 has about a 100-m wooded buffer with poorly drained soils in the lowland and well-drained soils on the upland. This site is underlain by a coarse-grained sandy shallow aquifer on granitic bedrock. Site 2 has well-drained soil, a 200-m wooded riparian buffer, and a medium- to coarse-grained shallow aquifer. Corn and soybeans were planted next to the stream on the opposite bank, which had no riparian buffer. Soils on the side with the buffer also were well drained. Site 3 has no buffer on the cultivated side, although the oppo-
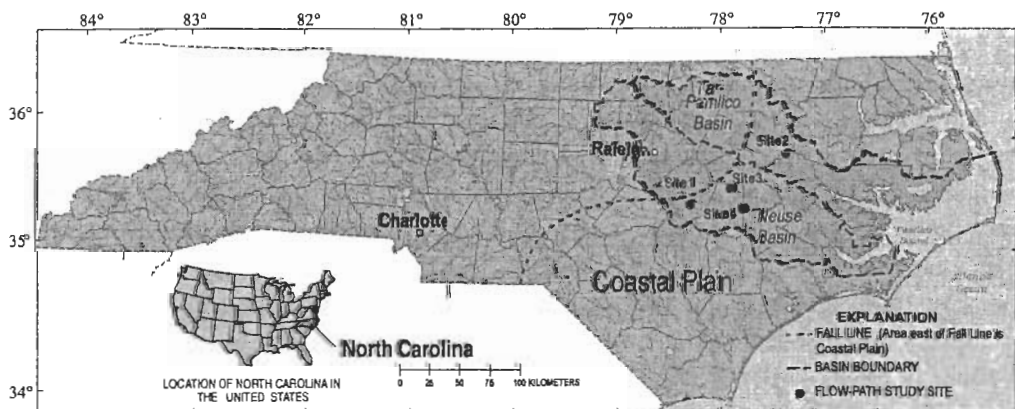

Figure 1 Location of flow-path study sites in the Tar-Pamlico and Neuse River Basins in North Carolina

site bank and areas upstream from the site are extensively wooded. Well-drained soils are located in the upland, and poorly drained but cultivated soils are in the flood plain of the stream. This site is underlain by a fine- to medium-grained aquifer that overlies a confined aquifer beneath. Site 4 had a 100-m buffer and moderate to well-drained soils in the uplands and poorly drained soils next to the stream. This site is underlain by a fine- to medium-grained shallow aquifer with a confined aquifer underlying it. Generalized cross sections of all four sites with associated site characteristics are shown in Figure 2.

Methods

The four flow-path study sites (Figure 1) were chosen on the basis of the presence or absence of a buffer and on the prevailing soil type (well drained or poorly drained). Sites were categorized primarily based on the hydrologic characteristics of the soils that were farmed. If large areas were used to grow crops in poorly drained soils, the site was categorized as poorly drained; if the site was used to grow crops in well-drained soils, it was categorized as well drained. Most sites actually had a mix of soil-drainage classes. Wells were
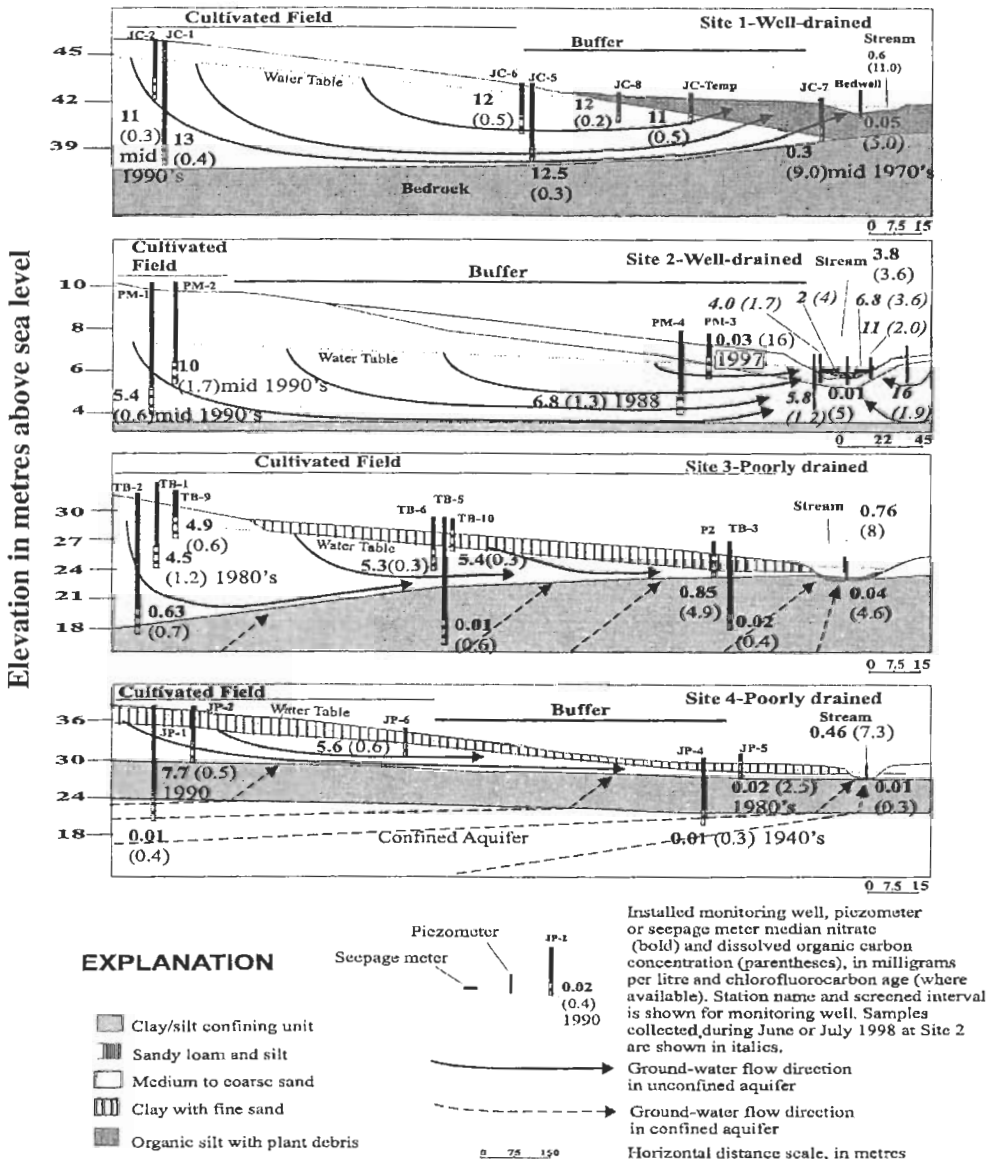

Figure 2 Cross sections of sites showing changes in nitrate-nitrogen along the flow path from recharge to discharge area

installed at Sites 1, 3, and 4 in November and December 1997 and at Site 2 in July 1998 (Figure 2). Wells were installed along transects from the high point in the field to the stream. Each site had one transect containing two to three well clusters. Each cluster included one to three wells, ranging in depth from the top of the water table to below the first confining layer. Water-quality samples were collected at each site at 1 to 2 month intervals between December 1997 and March 1999. Samples for dissolved gases, including nitrogen, were collected between January and March of 1999 (Figure 3). Water samples were collected from the stream and from beneath the stream by using a minipiezometer (Winter *et al.*, 1988) at each sampling. Water samples also were collected at Site 2 in June 1998 from minipiezometers placed at depths ranging from 0.3 to 2.5 m and from seepage meters placed on the streambed along a cross section of the stream to evaluate possible changes in ground-water quality within the streambed (Figure 4). Samples were collected from monitoring wells and prepared according to techniques presented in Koterba *et al.* (1995). Measurements were made in the field for pH, specific conductance, dissolved oxygen, and water temperature according to techniques described in Koterba *et al.* (1995). Routine samples were collected for dissolved organic carbon (DOC), dissolved nitrate, and dissolved chloride at each sampling event. The NCDENR Water-Quality Laboratory in Raleigh, NC, analyzed all routine samples. The USGS National Water Quality Laboratory in Denver, Colo., analyzed selected samples for complete ionic composition. Chlorofluorocarbons, for age dating ground water (Busenberg and Plummer, 1992) and nitrogen gas, to verify denitrification, were collected from selected wells and analyzed by the USGS Laboratory in Reston, Va. Correlation analysis was performed using the Spearman rho as the test statistic (Conover, 1980). Water-quality data collected for this study are presented in Howe and Breton (1999).

Results and discussion

Site 1 (well-drained with buffer) – Nitrate-nitrogen concentrations are high beneath the field, generally at 11–13 mg/L. Little difference in nitrate concentrations occurs in water collected from shallow and deeper wells (Figure 2). This is likely due to the fairly uniform
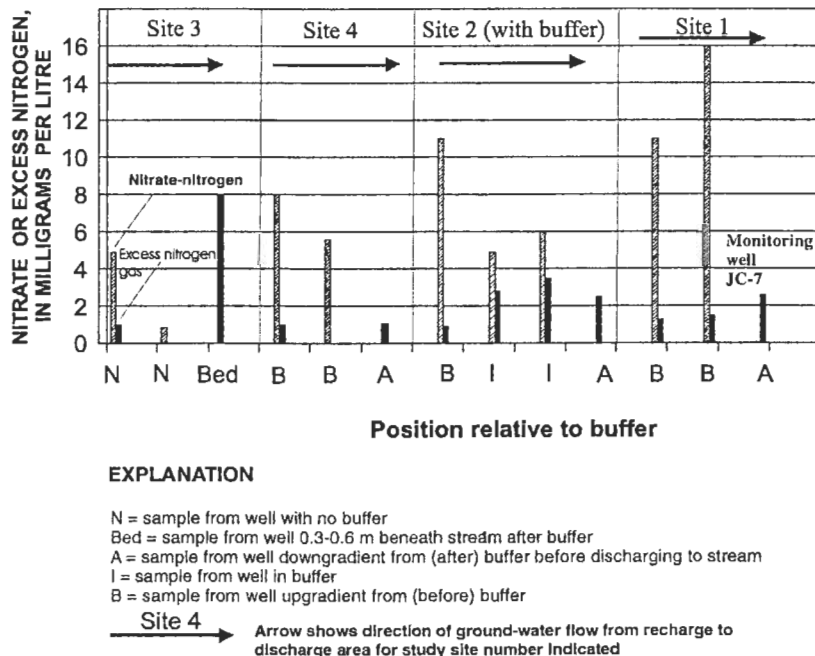

Figure 3 Nitrate and excess nitrogen gas measured in water samples from wells along ground-water flow path from recharge area to discharge area at four study sites in North Carolina Coastal Plain

and transmissive deposits (indicated by young ground water [mid-1990s in well JC-1] and early 1990s in well JC-4 [not shown], screened at the same depth and similar position as well JC-6), low DOC (< 0.5 mg/L), and the lack of a confining layer to impede the vertical transport of water and nutrients. Not only are concentrations uniform vertically throughout the aquifer, but nitrate-nitrogen concentrations are similar laterally in the downgradient wells. Samples from wells JC-8 and JC-Temp, which are located in the buffer and are screened in the sandy sediments 2 to 2.5 m below the land surface, contain as much nitrate as is found beneath the field. These two wells are located about 8 m inside the buffer where little or no effect on ground-water quality is evident. Samples from wells placed near the stream (JC-7) and in the stream (the bedwell) both contained little or no nitrate. However, the organic flood-plain deposits near the stream, composed of silt or organic debris, were not very transmissive as indicated by constant difficulty in collecting water from the mini-piezometer in the streambed and the old (1970s) water found in these deposits. This stream typically does not flow during the summer months. Because bedwell samples were collected only during the wet season when the stream was flowing, and because no bedwell samples could be collected when the stream was dry, the bedwell samples could possibly represent recent water stored in sandy pockets in the stream and flood-plain sediments.

The functionality of the buffer in reducing nitrate concentrations in discharging ground water may be entirely due to site hydrology because very little ground water passes through the buffer area to the stream, either because ground water is removed via the atmosphere through evapotranspiration or it discharges as underflow to another location. High DOC and low nitrate in samples from well JC-7 (Figure 2) indicate higher denitrification rates compared with the upgradient wells. More than 2.5 mg/L of excess nitrogen was measured in water from a sample collected from well JC-7 in February 1999 (Figure 3, A position, Site 1), also indicating denitrification was taking place. In small first or second order Coastal Plain streams near the Fall Line (Figure 1), it appears that vegetative water use and nutrient uptake may be as important as denitrification in limiting nitrate movement to streams in this setting.

Site 2 (well-drained with and without buffer) – Nitrate-nitrogen concentrations were greater than 5 mg/L beneath the farm field. In wells PM-2 and PM-1, the median nitrate concentrations were 10.0 and 5.4 mg/L at depths of 4 and 5.5 m, respectively (Figure 2), a decrease of about 50% in the 1.5-m distance between the two screens. This suggests that nitrate is either diluted by low nitrate water from some source or that some denitrification occurs at depth within the aquifer. Denitrification is the likely reason because there is no upward gradient from the underlying confined aquifer. A sample collected from well PM-1 in February 1999 had 5.07 mg/L of excess nitrogen (data not shown) measured; this sample contained less than 0.2 mg/L of dissolved oxygen and only 4 mg/L of nitrate, indicating that denitrification can occur, at least periodically, in recharge areas of this aquifer. Figure 4 shows changes in dissolved nitrate, nitrate to chloride ratio, DOC, and ammonium in the stream cross section from samples collected on June and July 1998 during baseflow conditions from the minipiezometer placed at different depths in the streambed.

Nitrate-nitrogen concentrations were higher (from 7–16 mg/L) in ground water discharging from the right bank (the side *without* a buffer) between the stream and the field compared to concentrations (4–9 mg/L) in ground water discharging from the left bank (the side *with* a buffer). Some denitrification occurred even in the upgradient well at this site, as indicated by about 1 mg/L of excess nitrogen production (Figure 3, Site 2, B position). Significant denitrification (greater than 2 mg/L of excess nitrogen) occurs in (Figure 3, Site 2, I positions) and after the buffer before discharging to the stream channel as indicated by no nitrate in the sample from the bank well (Figure 3, Site 2, A position). However, nitrate apparently continues to move to the stream at depth, on both sides of the stream. Nitrate-

nitrogen concentrations remain high, 7–11 mg/L on the right bank and 4–6 mg/L on the left bank about 0.7 m below the streambed (Figure 4). Nitrate concentrations are substantially reduced as water moves through the streambed. The seepage meter samples, which represent ground water after it has discharged vertically to the stream channel, contained concentrations of nitrate-nitrogen, after passing through the streambed, that were about 50% lower than concentrations in samples collected beneath the streambed (Figure 4).

The riparian buffer and streambed combined are effective in reducing nitrate-nitrogen concentrations in ground water at this site. Comparison of median concentrations of nitrate-nitrogen in water from the upgradient wells (about 8 mg/L in PM-1 and PM-2) and downgradient wells (about 4–5 mg/L in PM-3 and PM4) on the buffer side (Figure 2) indicates about a 3- to 4-mg/L loss of nitrate-nitrogen, or about a 35–40% reduction due to denitrification and(or) dilution within the aquifer. From the left bank to the discharge point in the stream channel, concentrations drop to 2 mg/L in the seepage meter samples, resulting in an additional 60% decrease in nitrate-nitrogen concentrations through the streambed, and an overall decrease of about 95%. This decrease is comparable to reductions estimated from the statistical study results reported in Spruill (2000), implying that the streambed in forested buffer areas may reduce most of the nitrate from ground water before discharging to a stream. Spruill *et al.* (1998) reported a sharp decrease in nitrate-nitrogen concentrations due to streambed processes. Despite the denitrification processes occurring at this site, ground water typically contributes nitrate-nitrogen to the stream at concentrations as much as 7 mg/L on the right bank side (Figure 2). The median nitrate-nitrogen concentration in the surface-water sample was about 4 mg/L (Figure 2), suggesting a major influence of non buffer high-nitrate discharge of ground water to the stream in this watershed.

Site 3 (poorly drained without buffer) – Most of the decrease in nitrate-nitrogen at this site appears to occur within the streambed sediments or by dilution from water moving into the stream from the confined aquifer (Figure 2). This was suggested by data collected from the streambed wells. Ground water sampled from the bedwells usually had elevated DOC (>3 mg/L), ammonium (0.3 mg/L, one order higher), low nitrate-nitrogen (< 0.5 mg/L), elevated iron (6,000 µg/L, two orders of magnitude greater), and phosphorus (0.6 mg/L, sixfold higher) compared with the upgradient wells sampled. The organic material in the
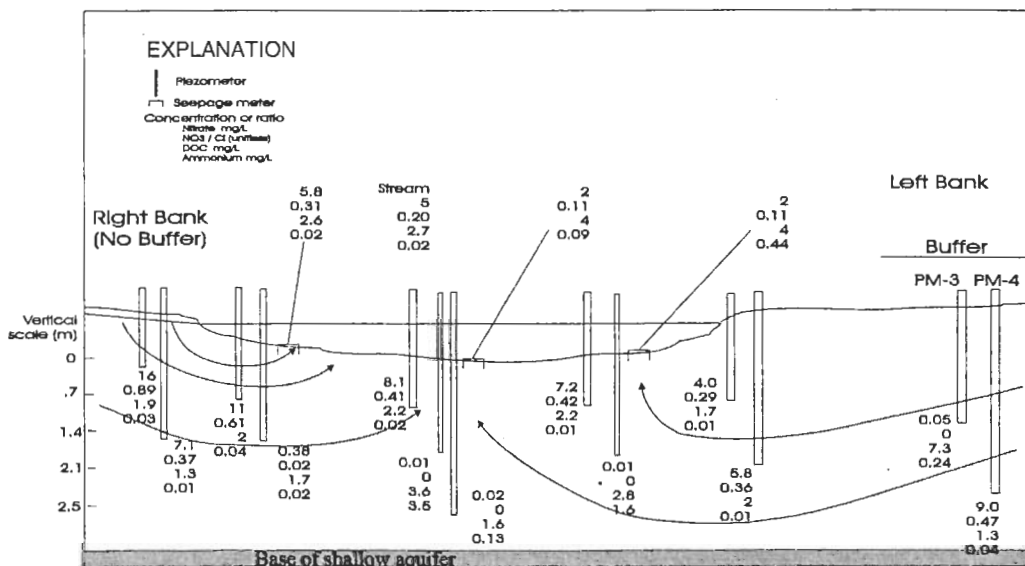

Figure 4 Stream cross section at Site 2 showing changes in nitrate, nitrate/chloride ratio, dissolved organic carbon (DOC) and ammonium in ground water discharging to the stream from the buffer side (left bank) and non buffer side (right bank) during June 1998

streambed provides a strongly reducing environment that promotes denitrification, as evidenced by 8 mg/L of excess nitrogen in the sample from the ground water discharging to the stream (Figure 3). These constituents are indicative of reducing conditions and were associated with buffer sites. It is hypothesized that the organic material on the streambed was derived from riparian vegetation located across and upstream of this site and emphasizes the importance of riparian buffers at the watershed scale. Defining the importance of these processes will be the focus of future work. This site also demonstrates the importance of understanding the hydrogeology in order to accurately evaluate the independent effects of geology, riparian buffers, and streambed processes on stream chemistry.

Site 4 (poorly drained with buffer) – Approximately 25% of the nitrate was removed from ground water as it moved downgradient through the aquifer from the recharge area (7.7 mg/L in well JP-2, Figure 2) to just upgradient from the riparian buffer (5.6 mg/L in well JP-6, Figure 2). Like the other sites examined for this study, some denitrification is taking place, as indicated by some excess nitrogen gas measured in both JP-2 (1.03 mg/L, Figure 3, Site 4, position B) and JP-5 (1.09 mg/L, Figure 3, Site 4, position A), although these low concentrations indicate processes other than denitrification are responsible for the decrease of nitrate concentrations at this site. Shallow ground water downgradient from the riparian buffer is, however, almost totally devoid of nitrate-nitrogen (0.02 mg/L in JP-5, Figure 2). The upward gradient observed in the downgradient deep well (JP-4, Figure 2) suggests that dilution by water from the confined aquifer or dilution by recharge through the buffer also may account for the low nitrate-nitrogen stream concentrations observed (0.46 mg/L, Figure 2).

Organic carbon is known to be important in denitrification reactions (Korom, 1992), and high concentrations of DOC are largely responsible for low nitrate concentrations (median = 0.05 mg/L) in shallow wells of the outer Coastal Plain of the Albemarle-Pamlico Drainage Basin (Spruill et al., 1998). Data collected from all sites for this study confirm a significant negative correlation between DOC and nitrate concentrations in ground water ($\rho = -0.64$, p <0.01). The highest DOC concentrations, lowest nitrate concentrations, and generally highest excess nitrogen occurred in water from wells located at the end of the flow paths in discharge areas at three of the four sites, particularly in streambed wells, indicating denitrification.

Findings and conclusions

In general we found that:

1. Nitrate concentrations in ground water were generally lower at the poorly drained sites compared with nitrate concentrations at the well-drained sites.
2. Riparian buffers are likely sources of organic material that provide conditions for nitrate reduction in ground water moving through streambeds of the Coastal Plain in North Carolina. Denitrification (50% or greater) occurred in discharging ground water within the streambed at all sites, even at sites that did not have a riparian buffer, further emphasizing the importance of the watershed-scale effects of riparian buffers on nitrate reduction in discharging ground water.
3. Based on excess nitrogen data, nitrate reduction can occur within an aquifer seasonally or periodically, even in recharge areas.
4. Even though nitrate was lower in wells located downgradient from the buffer at the poorly drained site, discharge from an underlying confined aquifer probably diluted nitrate concentrations in the shallow aquifer.
5. The occurrence of nitrate was negatively correlated with DOC (–0.64, p <0.01) in ground water. Generally the highest DOC concentrations at all sites occurred in ground water beneath the buffer and streambed in the vicinity of the discharge areas.

Riparian buffers generally are effective in reducing nitrate in ground water in both well-drained and poorly drained settings in the Coastal Plain of North Carolina because: (1) nitrate concentrations in ground water were lower downgradient from the riparian buffers compared with nitrate concentrations in upgradient wells at all sites having buffers; and (2) most of the nitrate reduction in the well-drained settings was due to denitrification occurring within the riparian buffer and streambed, as indicated by generally higher excess nitrogen concentrations detected in ground water within and downgradient from riparian buffers. Thus, even though nitrate in ground water may pass beneath the buffer, the relatively high organic carbon in the discharge zone at all sites, which is derived largely from riparian vegetation, ultimately provides an environment conducive to denitrification.

Acknowledgements

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