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Factors Affecting Nitrate Delivery to Streams from Shallow Ground Water in the North Carolina Coastal Plain

Scientific Investigations Report 2008–5021

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Conversion Factors, Datums, and Abbreviatied Water-Quality Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ((ft^3/s)/mi^2)	0.01093	cubic meter per second per square kilometer ((m^3/s)km^2)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Factors Affecting Nitrate Delivery to Streams from Shallow Ground Water in the North Carolina Coastal Plain

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Abstract

An analysis of data collected at five flow-path study sites between 1997 and 2006 was performed to identify the factors needed to formulate a comprehensive program, with a focus on nitrogen, for protecting ground water and surface water in the North Carolina Coastal Plain. Water-quality protection in the Coastal Plain requires the identification of factors that affect the transport of nutrients from recharge areas to streams through the shallow ground-water system. Some basins process or retain nitrogen more readily than others, and the factors that affect nitrogen processing and retention were the focus of this investigation to improve nutrient management in Coastal Plain streams and to reduce nutrient loads to coastal waters.

Nitrate reduction in ground water was observed at all five flow-path study sites in the North Carolina Coastal Plain, although the extent of reduction at each site was influenced by various environmental, hydrogeologic, and geochemical factors. Denitrification was the most common factor responsible for decreases in nitrate along the ground-water flow paths. Specific factors, some of which affect denitrification rates, that appeared to influence ground-water nitrate concentrations along the flow paths or in the streams include soil drainage, presence or absence of riparian buffers, evapotranspiration, fertilizer use, ground-water recharge rates and residence times, aquifer properties, subsurface tile drainage, sources and amounts of organic matter, and hyporheic processes. The study data indicate that the nitrate-reducing capacity of the buffer zone combined with that of the hyporheic zone can substantially lower the amount of ground-water nitrate discharged to streams in agricultural settings of the North Carolina Coastal Plain.

At the watershed scale, the effects of ground-water discharge on surface-water quality appear to be greatly influenced by streamflow conditions and the presence of extensive riparian vegetation. Streamflow statistics that reflect base flow and the general hydrologic dynamics of a stream are important in understanding nutrient transport from a watershed and may be useful indicators of watersheds that are likely to have higher yields of nutrients and water. Combining streamflow statistics with information on such factors as land use, soil drainage, extent of riparian vegetation, geochemical conditions, and subsurface tile drainage in the Coastal Plain can be useful in identifying watersheds that are most likely to export excessive nitrogen due to nonpoint-source loadings and watersheds that are effective in processing nitrogen.

Introduction

Both ground water and surface water are recognized by the United States Congress as worthy of protection and remediation under Section 1252 of the Clean Water Act (CWA; U.S. House of Representatives, 2000), and states were given the responsibility of protecting the quality of the Nation's waters:

> "*The Administrator shall, after careful investigation, and in cooperation with other Federal agencies, State water pollution control agencies, interstate agencies, and the municipalities and industries involved, prepare or develop comprehensive programs for preventing, reducing, or eliminating the pollution of the navigable waters and ground waters and improving the sanitary condition of surface and underground waters*."

The intent of the CWA is to protect and enhance water quality in two ways. One way is through establishment of effluent standards or limits for point sources and best-management practices on nonpoint sources so that the total maximum daily load (TMDL) of contaminants to surface waters does not impair the intended uses of the water (Sections 1311 and 1329, U.S. House of Representatives, 2000). The second way is through water-quality standards established to protect human health and recreational and wildlife uses (section 1313, U.S. House of Representatives, 2000). Implementation of the CWA has helped to control and reduce point-source pollutants; however, it has been more difficult to control pollutants derived from nonpoint sources (U.S. Geological Survey, 1999; Hirsch and others, 2006). The difficulty in controlling nonpoint-source pollution is understandable because nonpoint-source contaminant concentrations and loads are a function of many physical and environmental variables occurring within a watershed, whereas point-source control is primarily a function of an engineered treatment system having measurable inputs and outputs. Thus, the environmental effects of procedures and practices used to control or reduce nonpoint-source contaminants are less predictable because of incomplete understanding of the associated processes that occur in varied environmental settings.

Agricultural activities and urban runoff are among the leading sources of nonpoint-source pollutants, such as sediment and nutrients (U.S. Environmental Protection Agency, 2006). A commonly recognized transport pathway of nonpoint-source pollution is overland runoff of precipitation that carries contaminants into streams and rivers; however, nonpoint-source pollution of ground water also occurs when water containing contaminants percolates through soils to the underlying water table. The Federal and State water-quality standards developed to protect ground-water resources in North Carolina (U.S. Environmental Protection Agency, 2004; North Carolina Department of Environment and Natural Resources, 2005) are based on human-health considerations for the use of ground water as a water-supply source. Standards generally do not address the potential effects of both the quality and quantity of ground water discharging to a stream on surface-water quality and aquatic life. Previous studies have demonstrated that shallow ground water contributes at least 40 percent of the average annual streamflow in the Coastal Plain of North Carolina (Winner and Simmons, 1977; Harned and Davenport, 1990; McMahon and Lloyd, 1995; Harden and others, 2003) and in many areas throughout the United States (Wolock, 2003). Therefore, ground water is potentially a major contributor of chemical loadings to streams in the North Carolina Coastal Plain.

Although ground water may contain chemical constituents at concentrations that meet water-quality standards based on human health, it is possible that the mass of a constituent, such as nitrate, that is discharged to a receiving stream could be of sufficient quantity to have a deleterious effect on downstream water quality and aquatic life. In eastern North Carolina, excessive nutrient loadings have contributed to the degradation of surface-water quality in the Neuse and Tar-Pamlico River basins, particularly in the estuaries (Gilliam and others, 1997; Spruill and others, 1998; Luettich and others, 2000; Burkholder and others, 2006). In 1997, the North Carolina Environmental Management Commission adopted rules to reduce nitrogen loads to the Neuse River by 30 percent to support the Neuse River Nutrient Sensitive Waters Management Strategy (North Carolina Division of Water Quality, 2002b). Similarly, the North Carolina Environmental Management Commission adopted rules during 2000 and 2001 for the Tar-Pamlico River basin to reduce nitrogen loads by 30 percent and to control phosphorus loads at or below 1991 levels (North Carolina Division of Water Quality, 2002c).

Water-quality protection in the Coastal Plain requires the identification of factors that affect transport of nutrients from the recharge area to the stream through the shallow ground-water system. Some basins process and retain nitrogen more readily than others, and the factors that affect nitrogen processing and retention need to be identified for more effective nutrient management in Coastal Plain streams and to reduce nutrient loads to coastal waters. Process-oriented studies to identify these factors have been conducted or supported by the North Carolina Division of Water Quality (DWQ) for more than 10 years, including flow-path studies conducted by the DWQ and U.S. Geological Survey (USGS) in the North Carolina Coastal Plain (Spruill and others, 1998, 2005; Spruill and Galeone, 2000; Spruill, 2004; Tesoriero and others, 2005). The most extensive studies have been conducted at the Lizzie research site (Spruill and others, 2005; Tesoriero and others, 2005) and include data collection and analysis by several interdisciplinary groups, including DWQ, USGS, U.S. Environmental Protection Agency (USEPA), the National Oceanic and Atmospheric Administration, and North Carolina State University.

Purpose and Scope

The primary purpose of this report is to summarize and synthesize data collected at five flow-path study sites in the North Carolina Coastal Plain between 1997 and 2002 (Spruill, 2004; Spruill and others, 2005; Tesoriero and others, 2005) and more recently in 2006. Data from two Coastal Plain streams also are included in the synthesis to examine nutrient export at the watershed scale. Features are identified that seem to be important in affecting the amount of nitrogen transported in ground water beneath agricultural fields to surface water in receiving streams. These features include physiography, pedology, geology, geochemistry, hydrology, and land use. The data analysis contributes to a better understanding of the susceptibility of watersheds to nitrogen contamination from discharging ground water.

The ground-water and surface-water quality data collected between 1997 and 2006 at five flow-path sites were examined to determine changes in nitrate concentrations in ground water that flows from recharge areas to discharge areas. The flow-path study sites are located in agricultural fields of the North Carolina Coastal Plain, and the environmental setting is characterized for each site. Effects of the environmental setting on nitrate transport in shallow ground water are discussed. Hydrologic and water-quality data collected for the Middle Swamp and Bear Creek watersheds were compared to examine factors that may be important in identifying watersheds with a high potential to export nitrate derived from ground-water discharge.

Description of Study Sites

The study sites (fig. 1; table 1) were selected on the basis of the presence or absence of buffers, the prevailing soil-drainage classifications, and the types of fertilizer applied—inorganic or manure (Spruill, 2004; Spruill and others, 2005; Tesoriero and others, 2005). At sites 1, 3, 4, and 5 in the Neuse River basin and site 2 in the Tar-Pamlico River basin (fig. 1), data were collected from several locations along a ground-water flow path, including the agricultural fields, riparian buffers, and receiving streams. Corn and soybeans were the predominant crops grown at all sites.

The cultivated field at study site 1 consisted of predominately well-drained soils, and a riparian buffer was present along both sides of the receiving stream. The field at flow-path study site 2 also had well-drained soils, and a riparian buffer was next to the stream. The other side of the stream had no buffer but had cultivated, well-drained fields of corn and soybeans located directly next to the streambank. Conventional inorganic-fertilizers were used for crop production at both sites (table 1).

Most of the area at flow-path study site 3 consisted of a cultivated field with poorly drained soils that extended to the streambank. The opposite side of the stream was heavily wooded. A concentrated animal-feeding operation (CAFO) was located at this site, and swine manure was used for fertilizing crops. At study site 4, the cultivated field had predominately poorly drained soils, and a riparian buffer was present along both sides of the receiving stream. Conventional inorganic fertilizers were used for crop production at site 4 (table 1).

Site 5, or the Lizzie research site (fig. 2), was more extensively studied than the other sites (Spruill and others, 1998; Harden and Spruill, 2004; Spruill and others, 2005; Tesoriero and others, 2005). Two flow paths, referred to as 5A and 5B (fig. 2; table 1) were studied at site 5 and originated in moderately to poorly drained wooded uplands. Along flow path 5A, the upgradient agricultural fields were somewhat poorly drained and received spray applications of swine manure; the downgradient fields were well drained and received only conventional inorganic fertilizers. Flow path 5A terminated at third-order stream Sandy Run, which was bounded by a riparian buffer. Along flow path 5B, the agricultural spray fields consisted of somewhat poorly drained soils before transitioning to mostly well-drained soils. Flow path 5B terminated at first-order stream Plum Tree Branch, which was bounded by a riparian buffer. A transect of minipiezometers (referred to as 5PT1; fig. 2) located adjacent to flow path 5B was used to examine buffer zone processes near Plum Tree Branch. In 1995, a swine CAFO with lagoon and spray-field waste treatment was implemented at site 5. At that time, a shift in fertilizing practices occurred, and conventional inorganic fertilizers were replaced with lagoon effluent from the swine CAFO at the farm.

Methods

The water-quality data for sites 1–4 in this report were collected between November 1997 and March 1999 (Howe and Breton, 1999, 2000; Ragland and others, 1999, 2000). At each site, water samples were collected from monitoring wells, the stream, and beneath the streambed. At site 2, additional water samples were collected in June and July 1998 from minipiezometers placed at depths ranging from approximately 2 to 9 feet (ft) and from seepage meters placed on the streambed along a cross section of the stream. These data were used to evaluate possible changes in ground-water quality in the streambed at this site. Water-quality data for flow paths 5A and 5B at site 5 were obtained from samples collected between 1999 and 2003 (Howe and Breton, 2000, 2001; Ragland and others, 2000–2004; Howe and others, 2002–2005; Walters and others, 2005). Additional information on the installation of wells and piezometers and the water-quality sampling methods for the flow-path study sites can be obtained from Spruill (2004), Spruill and others (2005), and Tesoriero and others (2005).

In 2006, water-quality samples were collected at site 5 (U.S. Geological Survey, 2007b) from minipiezometers placed in the surficial aquifer along a transect of the riparian buffer (5PT1, fig. 2) to examine water-quality changes as ground water moved from the spray field through the buffer and discharged to Plum Tree Branch. Three clusters of three to four minipiezometers were installed at depths ranging from 4.2 to 9.5 ft below land surface, beginning at the field edge and ending at the stream edge. One minipiezometer was installed in the streambed (depth of 1 ft) of Plum Tree Branch and in the buffer on the opposite (west) side of the stream. The minipiezometers consist of a 0.25-inch (in.)-diameter Teflon tube connected to a stainless steel point having a 0.25-inch-long section with inlet holes for sampling. A peristaltic pump was used to collect samples from the minipiezometers. The samples were filtered and preserved in the field and shipped by overnight delivery to the USGS National Water Quality Laboratory in Denver, CO, for chemical analyses of nutrients, anions and cations, and dissolved organic carbon (DOC).

The nitrate concentration values presented in this report were measured as nitrite plus nitrate, in milligrams per liter, as nitrogen. Because nitrite typically represents a small fraction of the total concentration, the reported values are presented and discussed as nitrate. The data for nutrients and major ions collected from all study sampling locations and discussed in this report are published in USGS annual water-data reports (Howe and Breton, 1999–2001; Ragland and others, 1999, 2000–2004; Howe and others, 2002–2005; Walters and others, 2005; U.S. Geological Survey, 2007b). Furthermore, a list of the sampling sites and information about data access are presented in appendix table A1. Summaries of water-quality data from the flow-path sites are provided in appendix tables A2–A8.

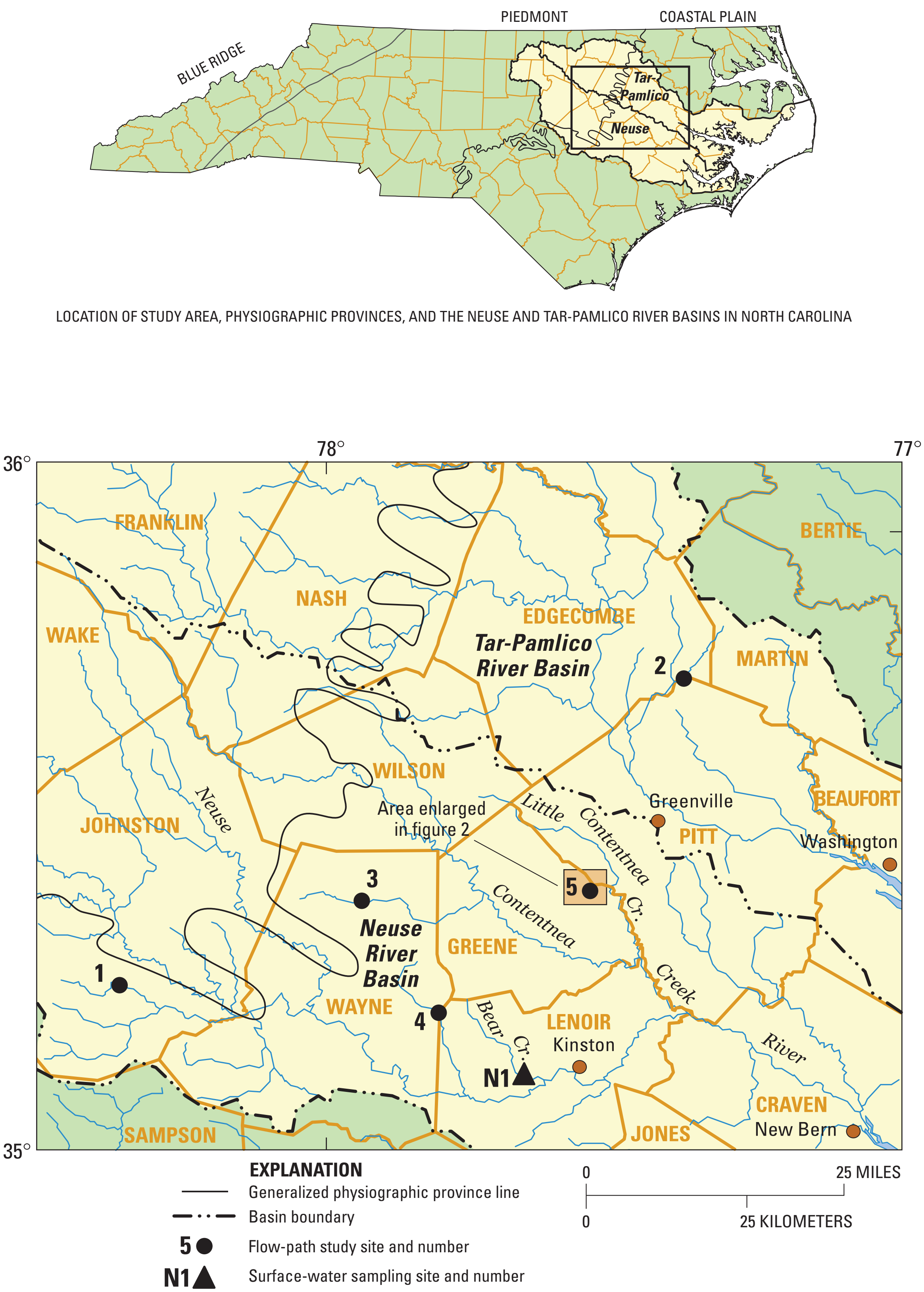

Figure 1. Locations of study sites in the Neuse and Tar-Pamlico River basins, North Carolina.

Table 1. Environmental characteristics of the flow-path study sites in the North Carolina Coastal Plain.

[ft, feet; —, not applicable]

Site (figs. 1, 2)	River basin	County	Data-collection period	Prevailing soil drainage	Approximate buffer width (ft)	Receiving stream (name and order)	Type of fertilizer application
1	Neuse	Johnston	1997–1999	Well drained	300	Unnamed, first order	Inorganic
2	Tar-Pamlico	Pitt	1998–1999	Well drained	600	Mitchell Swamp, second order	Inorganic
3	Neuse	Wayne	1997–1999	Poorly drained	—	Nahunta Swamp, third order	Swine manure
4	Neuse	Wayne	1997–1999	Poorly drained	300	Unnamed, first order	Inorganic
5A	Neuse	Greene	1999–2003	Poorly to well drained	300	Sandy Run, third order	Swine manure to inorganic
5B	Neuse	Greene	1999–2003	Well drained	150	Plum Tree Branch, first order	Swine manure
5PT1	Neuse	Greene	2006	Well drained	100	Plum Tree Branch, first order	Swine manure

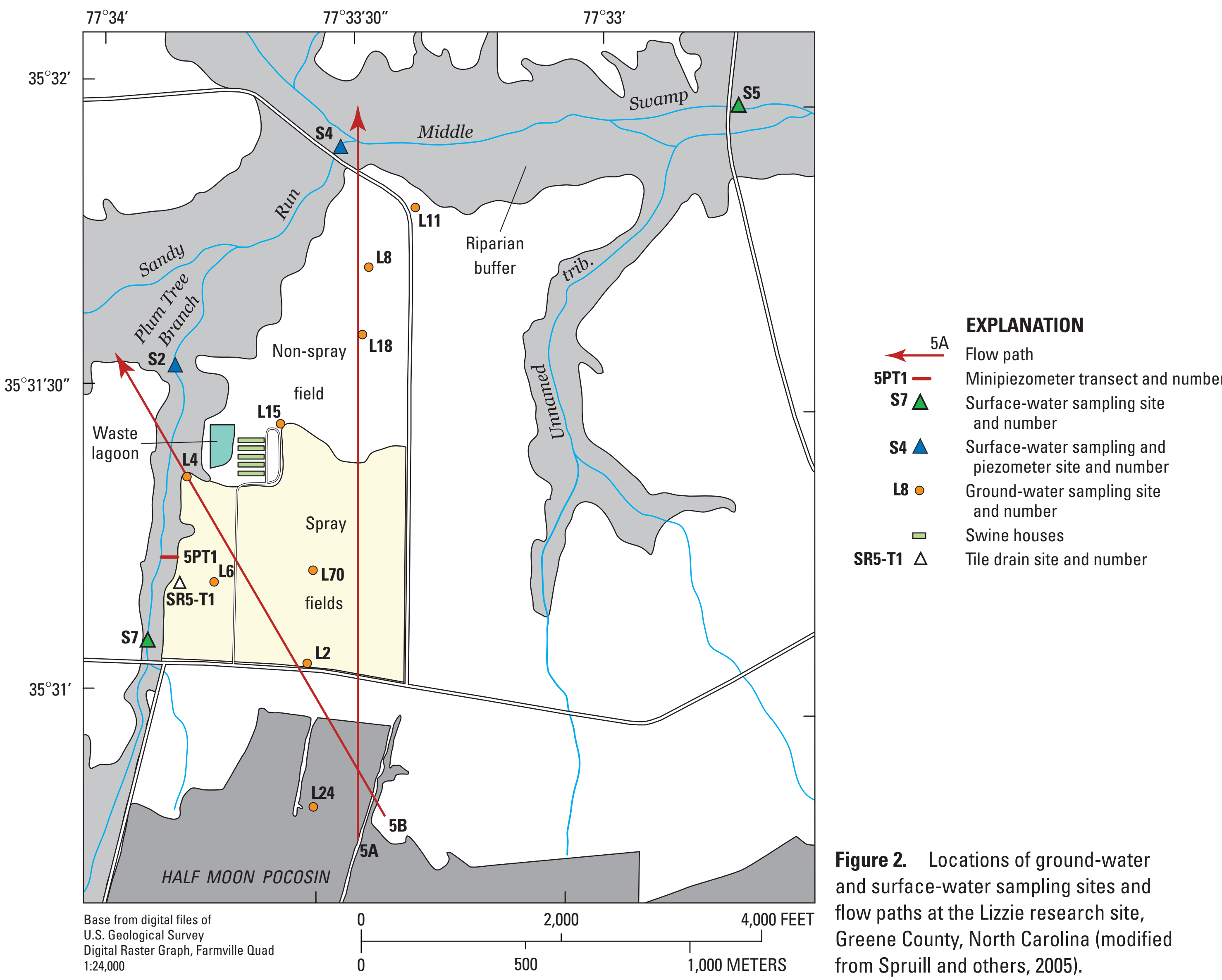

Figure 2. Locations of ground-water and surface-water sampling sites and flow paths at the Lizzie research site, Greene County, North Carolina (modified from Spruill and others, 2005).

Samples for chlorofluorocarbons (CFCs)—trichlorofluoromethane, CFC-11; dichlorodifluoromethane, CFC-12; and trichlorotrifluoroethane, CFC-113—and dissolved gases—nitrogen (N2) and argon (Ar)—were collected and analyzed as described in Busenberg and Plummer (1992) and Busenberg and others (1993), respectively. The CFC and dissolved-gas data were used to provide estimates of ground-water age and to verify denitrification in samples from selected wells at each flow-path study site (Spruill, 2004; Spruill and others, 2005; Tesoriero and others; 2005). The estimated age, or date of ground-water recharge, reflects the time of travel from the water table to the point of sampling. The N2 and Ar gas data were used to estimate the amount of nitrogen derived from denitrification (Busenberg and others, 1993). The presence of N2 dissolved in ground water in excess of the N2 concentration expected from equilibration with the atmosphere indicates that denitrification has occurred. The samples with excess N2 once contained elevated nitrate levels prior to entering an anaerobic portion of the aquifer where the nitrate was subsequently denitrified.

In determining the factors that affect nitrogen transport at the watershed scale, a two-step analysis was conducted to evaluate whether water yields can be used to estimate nitrogen yields. First, the relation between watershed yields of water and nitrogen was evaluated using data from 14 surface-water stations presented in Spruill and others (2005). Median water yields were estimated for each station by using median streamflow data for the periods of record and drainage areas presented in Spruill and others (2005). The total nitrogen-yield data used in the analysis for each site was for calendar year 2000 (Spruill and others, 2005). Correlation analysis between these two factors was then conducted using the Spearman rho (ρ) as the test statistic (Conover, 1980) to evaluate the one-tail significance of the positive relation between water yield and nitrogen yield. The second step of the analysis was to determine the relation between annual water yield and precipitation by using annual mean streamflow data for Bear Creek at Mays Store (Station 0208925200), Middle Swamp near Farmville (Station 02091736), and Plum Tree Branch (unnamed tributary near Lizzie, Station 0209173190) available from the USGS National Water Information System (NWIS). Annual precipitation data for the analysis were obtained from a nearby weather station in Kinston, NC (fig. 1; Southeast Regional Climate Center, 2006).

Site-Scale Factors Affecting Nitrate Concentrations along Flow Paths

Changes in nitrate concentrations in ground water that flows from beneath an agricultural field to a receiving stream have been evaluated in previous studies. Some of the factors reported to influence nitrate concentrations along a ground-water flow path include depth to water (Tesoriero and others, 2000), ground-water residence time (Puckett, 2004; Tesoriero and others, 2005; Seitzinger and others, 2006), organic carbon available to drive denitrification reactions (Korom, 1992), and presence of riparian buffers (Speiran and others, 1998; Puckett, 2004; Seitzinger and others, 2006). The amount of nitrate in ground water that passes through an aquifer to a receiving stream is influenced substantially by the process of denitrification. Conditions that generally promote denitrification in ground water occur when nitrate is present, dissolved oxygen (DO) concentrations are low—less than (<) 0.2 milligram per liter (mg/L), and electron donors (such as carbon) are present (Korom, 1992; Seitzinger and others, 2006). In evaluating the effects of riparian buffers on ground-water nitrate at 13 sites throughout the United States, Puckett (2004) noted that the reduction of nitrate by denitrification can occur in any portion of the flow path where reducing conditions are present, including the upgradient areas of the aquifer, buffer zone, and hyporheic zone. The hyporheic zone generally is defined as the zone near and under the stream where ground water and surface water mix. In a study of 14 different sites throughout Europe, Sabater and others (2003) determined that nitrogen loading and the ground-water hydraulic gradient had the most significant effects on the reducing capacity of riparian buffers, with nitrogen loading and hydraulic gradient inversely related to the nitrate-reducing capacity of riparian buffers.

This section incorporates the work of Spruill (2004) at flow-path sites 1–4 and Tesoriero and others (2005) at flow-path site 5, with new data collected at site 5 during this investigation to provide an overview of the factors that affect nitrate concentrations along flow paths at the individual site scale in the Coastal Plain of North Carolina. The intent of this discussion is to provide a framework for understanding relative reductions in concentrations of nitrate in different portions of the ground-water flow paths and in different environmental settings.

Although the site numbers used by Spruill (2004) to designate individual flow-path study locations (sites 1–4) are retained in this discussion, they are not presented in numerical order by site. For comparative purposes, the flow-path study sites are presented and discussed based on stream order, drainage characteristics of the soils that were farmed, and the presence or absence of a buffer. If a site had a mix of hydrologic soil-drainage classes, the site was categorized as poorly drained if large areas along the flow path were used to grow crops in poorly drained soils. If a site was used to grow crops in well-drained soils, the flow path was categorized as well drained.

Site 1 — First-Order Stream with Stream Buffer and Well-Drained Soil

Median nitrate concentrations ranged from 10.2 to 13 mg/L in water samples collected from wells JC–1, JC–2, JC–5, and JC–6 (fig. 3; table A2). Little difference in nitrate concentrations was observed in water samples collected from shallow and deeper wells. This was likely because of the

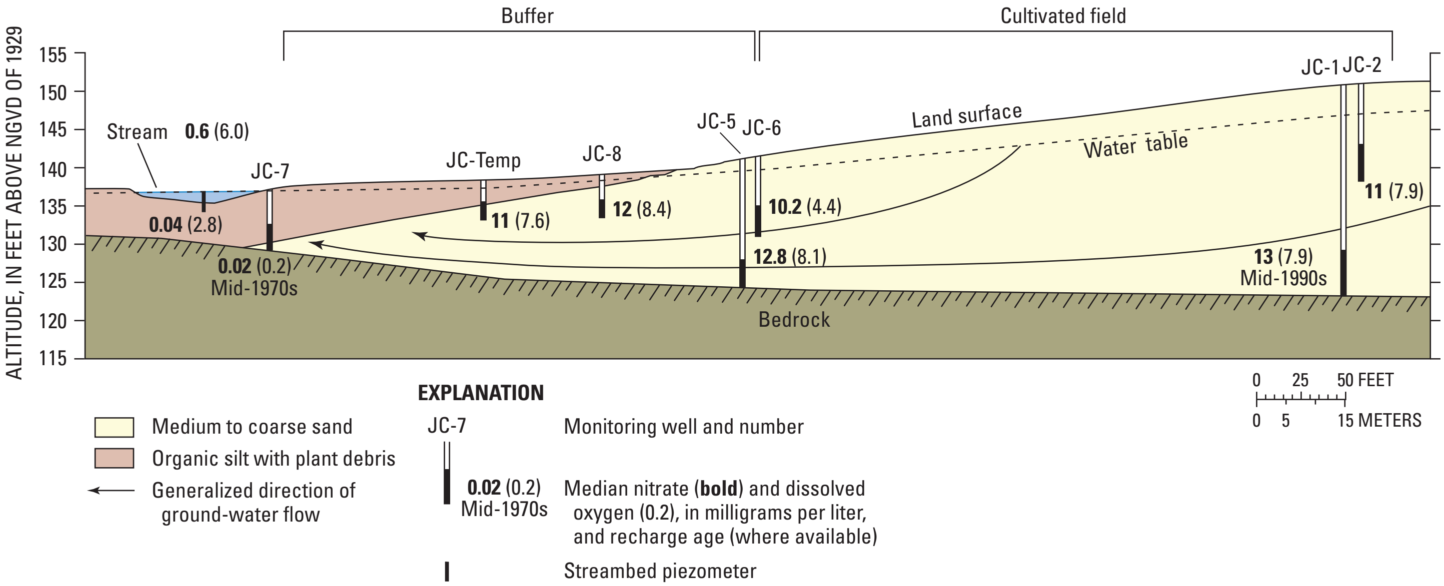

Figure 3. Sampling locations, flow-path features, and median nitrate and dissolved-oxygen concentrations at site 1 in the Neuse River basin, North Carolina (modified from Spruill, 2004).

fairly uniform and transmissive sandy deposits, as indicated by the relatively young ground-water ages measured in wells JC–1 (mid-1990s) and JC–4 (early 1990s) and the lack of a confining layer to impede the vertical transport of water and nutrients. Although well JC–4 is not shown in figure 3, this well was screened at the same depth and in a similar location along the buffer edge as well JC–6. Not only were concentrations vertically uniform, but nitrate concentrations were similar laterally in downgradient wells JC–8 (median nitrate = 12 mg/L) and JC–Temp (median nitrate = 11 mg/L) in the buffer zone. These two wells were screened in the sandy aquifer material beneath the buffer and contained as much nitrate as was found beneath the agricultural field (fig. 3).

The uniform nitrate concentrations combined with the relatively low DOC concentrations (<1 mg/L) and high DO concentrations (greater than (>) 4 mg/L) suggest that minimal denitrification occurred along much of the flow path from the upgradient wells in the field to downgradient wells JC–8 and JC–Temp in the buffer. A change in nitrate concentration was not observed along the flow path until the water reached the end of the buffer adjacent to the stream. Samples from well JC–7 (median nitrate = 0.02 mg/L) along the streambank and from the piezometer in the streambed (median nitrate = 0.04 mg/L) contained little nitrate. The decrease in median nitrate concentrations from the field edge to the stream edge indicates that much of the nitrate in ground water is removed within the riparian buffer in the downgradient portion of the flow path near the stream. The organic-rich flood-plain deposits near the stream likely provide sufficient organic carbon to enable denitrification, as reflected in the high DOC concentrations (>8 mg/L), high iron concentrations (>3,900 micrograms per liter (μg/L)), and low DO concentrations (<3 mg/L) detected in samples from well JC–7 and the streambed piezometer, compared with concentrations in samples from the upgradient well locations (fig. 3; table A2). The excess N_2 value of 2.6 mg/L measured in a sample from well JC–7 also indicated the occurrence of denitrification processes. Although minimal reduction in nitrate occurred in well-drained portions of the aquifer beneath much of the cultivated field and buffer zone, denitrification associated with the organic-rich sediments near the stream was important in lowering the ground-water transport of nitrate to the stream at site 1.

Water use during the growing season and the associated nutrient uptake by vegetation also can influence the amount of nitrate transported to streams. The stream at this site typically does not flow during the summer months when rates of evapotranspiration in the riparian buffer and field are at an annual high. Samples from the streambed piezometer were collected only during the wet season when the stream was flowing, and no samples were collected when the stream was dry.

Site 4 — First-Order Stream with Stream Buffer and Poorly Drained Soil

At flow-path site 4, a 60-percent decrease in median nitrate concentrations was observed in the surficial aquifer at wells JP–2 (7.6 mg/L) to JP–6 (3.0 mg/L) in the field portion of the flow path upgradient from the riparian buffer (fig. 4; table A3). Downgradient from the buffer, shallow ground water at well JP–5 (0.05 mg/L) and the streambed piezometer (0.01 mg/L) was almost devoid of nitrate. A decrease in median DO concentrations from 7.2 to 1.0 mg/L and increase in DOC concentrations from 0.5 to 1.8 mg/L also was observed in the surficial aquifer along the flow path in

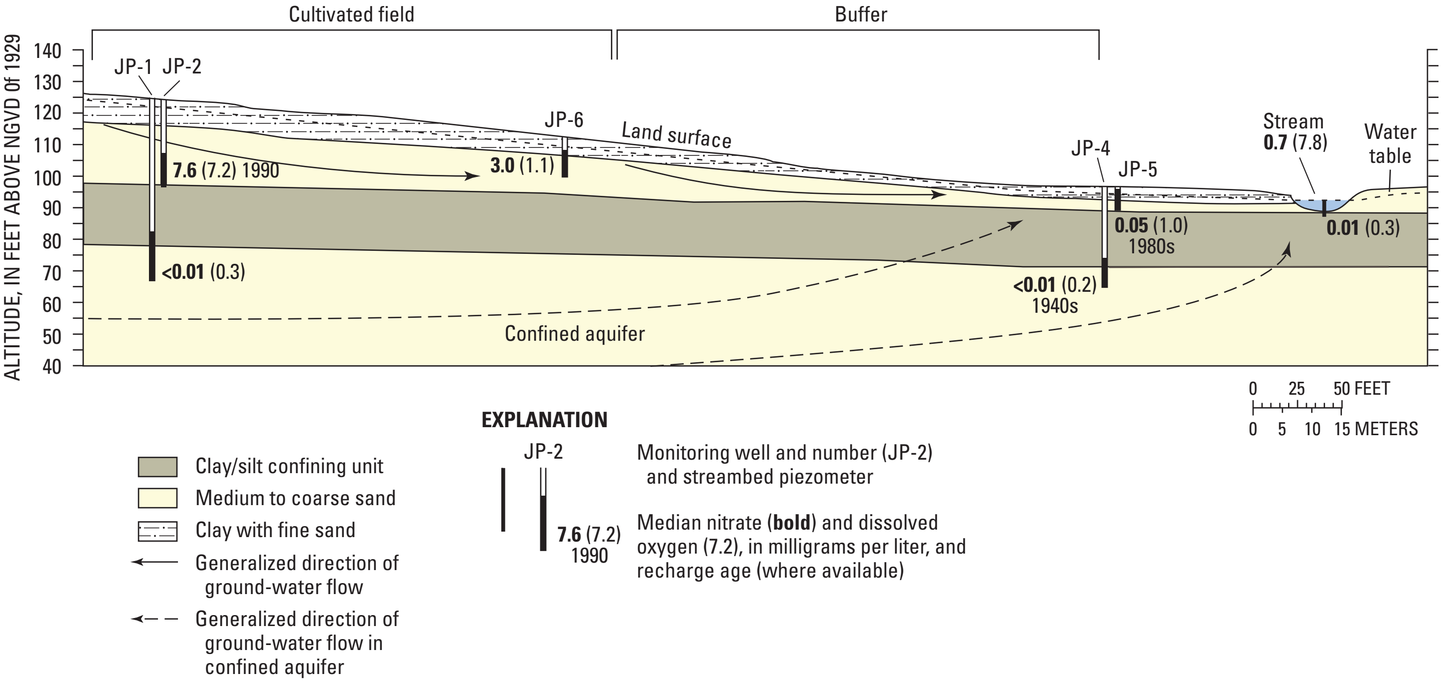

Figure 4. Sampling locations, flow-path features, and median nitrate and dissolved-oxygen concentrations at site 4 in the Neuse River basin, North Carolina (modified from Spruill, 2004).

wells JP–2 to JP–5. The measurement of excess N_2 in samples from wells JP–2 (1.0 mg/L) and JP–5 (1.1 mg/L) indicates that some denitrification may have occurred along the flow path, although the low concentrations also indicate that other processes, as described below, may be responsible for the decrease in nitrate concentrations at the site.

Little to no measurable nitrate was detected in samples from the deeper wells JP–1 and JP–4 screened in the underlying confined aquifer. Ground water in the confined aquifer is relatively old and occurs under reduced conditions, as evidenced by the low DO (less than or equal to (≤) 0.3 mg/L) and DOC (0.3 mg/L) concentrations. CFC analysis indicated a recharge age of the 1940s for ground-water samples from well JP–4. Any nitrate that was once present in the older water in the confined aquifer has likely been denitrified.

At downgradient well cluster JP–4 and JP–5 near the stream, the vertical hydraulic gradient was upward from the confined aquifer into the overlying surficial aquifer (fig. 4). The low median nitrate concentrations observed in shallow ground-water samples from well JP–5, the streambed piezometer, and the stream water (nitrate = 0.7 mg/L) may be a result of dilution with ground water from the underlying confined aquifer, which has no nitrate. The minimal nitrate concentration (0.01 mg/L) and excess N_2 value of 2.4 mg/L measured from the streambed piezometer (table A3) also indicate the occurrence of denitrification processes in the hyporheic zone. Therefore, both hydrologic and geochemical factors may affect the amount of nitrate discharged to the stream at flow-path site 4.

Site 2 — Second-Order Stream with and without Stream Buffer and Well-Drained Soil

Nitrate concentrations decreased with depth at the upgradient portion of the flow path beneath the farm field at site 2. The median nitrate concentrations in wells PM–2 and PM–1 were 9.4 and 5.5 mg/L at depths of 13.3 and 17.4 ft, respectively (fig. 5). An increase in measured excess N2 concentrations from 0.8 to 5.1 mg/L and a decrease in median DO concentration from 2.0 to 0.2 mg/L were observed in samples collected from shallow well PM–2 and deeper well PM–1, respectively (fig. 5; table A4). The elevated excess N_2 and lower DO values with depth indicate that much of the decrease in nitrate concentration between wells PM–2 and PM–1 is likely a result of denitrification. In contrast to upgradient well cluster PM–1 and PM–2, an increase in nitrate concentration occurred with depth at downgradient well cluster PM–3 and PM–4 in the buffer zone (fig. 5). The difference in median nitrate concentrations between shallow well PM–3 (0.03 mg/L) and deeper well PM–4 (6.8 mg/L) likely reflects differences in source inputs and the amount of denitrification that occurred in ground water moving along different flow paths beneath the riparian buffer, as described below.

The shallower and younger ground water (1997) at well PM–3 likely contained a larger proportion of recharge that originated in the riparian buffer than the deeper ground water at well PM–4 where a larger proportion of recharge likely originated in the cultivated field. In addition, recharge through the buffer zone likely contained less nitrate than recharge

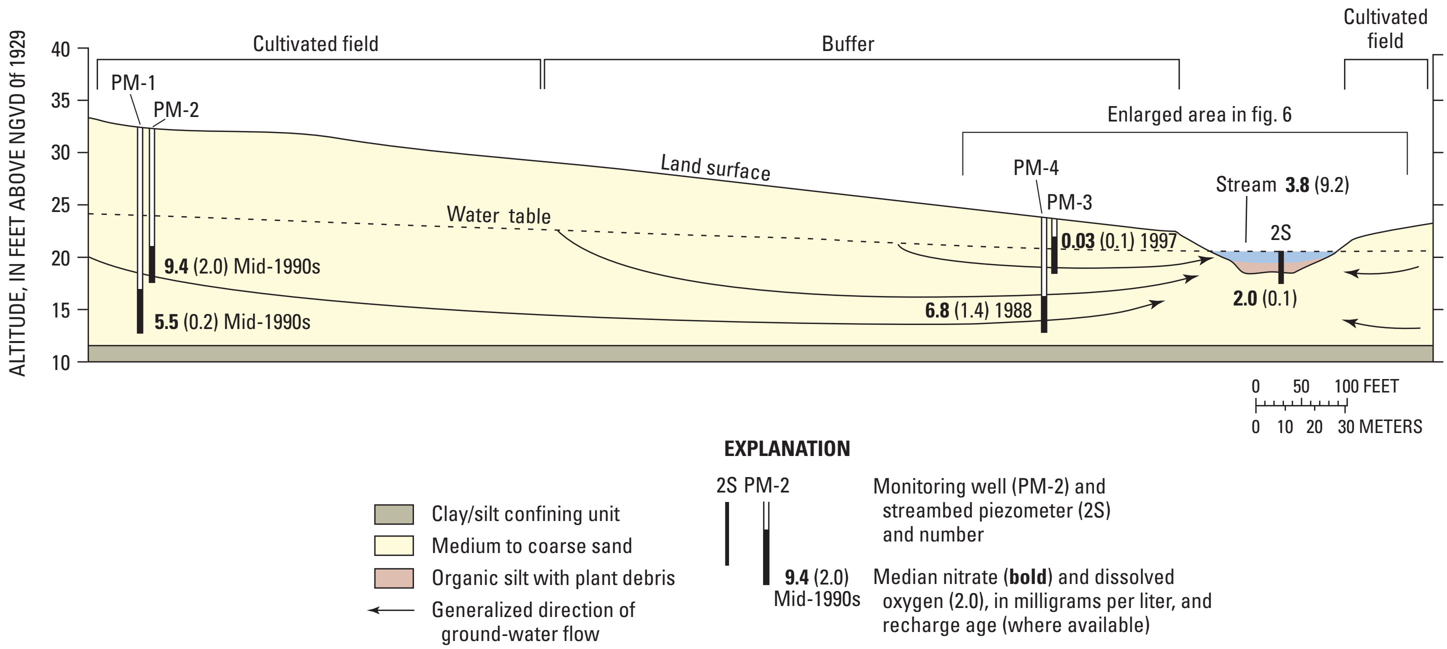

Figure 5. Sampling locations and median nitrate and dissolved-oxygen concentrations at site 2 along the flow path during April 1998 through May 1999 in the Tar-Pamlico River basin, North Carolina (modified from Spruill, 2004).

through the cultivated field where fertilizer was applied to the crops. Regardless of initial nitrate concentrations, excess N_2 values of 2.8 and 3.5 mg/L measured in wells PM–3 and PM–4, respectively, (table A4) indicate that denitrification of nitrate occurred in ground water flowing directly beneath the buffer. Shallow ground water at well PM–3 flows through organic-rich deposits directly beneath the riparian buffer where strongly reducing conditions were present, as indicated by the high DOC (15.0 mg/L) and low DO (<0.1 mg/L) concentrations. The median DOC (1.2 mg/L) and DO (1.4 mg/L) concentrations measured in well PM–4 indicate, however, that reducing conditions were not as strong in the deeper part of the aquifer beneath the buffer as in the shallower part of the aquifer. Indeed, the constituent values for well PM–4 are similar to the constituent values in upgradient wells PM–1 and PM–2 located in the field (table A4). Although concentrations of nitrate in ground water beneath the field and buffer zone were reduced by denitrification, some nitrate was still present in ground water at the end of the flow path, as indicated by the median nitrate concentration of 2.0 mg/L at streambed piezometer 2S (fig. 5). This nitrate appears to have been derived from deeper ground water flowing beneath the riparian buffer and(or) from ground-water discharge from the opposite side of the stream, which has no riparian buffer.

Additional samples were collected in June and July 1998 (table A5) from minipiezometers placed along the streambanks and in the streambed, and from wells PM–3 and PM–4 in order to better examine changes in nitrate concentrations at the discharge zone (fig. 6). Nitrate concentrations of 4.0 and 5.8 mg/L for streambank piezometers LBS and LBI, respectively, on the buffered side of the stream were lower than the nitrate concentrations of 7.1 and 16.0 mg/L from the streambank piezometers RBI and RBS, respectively, on the non-buffered side of the stream (fig. 6). Both sides of the stream had well-drained soils that were cultivated for corn and soybeans and received applications of inorganic fertilizer. The high nitrate concentration of 16.0 mg/L for piezometer RBS possibly reflects less reduction in ground water because the field extends to the streambank, which has no riparian buffer. In addition, the nitrate value for piezometer RBS is more than the highest measured nitrate value for the buffered side of the stream (11.0 mg/L for well PM–2 in the cultivated field, table A4), which may indicate higher fertilizer application rates on the non-buffered side of the stream.

Nitrate concentrations ranging from 7.2 to 11.0 mg/L for streambed piezometers 1S, 2S, and 3S (table A5) indicate high levels of ground-water nitrate in the shallow streambed deposits of the hyporheic zone. The lower concentrations of nitrate (< 0.4 mg/L) and DO ($\leq$0.2 mg/L) measured in ground-water samples from piezometers (1I, 2I, 2D, and 3I) indicate that more strongly reduced conditions were present in the deeper sediments beneath the streambed. Measured excess N_2 values for piezometers 1S (2.5 mg/L), 1I (4.9 mg/L), and 2S (7.2 mg/L) indicate that some denitrification has occurred in ground water flowing through the sediments in the discharge zone. The distribution of nitrate in the shallow hyporheic deposits appears to reflect a mixture of ground water originating from both the buffered and non-buffered sides of the stream, where the amount of nitrate in ground water discharged from shallow and deep flow paths on each side may have varied. On the buffered side of the stream, the nitrate concentration for streambed piezometer 1S (7.2 mg/L)

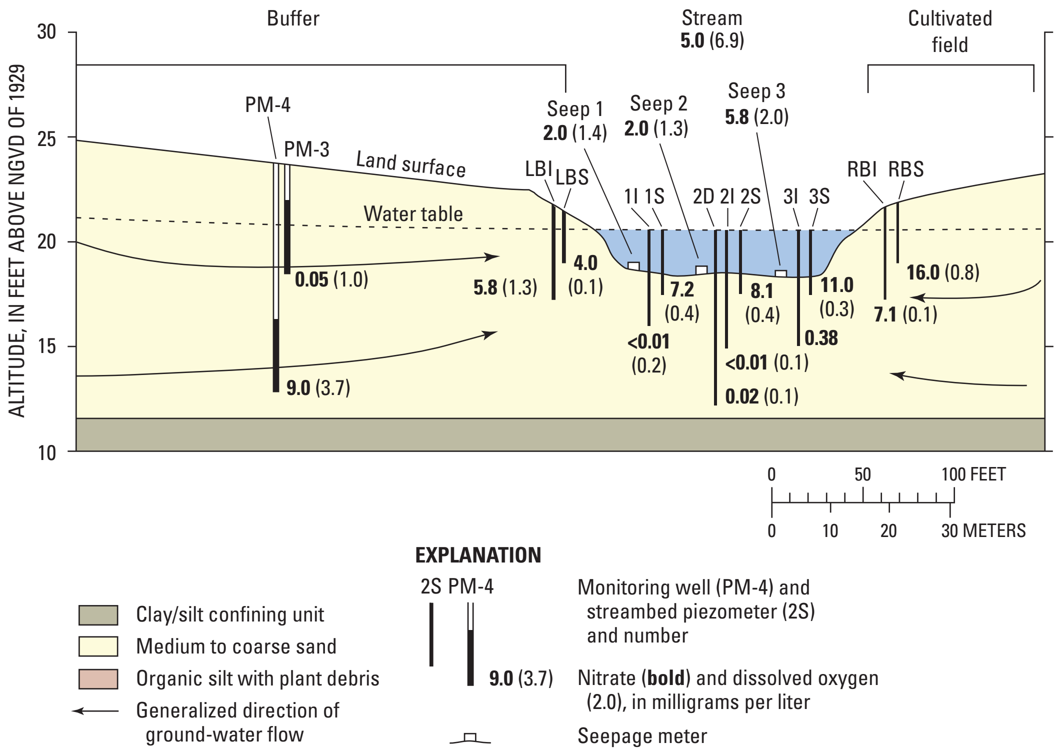

Figure 6. Sampling locations and median nitrate and dissolved-oxygen concentrations at site 2 along the stream cross section during June and July 1998 in the Tar-Pamlico River basin, North Carolina (modified from Spruill, 2004).

is higher than the nitrate concentrations at streambank locations LBS (4.0 mg/L) and LBI (5.8 mg/L) but less than in well PM–4 (9.0 mg/L), which indicates that the nitrate likely is derived from the deeper part of the surficial aquifer beneath the riparian buffer (fig. 6). Conversely, the nitrate concentration for streambed piezometer 3S (11.0 mg/L) is intermediate to the nitrate concentrations at streambank locations RBI (7.1 mg/L) and RBS (16.0 mg/L) on the non-buffered side of the stream, possibly indicating higher nitrate inputs from shallow ground water flowing beneath the cultivated field.

Results from the seepage-meter samples (Seep1, Seep2, and Seep3, fig. 6; table A5), which represent ground water after it has discharged vertically to the stream channel, indicate that nitrate concentrations were substantially reduced as ground water passed through the shallow streambed deposits of the hyporheic zone into the overlying stream. The nitrate concentration of 2.0 mg/L in the sample from Seep1 on the buffered side of the stream is 65 percent lower than the mean concentration of 5.7 mg/L for shallow piezometers LBS, LBI, and 1S. The nitrate concentration of 5.8 mg/L for the sample from Seep3 on the non-buffered side of the stream is 49 percent lower than the mean concentration of 11.4 mg/L for shallow piezometers RBS, RBI, and 3S.

The distribution and transport of nitrate in ground water at flow-path site 2 was influenced by a combination of factors, including the source area for ground-water recharge, nitrogen loadings, denitrification processes, presence or absence of a riparian buffer, and interaction with the hyporheic zone. The cumulative effect of these processes helped reduce the amount of ground-water nitrate that was discharged to surface water at this site; however, the stream nitrate concentration of 5.0 mg/L (fig. 6) indicates a significant influence of non-buffer high-nitrate discharge of ground water to the stream in this watershed.

Site 3 — Third-Order Stream without Stream Buffer and Poorly Drained Soil

At flow-path site 3, wells are located along a transect through a cultivated field that terminates at a stream (fig. 7). Lower nitrate and DO concentrations were present in ground-water samples collected from the deeper portion of the flow path in the clay/silt confining unit than in the medium to coarse sand. The relatively wide ranges of DO concentrations measured in deeper wells TB–2 (0.1–8.0 mg/L) and TB–5 (0.3–4.0 mg/L, table A6) indicate that low DO conditions that promote denitrification can occur as ground water moves into deeper portions of the aquifer. The relatively low excess N_2 value of 1.0 mg/L measured in a sample from well TB–1 indicates that some denitrification may occur at this upgradient portion of the flow path.

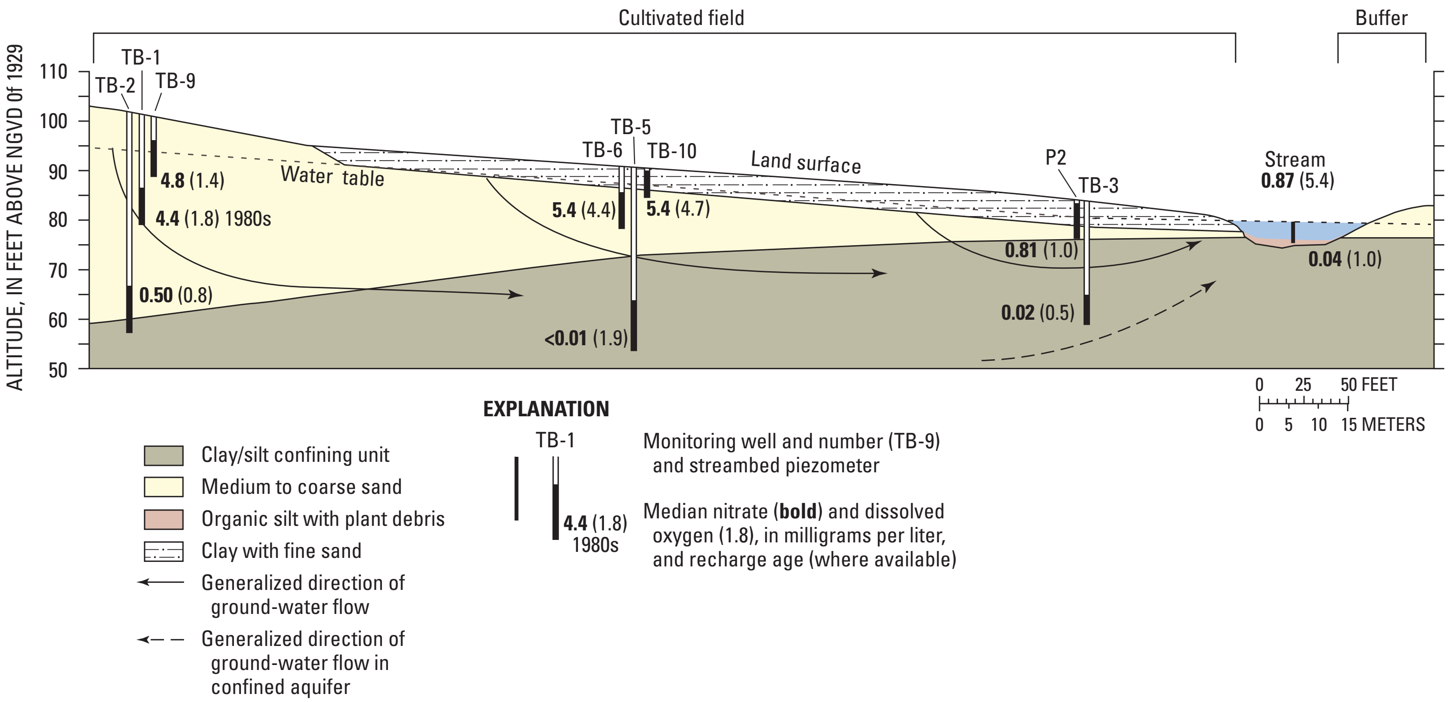

Figure 7. Sampling locations, flow-path features, and median nitrate and dissolved -oxygen concentrations at site 3 in the Neuse River basin, North Carolina (modified from Spruill, 2004).

A relatively low median nitrate concentration of 0.81 mg/L measured in well P2 may indicate increased denitrification in this area. Median DOC concentrations generally were low (0.3 to 1.2 mg/L) in samples from the shallow aquifer at the upgradient and middle well clusters (table A6). An elevated DOC concentration of 5.8 mg/L was measured in shallow well P2 in the downgradient portion of the flow path near the stream where flood-plain deposits with high levels of organic matter may enhance reducing conditions and denitrification processes.

A significant decrease in median nitrate concentration was observed in samples from well P2 to the piezometer located in the organic-rich deposits that line the streambed (fig. 7). Little nitrate (0.04 mg/L) was detected in ground water that discharges through the streambed. The high organic-matter content in the streambed deposits provides a strongly reducing environment that promotes denitrification, as evidenced by elevated values of excess N_2 (3.7 mg/L), ammonia (0.53 mg/L), dissolved phosphorus (0.48 mg/L), DOC (3.7 mg/L), and iron (5,200 µg/L) measured in samples collected from the streambed piezometer (table A6). The organic materials that line the streambed probably originated from riparian vegetation across and upstream from this site. Organic materials supplied to the stream from upstream areas may help reduce the amount of nitrate discharged through the streambed in reaches lacking riparian buffers thereby indicating how riparian vegetation can influence water quality at field and watershed scales.

Site 5 — First- and Third-Order Streams with Stream Buffers and Well to Poorly Drained Soils

Two flow paths were examined at the Lizzie research site. Flow path 5A drains to third-order stream Sandy Run (figs. 2, 8) and flow path 5B drains to first-order stream Plum Tree Branch (figs. 2, 9). A summary of analytical results for samples collected from 1999 through 2003 for wells, piezometers, and surface-water sites for flow paths A and B is provided in table A7. Detailed discussions on the hydrogeologic and geochemical settings for the Lizzie research site are provided in Spruill and others (2005) and Tesoriero and others (2005).

Three general scenarios concerning the history of nitrate contamination have been described for this site (Tesoriero and others, 2005). First, ground water that is younger than about 10 years tends to be oxic and have elevated nitrate concentrations, reflecting both the oxic conditions in the upper part of the surficial aquifer and a recharge period corresponding to high nitrogen applications on the land. An example of this scenario is represented by well L6 (fig. 9), which had a median nitrate concentration of 41.3 mg/L, a DO concentration of 1.3 mg/L, and a recharge age of 1990. Second, ground water at this site with ages of about 10 to 30 years has low nitrate and DO concentrations and high excess N_2 values. These conditions indicate that these waters once contained elevated nitrate concentrations that have since been reduced by denitrification. An example of this scenario is represented by well L6D (fig. 9), which had a nitrate concentration of 0.12 mg/L, a DO

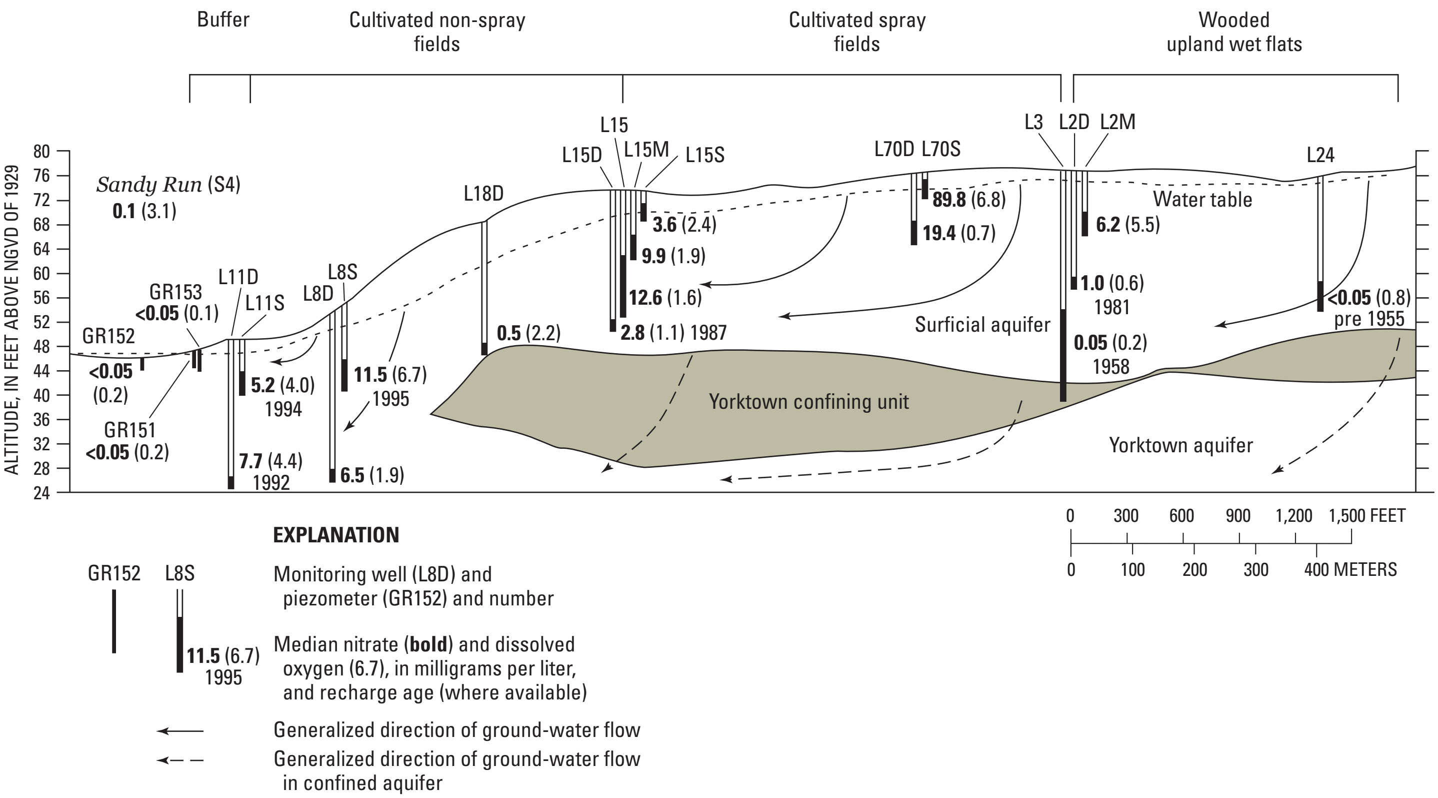

Figure 8. Sampling locations, flow-path features, and median nitrate and dissolved-oxygen concentrations at site 5A in the Neuse River basin, North Carolina (modified from Tesoriero and others, 2005).

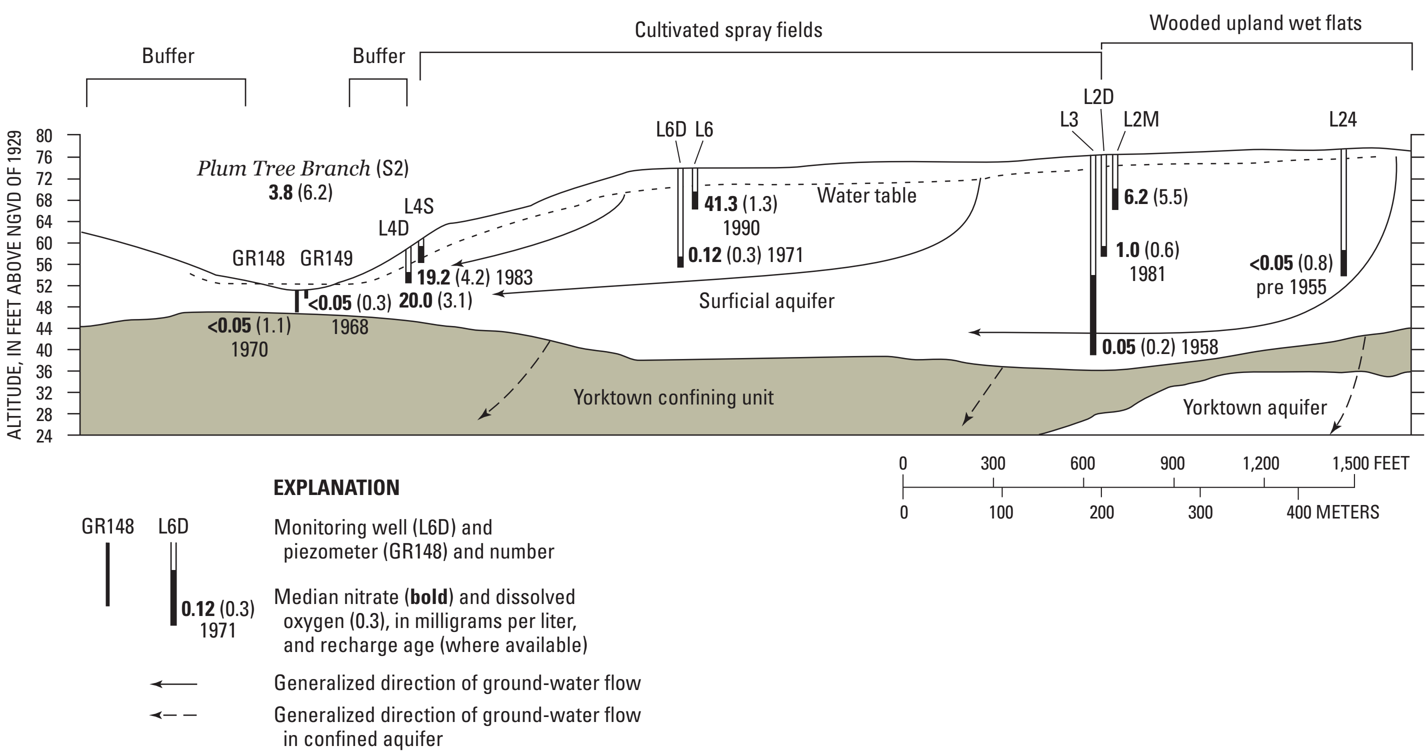

Figure 9. Sampling locations, flow-path features, and median nitrate and dissolved-oxygen concentrations at site 5B in the Neuse River basin, North Carolina (modified from Tesoriero and others, 2005).

concentration of 0.3 mg/L, an excess N_2 value of 3.6 mg/L, and a recharge age of 1971. The third scenario is for ground water older than about 30 years that has low nitrate and DO concentrations and high concentrations of iron available for nitrate reduction but little or no excess N_2, which indicates that this older water never contained elevated nitrate concentrations. These conditions were observed in well L3 (fig. 8; table A7), which is screened at the base of the surficial aquifer upgradient from the spray fields.

Ground water in areas hydraulically upgradient from the Lizzie spray fields does not appear to be a major source of nitrate (figs. 8, 9). A notable increase in nitrate concentrations was observed in samples from wells located within or along the downgradient side of the fields that received spray applications of the lagoon effluent. The highest median nitrate concentration observed along flow path 5A (fig. 8) was for shallow well L70S (89.8 mg/L) located at the top of the water table and directly beneath the spray field. Comparison of nitrate and DO concentrations in this well and companion well L70D, which is approximately 7 ft deeper, indicates a large reduction in nitrate (from 89.8 to 19.4 mg/L) and DO (from 6.8 to 0.7 mg/L) with depth at this location. Lithologic data for this well-cluster site indicate the presence of clay and sandy clay between the screened intervals of these wells. The clay zone at this well-cluster site may locally retard the downward percolation of water, thereby increasing the amount of time that nitrate in saturated soils near the top of the water table can be influenced by vegetative uptake and denitrification.

The recharge age of 1987 for deep well L15D on flow path 5A (fig. 8) indicates a fairly high rate of ground-water recharge through the moderately well-drained soils along this portion of the flow path. Thus, the elevated nitrate concentrations at L15M (9.9 mg/L) and L15 (12.6 mg/L) likely reflect the downward transport of recently recharged ground water with nitrate derived from swine-waste applications. Ground water at deeper well L15D, with a recharge age that predates the swine-waste spraying, had a lower nitrate concentration of 2.8 mg/L. The high excess N2 value of 7.0 mg/L at L15D (table A7) indicates that substantial denitrification occurred in this portion of the aquifer.

Near the end of flow path 5A, a deep zone of oxic ground water with elevated nitrate was observed at wells L8S (11.5 mg/L) and L8D (6.5 mg/L) in the non-spray field and wells L11S (5.2 mg/L) and L11D (7.7 mg/L) near the buffer. The younger (1990s) and more oxic water found at greater depths in this portion of flow path 5A (fig. 8) indicates that ground water in this area is derived from recharge directly above or from the movement of water from Sandy Run directly into the aquifer (Tesoriero and others, 2005). The low concentrations of nitrate and DO and elevated concentrations of ammonia, phosphorus, DOC, and iron at streambank piezometers GR151 and GR153 and streambed piezometer GR152 (table A7) indicate that highly reduced conditions that promote denitrification are present in the organic-rich deposits of the buffer zone and hyporheic sediments. Consequently, little ground-water discharge of nitrate occurs to third-order Sandy Run, where surface water had a median nitrate concentration of 0.1 mg/L.

The change in fertilizer use during 1995 from conventional applications of inorganic fertilizer to field spraying of lagoon effluent from the swine operation is reflected in water-quality data collected along flow path 5B (fig. 9). In 1995, a sample from shallow well L6 beneath the spray fields had a nitrate concentration of 10 mg/L (Spruill and others, 2005). A median nitrate concentration of 41.3 mg/L was measured in well L6 during 1999 to 2003, indicating a four-fold increase in ground-water nitrate, which is most likely related to the different fertilization methods. Deeper ground water in companion well L6D, with minimal nitrate (0.12 mg/L), DO (0.3 mg/L), and a recharge age of 1971, does not appear to have been affected by the swine-waste applications. However, the excess N_2 value of 3.6 mg/l for well L6D (table A7) indicates that higher nitrate levels were once present in this older water and that denitrification has occurred.

Near Plum Tree Branch, the surficial aquifer thins, and ground water in this area is derived from a mixture of upgradient, shallow and deep water from the surficial aquifer. Surface water in Plum Tree Branch during base flow is derived from the surficial aquifer with limited or no contribution from the deeper confined Yorktown aquifer (Tesoriero and others, 2005). The recharge age of about 1970 for streambed piezometers GR148 and GR149 (fig. 9) indicates that the ground water sampled at these locations was derived from deeper flow paths in the surficial aquifer. This ground water also was devoid of nitrate (<0.05 mg/L), likely a result of denitrification processes, and highly reduced, as indicated by the low DO and elevated ammonia, dissolved phosphorus, DOC, and iron concentrations (table A7). Unlike the low median nitrate concentration at Sandy Run (0.1 mg/L), the median nitrate concentration in Plum Tree Branch (3.8 mg/L at site S2, table A7; figs. 8, 9) indicates a source of nitrate to this first-order stream, possibly from upstream or the discharge of younger ground water from shallower flow paths in the surficial aquifer.

In 2006, minipiezometers were installed along transect 5PT1 in the riparian buffer at Plum Tree Branch (figs. 2, 10) to examine changes in nitrate concentrations that occur as ground water moves from the spray fields through the buffer zone to the receiving stream. At the upgradient edge of the buffer zone (fig. 10; table A8), aerobic conditions and high nitrate concentrations, ranging from 8.5 to 18.8 mg/L, were observed in the upper portion of the surficial aquifer. The elevated nitrate concentrations of about 26 mg/L at the middle cluster (PT1–2A, 2B, and 2C) may reflect either a slug of water with higher nitrate concentrations that has already passed by the field edge or localized differences in the shallow ground-water flow paths sampled. Regardless, the minipiezometer data indicate that oxic ground water enriched with nitrate is flowing from the spray field along shallow flow paths beneath the riparian buffer (fig. 10).

The ground-water nitrate concentrations beneath the buffer along transect 5PT1 decreased at the minipiezometer

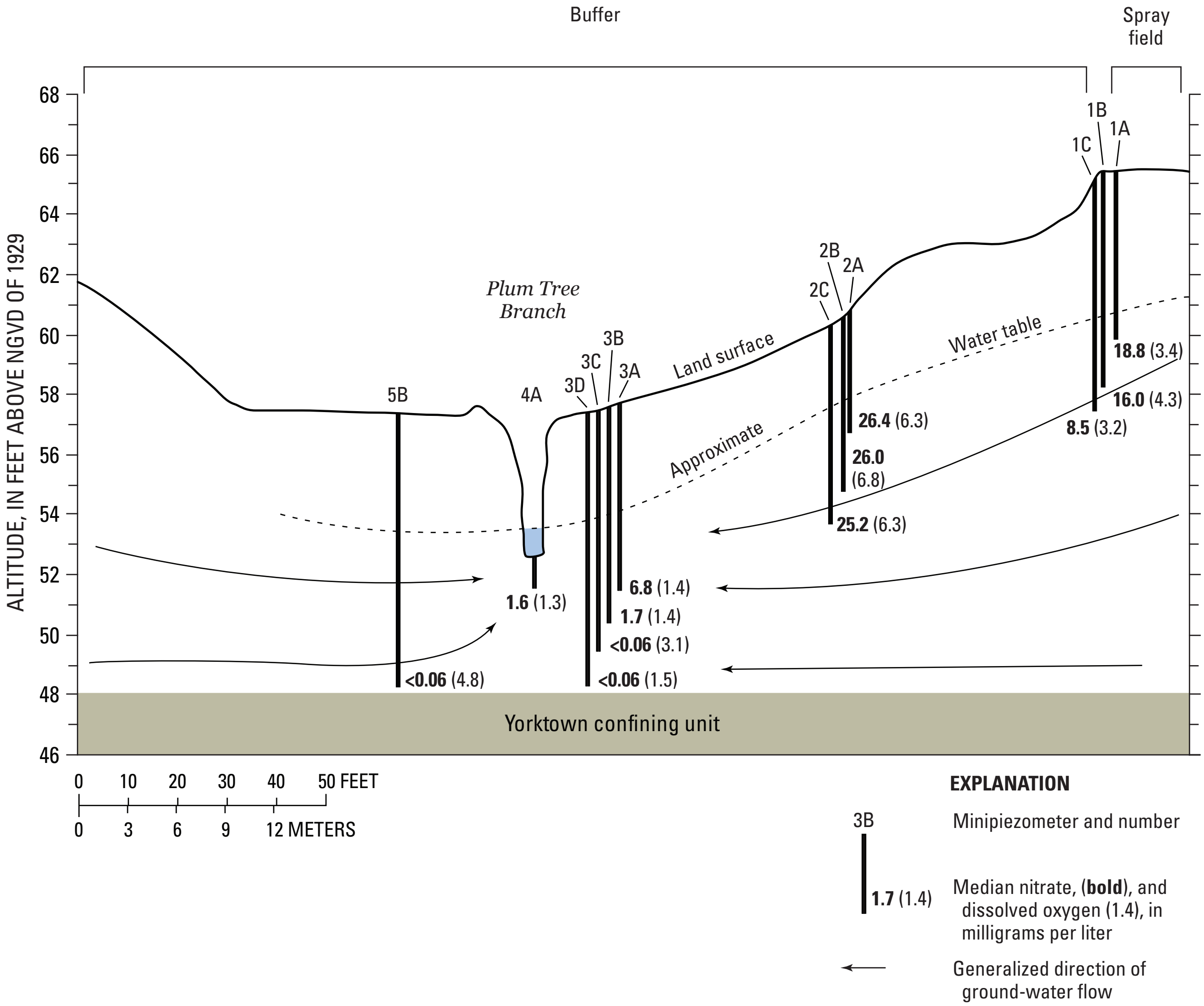

Figure 10. Sampling locations and median nitrate and dissolved-oxygen concentrations at site 5PT1 in the Neuse River basin, North Carolina.

cluster (3A–3D) near Plum Tree Branch (fig. 10; table A8). The decrease in nitrate concentrations and increase in ammonia and iron concentrations with depth at these minipiezometers indicate that enhanced reducing conditions that promote denitrification exist in some portions of the hyporheic sediments near the stream. Surface-water data for Plum Tree Branch (fig. 2; table A8) indicate a gain in median nitrate concentration from 2.1 mg/L at upstream site S7 (USGS site number 0209173150) to 6.1 mg/L at downstream site S2 (USGS site number 0209173190). The median nitrate concentration of 1.6 mg/L from minipiezometer 4A in the streambed indicates that some of the nitrate gain in Plum Tree Branch may be derived from ground water discharging along shallower flow paths beneath the riparian buffer (fig. 10).

The gain in surface-water nitrate at downstream site S2 also may include nitrate that was nitrified from ammonia. The reduction of nitrate under anaerobic conditions can occur by two primary metabolic processes—denitrification and dissimilatory nitrate reduction to ammonia (DNRA; see Korom, 1992). Nitrate reduction in ground water through DNRA can result in an increase of ammonia concentrations in ground water that discharges to the stream. Ammonia also can be released during the mineralization of organic matter in anoxic sediments. The highest ammonia concentration measured in Plum Tree Branch was 3.33 mg/L for streambed minipiezometer PT1–4A (table A8). The increase in median ammonia concentration of 0.06 mg/L from upstream site S7 to 0.76 mg/L at downstream site S2 indicates a source of ammonia to the stream. Ammonia that is released into oxygenated surface waters of Plum Tree Branch possibly can be converted back to nitrate through nitrification (Korom, 1992; Tesoriero and others, 2000), thereby increasing nitrate concentrations at downstream site S2.

Some of the nitrate gain in Plum Tree Branch also may reflect contributions of high nitrate water from tile-drain site SR5-T1 located between upstream site S7 and downstream site S2 (fig. 2). Nitrate concentrations in the tile drainage ranged from 30 to 46 mg/L during August 2000 to August 2001 (Harden and Spruill, 2004). Ground water that is intercepted by this subsurface tile is routed through a ditch to Plum Tree Branch, bypassing the riparian zone processes that normally would reduce nitrate fluxes. Results of nutrient analyses and discharge measurements obtained periodically from sites S7, S2, and SR5–T1 (Ragland and others, 2002–2004; Walters and others, 2005; U.S. Geological Survey, 2007b) indicate that the tile potentially can contribute up to 35 percent of the nitrate load to Plum Tree Branch while only contributing 10 percent of the water gained between upstream site S7 and downstream site S2. Therefore, tile drainage appears to be a major component of the nitrate flux to Plum Tree Branch.

Summary of Nitrate-Reducing Capacity in Different Hydrogeologic Settings

The reduction of nitrate in ground water was observed at all study sites, although the extent of reduction at each site was influenced by various environmental, hydrogeologic, and geochemical factors along the ground-water flow paths. The following discussion incorporates results and observations made at the five flow-path study locations to summarize the important factors found to influence ground-water transport of nitrate and to categorize the nitrate-reducing capacity of the different flow-path zones.

Denitrification was the most commonly observed factor responsible for decreases in ground-water nitrate along the study-site flow paths. A significant negative correlation was noted between DOC, which is known to be important in denitrification reactions (Korom, 1992), and nitrate concentrations in ground water at flow-path sites 1 through 4 (Spruill, 2004). In general, the lowest nitrate concentrations, lowest DO concentrations, highest DOC concentrations, and highest excess N_2 occurred in ground-water samples collected from the deeper portions of the surficial aquifer or at the end of the flow paths in discharge areas. The main factors that appear to influence ground-water nitrate concentrations, in association with or independently of denitrification, along the flow paths or at the streams include:

Environmental Factors

- Soil properties—drainage characteristics and thickness
- Riparian buffers—presence or absence, width
- Evapotranspiration—vegetative use of water and nutrients
- Fertilizer applications—types, amounts, historical use

Hydrogeologic Factors

- Ground-water recharge—rates, land use in source area
- Flow paths—length of flow paths, residence times
- Lithologic properties—permeability of aquifer material
- Vertical hydraulic gradients—influence of deeper confined aquifer
- Saturated zone—surficial aquifer thickness beneath field, buffer, and stream
- Subsurface tile drains—tile drainage may bypass riparian processes

Geochemical Factors

- Denitrification—removal of nitrate under reducing conditions
- Reducing environments—occurrence along flow paths
- Organic carbon—sources, amounts
- Dissolved oxygen—anoxic conditions promote denitrification
- Hyporheic processes—presence of organic-rich streambed deposits

Nitrate-reducing processes differed among the field, buffer, and hyporheic zones. For a given zone, ground-water nitrate concentrations at the upgradient and downgradient edges of the zone were used to compute the percentage of nitrate reduction in water moving through the zone. In this context, nitrate reduction is taken to represent all factors, not just denitrification, contributing to the overall decrease in nitrate concentration within a zone, which provides a mechanism for examining the relative capacity of each zone to process nitrate.

The percentages of nitrate reductions computed for the different flow-path zones at each site are summarized in table 2. In some cases, an average nitrate value derived from multiple wells was used to represent a specific point along the flow path. Nitrate reduction in ground water within the field zone at well-drained flow-path sites 1 and 5B ranged from 4 to 54 percent. In the same zone at poorly drained sites 4 and 3, nitrate was reduced from 61 to 87 percent, respectively. An intermediate reduction of 42 percent was noted in the poorly to well-drained field zone at flow-path site 5A. The poorly drained fields appear to have a higher capacity for reducing nitrate, possibly reflecting increased denitrification and vegetative uptake because of the longer residence times associated with the slower infiltration rates in soils at these sites. In studying the effect of soil drainage on nitrate losses from agricultural fields in the North Carolina Coastal Plain, Gambrell and others (1975) noted that denitrification in poorly drained soil was greater than denitrification in moderately

Table 2. Summary of nitrate reduction in ground water, characterized by flow-path zone, at each study site in the Neuse and Tar-Pamlico River basins, North Carolina.

[mg/L, milligram per liter; —, not applicable; nd, no data; <, less than]

Site classification	Flow-path site (figure)	Approximate flow-path position and nitrate concentration (mg/L)				Nitrate reduction (percent)		
		Upgradient field	Downgradient field/upgradient buffer	Downgradient buffer/stream edge	Streambed	Field zone	Buffer zone	Hyporheic zone
First-order stream, well-drained soil with buffer	1 (fig. 3)	JC–1, JC–2 12.0	JC–5, JC–6 11.5	JC–7 0.02	Piezometer 0.04	4	99	—[a]
First-order stream, poorly drained soil with buffer	4 (fig. 4)	JP–2 7.6	JP–6 3.0	JP–5 0.05	Piezometer 0.01	61	98	—[a]
Second-order stream, well-drained soil with buffer	2 (fig. 5)	PM–1, PM–2 7.4	nd	PM–4 6.8	2S 2.0	nd	8[b]	71
Second-order stream, well-drained soil with buffer	2 (fig. 6)	—	—	LBI, LBS, 1S 5.7	Seep1, Seep2 2.0	—	—	65
Second-order stream, well-drained soil without buffer	2 (fig. 6)	—	—	RBS, RBI, 3S 11.4	Seep3 5.8	—	—	49
Third-order stream, poorly drained soil without buffer	3 (fig. 7)	TB–1, TB–2, TB–9 3.2	—	P2, TB–3 0.42	0.04	87	—	90
Poorly to well-drained spray field	5A (fig. 8)	L70D 19.4	L15, L15M 11.2	—	—	42	—	—
Third-order stream, well-drained non-spray field with buffer	5A (fig. 8)	—	L11S, L11D 6.4	GR151, GR153 <0.05	GR152 <0.05	—	99	—[a]
First-order stream, well-drained spray field with buffer	5B (fig. 9)	L6 41.3	L4S 19.2	—	—	54[c]	—	—
First-order stream, well-drained spray field with buffer	5PT1 (fig. 10)	L6 41.9	1A–C, 2A–C 20.2	3A, 3B 4.2	4A 1.6	52	79	62

[a] Little nitrate deetected at the end of the buffer zone or hyporheic zone at this location.

[b] Represents combined reductions in both the field and buffer zones.

[c] For flow path 5B, a nitrate-reduction percentage only was computed for the field zone. The limited data available from the downgradient edge of the buffer and hyporheic zones were not considered sufficient for understanding the potential effects of swine-waste applications along this portion of the flow path.

well-drained soil, reflecting increased organic carbon and a more favorable reducing environment.

Regardless of the soil-drainage classification, the amount of nitrate entering the buffer zone at sites 1, 4, and 5A was almost entirely reduced by the end of the buffer (>98 percent) such that no nitrate was present in the hyporheic zone (table 2). A lower reduction (79 percent) was noted in the buffer zone at site 5PT1; however, this site also had considerably more nitrate (20.2 mg/L) at the beginning of the buffer relative to sites 1, 4, and 5A ($\leq$11.5 mg/L). Based on samples collected along flow-path site 2 from April 1998 to May 1999 (fig. 5), a minimal nitrate reduction (8 percent) was noted from the upgradient portion of the field (nitrate = 7.4 mg/L) toward the end of the buffer zone (nitrate = 6.8 mg/L). However, this nitrate was reduced to 2.0 mg/L, or 71 percent, as the water moved into the hyporheic zone. Based on data from the stream piezometer transect at site 2 (fig. 6), greater nitrate reduction of 65 percent was noted in ground water discharging into the hyporheic zone from the buffered side of the stream compared to the 49-percent reduction noted for the non-buffered side of the stream (table 2). At site 5PT1, the high nitrate concentration (20.2 mg/L) in ground water flowing beneath the buffer in the upper portion of the surficial aquifer is reduced by 79 percent to 4.2 mg/L at the downgradient edge of the buffer. This value is reduced further by 62 percent to 1.6 mg/L as the water continues through the hyporheic zone. The hyporheic zone, with nitrate-reduction percentages ranging from 49 to 90 percent, has a substantial capacity to lower nitrate concentrations in ground water.

Based on these flow-path data, the nitrate-reducing capacity of the buffer zone combined with that of the hyporheic zone can substantially lower the amount of ground-water nitrate discharged to streams in agricultural settings of the North Carolina Coastal Plain. However, the beneficial effects of riparian buffers and hyporheic zones may be diminished by subsurface tile drainage that allows ground water beneath cultivated fields to bypass natural streamside buffers and organic carbon-rich streambeds that normally would reduce nitrate concentrations in the ground water before it discharges to streams. Additional information on the influence of nitrate-reduction factors described for the flow-path study sites is needed to better evaluate the transport of nutrients from watersheds throughout the Coastal Plain. For example, what is the land use and distribution of soils within a watershed? How much tile drainage is present in Coastal Plain watersheds? How much of the stream reach is bounded by a riparian buffer? Is riparian vegetation being removed or added, and how does this affect instream organic matter? Is there a limit to the denitrification potential of streamside buffers and hyporheic zones? What is the streamflow and base-flow contribution from ground-water discharge? The answers to these questions may provide important insights into the amount of nitrate processed and exported by a watershed.

In this study, the highest observed nitrate concentrations (>40 mg/L between 1999 and 2006) observed in ground water were beneath the spray fields at site 5. Nevertheless, nitrate reduction in ground water at site 5 was substantial. First-order stream Plum Tree Branch, which receives drainage from site 5, had a median nitrate concentration of 3.8 mg/L at downstream surface-water site S2 during 1999–2003 (table A7). Third-order stream Sandy Run, which receives drainage from Plum Tree Branch and the 28-square-mile (mi^2) area upstream containing about 20 other swine CAFOs, had a median nitrate concentration of 0.1 mg/L in surface water (site S4, fig. 2; table A7). This unusually low nitrate concentration indicates that other factors at the watershed scale may exert considerable influence in determining the relative effect of ground-water discharge on surface-water quality, particularly with regard to nutrients that have important biological considerations.

Watershed-Scale Factors Affecting Nitrogen and Water Yields—A Comparison of Two Watersheds

Bear Creek (USGS station 0208925200; site N1, fig. 1) and Middle Swamp (USGS station 02091736; site S5, fig. 2) are both in the Neuse River basin in watersheds that have no reported point-source inputs (North Carolina Division of Water Quality, 2002a). Data from these stations were used to evaluate effects from nonpoint sources of nitrogen on instream water quality. Sandy Run receives drainage from Plum Tree Branch and the Lizzie research site and is a tributary of the Middle Swamp watershed. Bear Creek and Middle Swamp have many similar watershed characteristics (table 3) and yet have different annual and seasonal nitrogen yields (Spruill and others, 2005).

Bear Creek illustrates the effect that a single stream can have on nutrient yields to the Neuse River. The Bear Creek watershed has a drainage area of 57.7 mi^2, or about 1.5 percent of the total land area of the non-tidal portion (3,900 mi^2) of the Neuse River at Fort Barnwell. In 2000, Bear Creek had a median nitrate concentration of about 3 mg/L during base flow and delivered approximately 200 tons of nitrogen to the Neuse River, or about 5 percent of the total annual nitrogen load of the Neuse River at Fort Barnwell (Spruill and others, 2005). In contrast, the Middle Swamp watershed (51.0 mi^2), which is similar to Bear Creek in drainage area and land-use characteristics, delivered 38 tons of nitrogen to the Neuse River. Interestingly, the average population of swine raised in the Middle Swamp watershed (104,805) is about 2.5 times higher than in the Bear Creek watershed (40,624), but Middle Swamp exports less nitrogen. The difference in nitrogen yields may indicate a difference in the capacity of each watershed to process nitrogen and it is this feature that may allow different nutrient-management strategies to be used for controlling nitrogen transport in the North Carolina Coastal Plain.

Hydrologic data obtained from gaging stations offer useful insights into runoff characteristics and the relative importance of ground water and surface runoff within

Table 3. Land use, basin, and streamflow characteristics in the Bear Creek and Middle Swamp watersheds, North Carolina, 1999–2002 (modified from Spruill and others, 2005).

[mi^2, square mile; ft^3/s, cubic foot per second; in., inch]

Map no. (figs. 1, 2) and station name	USGS station no.	Drainage area (mi^2)	Land use (in percent)					Swine population (average)	Median stream-flow (ft^3/s)	Annual runoff ($[ft^3/s]/mi^2$)[a]	Base-flow index (annual base flow [in.]/annual total flow [in.])
			Agri-culture	Forest	Urban	Water	Wet-land				
N1-Bear Creek at Mays Store	0208925200	57.7	59.9	22.9	11.9	0.7	4.4	40,624	37	1.50	68.1
S5-Middle Swamp near Farmville	02091736	51.0	50.1	32.7	5.4	0.2	11.4	104,805	7.4	0.75	51.2

[a]The annual runoff in cubic foot per second per square mile ($[ft^3/s]/mi^2$) is the average number of cubic feet of water flowing per second from each square mile of area drained, assuming the runoff is distributed uniformly in time and area.

watersheds. Although Bear Creek and Middle Swamp have similar drainage areas, the volume of water discharged from Bear Creek between 2000 and 2001 was approximately double the amount discharged from Middle Swamp (fig. 11*A*). From 1999 through 2002, the mean annual runoff was 1.50 cubic feet per second per square mile [$(ft^3/s)/mi^2$] for Bear Creek and 0.75 $(ft^3/s)/mi^2$ for Middle Swamp (table 3). The seasonal base-flow index during 2000 and 2001 indicates that ground water contributed between 70 to 95 percent of the total runoff from Bear Creek. In contrast, ground water in Middle Swamp generally contributed about 60 percent of the total runoff during the winter and 20 percent during the summer months (fig. 11*B*). The anomalous base-flow index of 100 during October - December 2001 for Middle Swamp reflects an extremely dry period when most of the surface water was derived from ground water and minimal discharge occurred from the watershed (fig. 11*A*).

Patterns of nutrient transport are similar to patterns of water fluxes from the two watersheds. The nitrogen load from Bear Creek is approximately 5 to 10 times higher than the nitrogen load from Middle Swamp (fig. 11*C*). In 2000, an average precipitation year, the annual total nitrogen load was 201 tons for Bear Creek and 38 tons for Middle Swamp (table 4). Total phosphorus loads also were higher in Bear Creek than in Middle Swamp. In 2000, the annual total phosphorus load was 9.9 tons for Bear Creek and 6.3 tons for Middle Swamp (table 4), even though the median total phosphorus concentration of 0.35 mg/L for Middle Swamp was several times higher than the median concentration of 0.08 mg/L for Bear Creek (table 5).

Lower streamflow during 2001 led to a decrease in annual nutrient loads for Bear Creek (150 tons for nitrogen and 8.9 tons for phosphorus) and Middle Swamp (17 tons for nitrogen and 3.7 tons for phosphorus). Precipitation data from a weather station in Kinston, NC (fig. 1), indicate an annual rainfall of 47.2 in. during the year 2000, which is similar to the long-term average of 48.7 in. during the period 1966–2006 (Southeast Regional Climate Center, 2006). A substantially lower annual rainfall of 37.7 inches occurred during 2001. The decrease in nutrient loads from 2000 to 2001 in each watershed appears to reflect lower water yields. The lower nutrient loads observed for Middle Swamp than for Bear Creek (table 4) reflect both lower water yields and differences in constituent concentrations (table 5). These data indicate that flow statistics that include base flow and the general hydrologic dynamics of a stream are important in understanding nutrient transport from a watershed and may be useful indicators of watersheds that are likely to have higher yields of nutrients and water.

As previously stated, the annual stream runoff of 1.50 $(ft^3/s)/mi^2$ for Bear Creek was twice that of 0.75 $(ft^3/s)/mi^2$ for Middle Swamp (table 3). Ground-water discharge also constituted a larger percentage of the overall streamflow for Bear Creek than Middle Swamp, as indicated by the annual base-flow index values of 68.1 and 51.2, respectively. During 2000 with average annual precipitation, the median concentrations of DO and nitrate were significantly higher in Bear Creek (8.5 and 2.6 mg/L, respectively) than in Middle Swamp (3.4 and 0.04 mg/L, respectively), indicating an oxidizing environment in Bear Creek and a reducing environment in Middle Swamp (table 5). The higher median concentrations of DOC, ammonia plus organic nitrogen, and phosphorus for Middle Swamp relative to Bear Creek further indicate reducing conditions in Middle Swamp. Nitrate does not appear to be as stable under the lower velocity and more reducing conditions in Middle Swamp than in the higher velocity and more oxidizing conditions in Bear Creek, thereby indicating a higher potential for nitrate export from the Bear Creek watershed. If the terrestrial loading of nitrogen is similar in each watershed, then nitrate loss occurs in the stream and(or) in the ground water before it discharges to the stream.

The two watersheds have few major differences in land use (table 3). Bear Creek and Middle Swamp are similar in drainage area and have similar percentages of agricultural

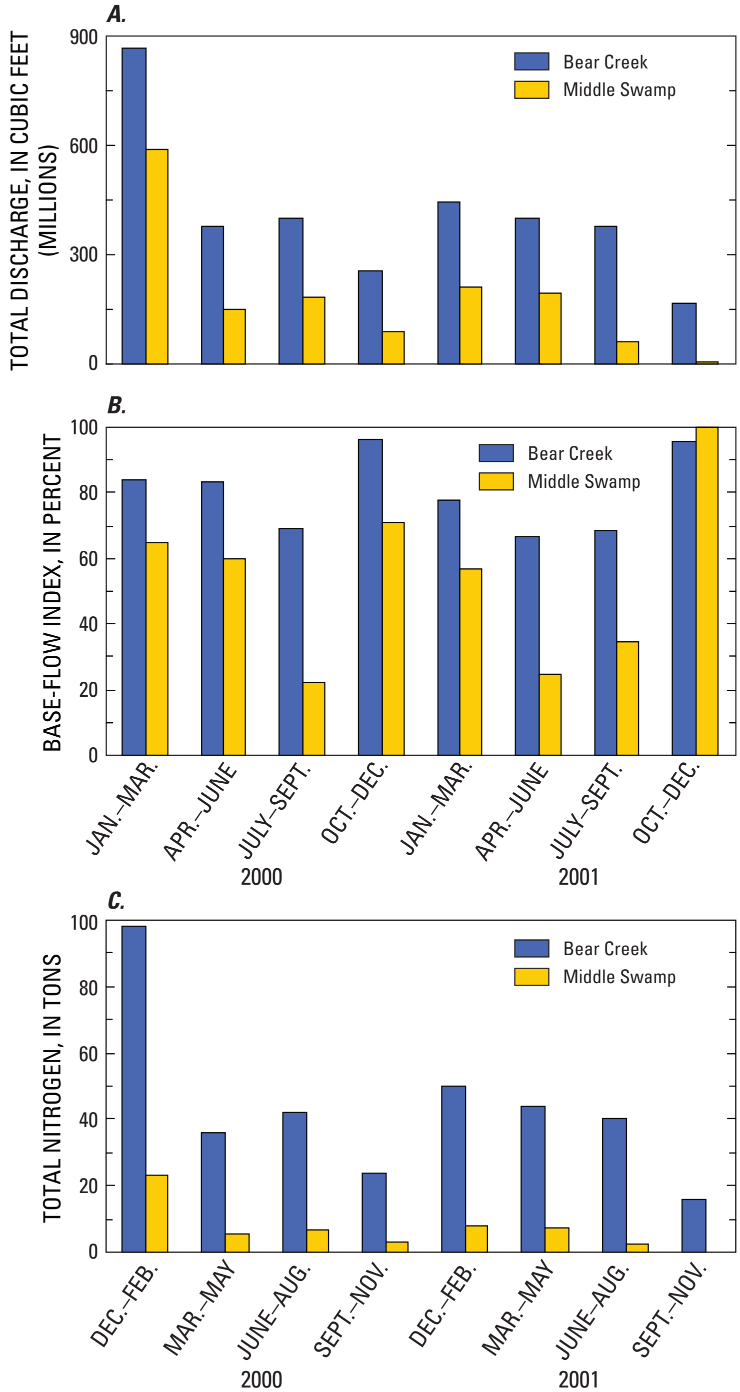

Figure 11. Seasonal *(A)* discharge, *(B)* base-flow index, and *(C)* total nitrogen transport in Bear Creek and Middle Swamp in the Neuse River basin, North Carolina.

land and urban areas. These two watersheds also are located in the same physiographic province (inner Coastal Plain; North Carolina Geological Survey, 2004) and hydrogeologic regions (middle Coastal Plain upland and alluvial and estuarine valley lowland; Ator and others, 2005). One observed difference in land use is that the combined percentage of forested and wetland areas in Bear Creek (27.3 percent) is lower than in Middle Swamp (44.1 percent).

The extent of riparian buffers along Bear Creek and Middle Swamp also was examined. In each watershed, the stream centerlines (1:24,000 scale) from the USGS National Hydrography Dataset (U.S. Geological Survey, 2007a) were coupled with true color orthophotography (1-meter resolution) from the 2005 National Agricultural Imagery Program (U.S. Department of Agriculture, 2005) to determine the amount of

Table 4. Seasonal and annual loads and yields of total nitrogen and phosphorus in the Bear Creek and Middle Swamp watersheds, North Carolina, December 1999–November 2001.

[N, nitrogen; tons/mi^2, tons per square mile; P, phosphorus]

Station	Seasonal total N load (tons)				Annual total N load (tons)	Annual total N yield (tons/mi^2)	Seasonal total P load (tons)				Annual total P load (tons)	Annual total P yield (tons/mi^2)
	Winter Dec–Feb	Spring Mar–May	Summer June–Aug	Fall Sept–Nov			Winter Dec–Feb	Spring Mar–May	Summer June–Aug	Fall Sept–Nov		
December 1999–November 2000												
Bear Creek	98	36	42	24	201	3.4	4.3	1.7	3.2	0.6	9.9	0.17
Middle Swamp	23	5.4	6.8	3.0	38	0.74	2.7	1.1	1.9	0.65	6.3	0.12
December 2000–November 2001												
Bear Creek	50	44	40	16	150	2.6	2.0	3.4	3.2	0.28	8.9	0.15
Middle Swamp	7.8	7.4	2.2	0.01	17	0.34	1.1	1.7	0.83	0.04	3.7	0.07

Table 5. Summary of selected chemical constituent concentrations in the Bear Creek and Middle Swamp watersheds, North Carolina, 2000–2001.

[mg/L, milligram per liter; N, nitrogen]

Station	Number of samples	Dissolved oxygen (mg/L)		Dissolved organic carbon (mg/L)		Dissolved ammonia + organic N (mg/L)		Dissolved nitrate (mg/L)		Total phosphorus (mg/L)	
		Range	Median	Range	Median	Range	Median	Range	Median	Range	Median
Year 2000											
Bear Creek	5	6.5–10.2	8.5	2.1–8.3	3.0	0.2–0.72	0.38	1.9–2.9	2.6	0.06–0.24	0.12
Middle Swamp	11	0.7–10.7	3.4	5.5–20	14	0.53–1.1	0.84	0.02–0.61	0.04	0.11–0.60	0.35
Year 2001											
Bear Creek	8	6.6–10.3	8.6	2.3–6.5	3.2	0.2–0.57	0.34	1.8–3.0	2.6	0.05–0.17	0.08
Middle Swamp	12[a]	2.7–10.2	4.1	9.9–17	12	0.40–1.1	0.71	0.02–0.40	0.05	0.12–0.44	0.25

[a] Only nine samples were analyzed for dissolved organic carbon.

vegetation within a 50-ft zone on each side of the streams in each watershed. Approximately 42 percent of the area within the 50-ft zone for Bear Creek contained riparian vegetation, including such things as trees and shrubs but not grassland, compared to 60 percent for Middle Swamp. This difference between watersheds may be an important factor in controlling both water and nutrient fluxes through the watershed, especially in areas where the water table is near land surface. Where the water table is within 15 ft of land surface, tree roots can take up nitrate or bacteria can reduce nitrate by using carbon, which may be derived either from vegetation as a leachate (Thurman, 1985) or as organic material in aquifer sediments (Speiran, 1996; Korom, 1992). This information, along with the previously discussed data from flow-path study sites 1–5, indicate that the extent of riparian buffers along a stream have an important effect on the amount of nitrate discharged in ground water to the stream.

General hydrologic information from watersheds can be useful in identifying basins that likely have elevated nutrient transport resulting from ground-water discharge. For example, using nutrient-yield data for the 14 streams presented in Spruill and others (2005), it was determined that the nutrient yields had a significant positive correlation to water yields from the watersheds (Spearman $\rho = 0.59$, $p < 0.025$, $n = 14$). Because a significant relation was detectable, increased water yields should result in increased nutrient yields for similar basin nutrient-loading rates. Therefore, knowledge of annual variations in water yields coupled with information on other hydrologic variables, such as evapotranspiration, depth to ground water, and hydraulic conductivity, may be used to categorize streams based on estimated nutrient yields.

Streamflow is the surrogate variable that integrates many of the hydrologic processes occurring within a watershed, and annual water yields are loosely related to annual precipitation amounts. Linear regression analysis was conducted between annual precipitation and annual water yields (fig. 12) for three watersheds in the Neuse River basin (fig. 1). Regression of available data for Bear Creek (1988–2005), Middle Swamp (2000–2004), and Plum Tree Branch (2000, 2003, and 2004) indicates that the ratios of water yield to annual precipitation are greater for Middle Swamp and Plum Tree Branch, both lower water- and nutrient-yield watersheds, than for Bear Creek, the higher water- and nutrient-yield watershed. These relations indicate that transport from Bear Creek will be relatively higher during low flows compared with transport from the more sluggish Middle Swamp and Plum Tree Branch streams, possibly reflecting the larger amount of base flow in Bear Creek during the summer and fall months (fig. 11).

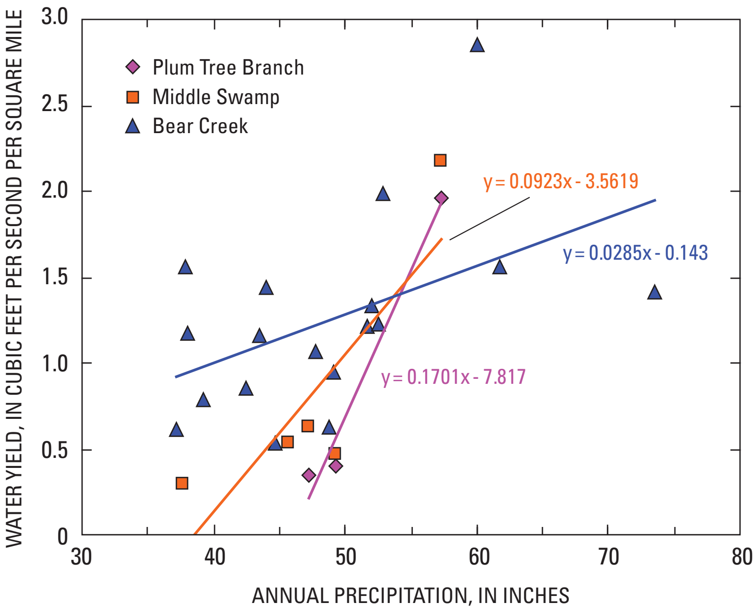

Figure 12. Relation between annual precipitation and water yield for Plum Tree Branch, Middle Swamp, and Bear Creek in the North Carolina Coastal Plain.

The smaller amount of base flow in Middle Swamp and Plum Tree Branch during summer and fall is presumably because of the greater evapotranspiration that occurs in the more extensive riparian buffers and wetlands associated with these watersheds.

The regression plots also indicate that water yields in swamp-type watersheds such as Middle Swamp may be higher during wetter years with increased precipitation when compared to water yields from Bear Creek. In any case, many flow statistics, such as flow duration, 7-day low flow, days of no flow, percentage of base flow, etc., that reflect differences in hydrologic conditions could be useful in identifying watersheds that pose high water-quality degradation potential and watersheds that are effective in processing nitrogen. This brief analysis of data indicates that streamflow statistics are a useful way to identify watersheds that are likely to be high exporters of nutrients. Further study will be needed to more fully evaluate the potential of this approach for identifying watersheds that are most likely to export nitrogen from nonpoint-source pollution in the North Carolina Coastal Plain.

Summary and Conclusions

The transport of nitrate in ground water from agricultural fields to receiving streams in the North Carolina Coastal Plain is influenced by various environmental, hydrogeologic, and geochemical factors. At five study sites, denitrification was the most common factor responsible for decreases in nitrate along the ground-water flow paths. Some additional factors that appeared to influence ground-water nitrate concentrations along the flow paths or at the streams include soil drainage, presence or absence of riparian buffers, evapotranspiration, fertilizer use, ground-water recharge rates and residence times, aquifer properties, subsurface tile drainage, sources and amounts of organic matter, and hyporheic processes.

Nitrate-reducing processes differed among the field, buffer, and hyporheic zones. Ground-water nitrate concentrations at the upgradient and downgradient edges of each zone were used to examine the relative capacity of each zone to process nitrate. Nitrate reduction in ground water beneath the agricultural fields and upgradient from the riparian buffers ranged from 4 to 54 percent at well-drained sites and from 61 to 87 percent at poorly drained sites. The poorly drained fields appear to have a higher capacity for reducing nitrate, possibly reflecting increased denitrification and vegetative uptake because of the longer residence times associated with the slower infiltration rates in soils at these sites. The most substantial nitrate reduction along the ground-water flow paths occurred in the riparian buffer zone and the hyporheic zone at the stream. At three sites, the amount of nitrate entering the buffer zone was almost entirely reduced (>98 percent) in that no nitrate was present in the hyporheic zones. At other sites, the hyporheic zone had nitrate reductions ranging from 49 to 90 percent, indicating a significant capacity to lower the amount of nitrate discharged in ground water to streams.

The study data indicate that the nitrate-reducing capacity of the buffer zone combined with that of the hyporheic zone can substantially lower the amount of ground-water nitrate discharged to streams in agricultural settings of the North Carolina Coastal Plain. In some cases, nitrate can move through transmissive layers rapidly so that the ground-water residence time is too short to allow complete reduction of the nitrate before discharging to a stream. Relatively young ground water may move along shallow flow paths in the upper portion of the water table, and discharge may occur along seeps or channel walls that bypass the highly organic fluvial material in the hyporheic zone. If this water contains nitrate that has moved through the riparian buffer, it can affect the nitrate concentration in the receiving stream.

At the watershed scale, the effects of ground-water discharge on surface-water quality appear to be influenced greatly by streamflow conditions and the presence of extensive riparian vegetation. A comparison of the Bear Creek and Middle Swamp watersheds indicates that although these watersheds are similar in size and land use, the capacity of each watershed to process nitrogen differs. Between 2000 and 2001, the water yield from Bear Creek was approximately two times the water yield from Middle Swamp, and the nitrogen yield was 5 to 10 times higher in Bear Creek than Middle Swamp. The lower velocity and more geochemically reduced conditions in Middle Swamp are less conducive for nitrate export than in the higher velocity and more oxidizing conditions observed in the Bear Creek watershed. More extensive riparian vegetative cover also was noted along the stream reach in Middle Swamp (60 percent) than in Bear Creek (42 percent), indicating that the difference in riparian buffers between watersheds may be an important factor in controlling both water and nutrient fluxes through the watersheds.

Flow statistics that reflect base flow and general hydrologic dynamics of a stream provide important data for understanding nutrient transport from a watershed. Additional information on the influential nitrate-reduction factors described for the flow-path sites is needed at watershed scales to better evaluate nutrient transport throughout the Coastal Plain. Combining streamflow statistics with information on such things as land use, soil drainage, extent of riparian vegetation, geochemical conditions, and subsurface tile drainage in the North Carolina Coastal Plain could be useful in identifying watersheds that are most likely to export nitrogen from nonpoint-source pollution, as well as watersheds that are effective in processing nitrogen.

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Appendix Tables

Table A1. Data available for stations included in the flow-path studies in the North Carolina Coastal Plain and watershed comparisons.

USGS site number	Local field name	Web address
Flow path Site 1: Ground-water stations		
352835078181801	JC-1	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352835078181801
352835078181802	JC-2	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352835078181802
352833078181601	JC-5	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352833078181601
352833078181602	JC-6	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352833078181602
352833078181603	JC-7	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352833078181603
352834078181401	JC-8	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352834078181401
352834078181402	JC-Temp	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352834078181402
352833078181604	Bedwell	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352833078181604
Flow path Site 1: Surface-water station		
352833078181605	Stream	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=352833078181605
Flow path Site 2: Ground-water stations		
354603077293301	PM-1	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354603077293301
354603077293302	PM-2	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354603077293302
354602077293401	PM-3	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354602077293401
354602077293402	PM-4	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354602077293402
354601077293612	LBI	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293612
354601077293611	LBS	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293611
354601077293614	RBI	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293614
354601077293613	RBS	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293613
354601077293602	1I	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293602
354601077293601	1S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293601
354601077293604	2I	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293604
354601077293603	2S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293603
354601077293605	2D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293605
354601077293607	3I	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293607
354601077293606	3S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293606
354601077293608	Seep 1	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293608
354601077293609	Seep 2	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293609
354601077293610	Seep 3	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=354601077293610
Flow path Site 2: Surface-water station		
02083833	Stream	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=02083833
Flow path Site 3: Ground-water stations		
353056077551801	TB-1	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353056077551801
353056077551802	TB-2	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353056077551802
353049077551601	TB-3	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353049077551601
353053077551702	TB-5	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353053077551702
353053077551703	TB-6	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353053077551703
353056077551803	TB-9	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353056077551803
353053077551701	TB-10	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353053077551701
353049077551901	P2	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353049077551901
353049077551602	Bedwell	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353049077551602
Flow path Site 3: Surface-water station		
353049077551603	Stream	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=353049077551603
Flow path Site 4: Ground-water stations		
352439077531001	JP-1	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352439077531001
352439077531002	JP-2	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352439077531002
352436077525501	JP-4	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352436077525501
352436077525502	JP-5	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352436077525502
352438077525801	JP-6	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352438077525801
352434077525301	Bedwell	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=352434077525301
Flow path Site 4: Surface-water station		
352434077525302	Stream	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=352434077525302

Table A1. Data available for stations included in the flow-path studies in the North Carolina Coastal Plain and watershed comparisons. — Continued

USGS site number	Local field name	Web address
Flow path Site 5: Ground-water stations		
353103077333407	L2M	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353103077333407
353103077333402	L2D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353103077333402
353103077333403	L3	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353103077333403
353122077334904	L4S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353122077334904
353122077334903	L4D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353122077334903
353111077334402	L6	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353111077334402
353111077334404	L6D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353111077334404
353142077332702	L8S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353142077332702
353142077332703	L8D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353142077332703
353148077332103	L11S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353148077332103
353148077332102	L11D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353148077332102
353127077333702	L15	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353127077333702
353127077333703	L15S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353127077333703
353127077333705	L15M	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353127077333705
353127077333704	L15D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353127077333704
353135077332704	L18D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353135077332704
353050077333402	L24	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353050077333402
353114077333101	L70S	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077333101
353114077333102	L70D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077333102
353137077334604	GR-148	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353137077334604
353137077334605	GR-149	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353137077334605
353153077333203	GR-151	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353153077333203
353153077333204	GR-152	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353153077333204
353153077333206	GR-153	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353153077333206
353114077334801	PT1-1A	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334801
353114077334802	PT1-1B	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334802
353114077334803	PT1-1C	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334803
353115077334901	PT1-2A	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353115077334901
353115077334902	PT1-2B	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353115077334902
353115077334903	PT1-2C	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353115077334903
353114077334901	PT1-3A	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334901
353114077334902	PT1-3B	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334902
353114077334903	PT1-3C	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334903
353114077334904	PT1-3D	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077334904
353114077335001	PT1-4A	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077335001
353114077335002	PT1-5B	http://waterdata.usgs.gov/nc/nwis/gwsi/?site_no=353114077335002
Flow path Site 5: Surface-water stations		
0209173190	(S2) Unnamed trib to Sandy Run near Lizzie	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=0209173190
0209173200	(S4) Sandy Run near Lizzie	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=0209173200
0209173150	(S7) Unnamed trib to Sandy Run at SR1335 near Lizzie	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=0209173150
Watersheds: Surface-water stations		
02091736	(S5) Middle Swamp near Farmville	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=02091736
0208925200	Bear Creek at Mays Store	http://waterdata.usgs.gov/nc/nwis/inventory/?site_no=0208925200

Table A2. Summary of analytical data (November 1997–February 1999) for water samples collected at site 1 in the Neuse River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; —, not applicable; <, less than; P, phosphorus; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	Stream	Streambed Piezometer	JC-7	JC-Temp	JC-8	JC-5	JC-6	JC-1	JC-2
Nitrate (mg/L as N)									
Median	0.6	0.04	0.02	11.0	12.0	12.8	10.2	13.0	11.0
Range	0.01 – 1.1	0.01 – 0.25	0.01 – 0.05	—	6.0 – 13.0	12.0 – 13.0	6.6 – 13.0	0.11 – 14.0	7.7 – 13.0
Number of samples	8	4	10	1	5	10	10	8	9
Ammonia (mg/L as N)									
Median	0.04	0.04	0.13	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Range	<0.01 – 0.10	<0.01 – 0.13	<0.02 – 0.21	—	<0.01 – 0.07	<0.01 – 0.05	<0.01 – 0.21	<0.01 – 0.09	<0.01 – 0.09
Number of samples	8	4	10	1	5	10	10	8	9
Dissolved phosphorus (mg/L as P)									
Median	0.05	<0.01	0.01	0.04	0.01	<0.01	<0.01	<0.01	<0.01
Range	0.01 – 0.13	<0.01 – 0.03	<0.01 – 0.06	—	0.01 – 0.04	<0.01 – 0.02	<0.01 – 0.06	<0.01 – 0.04	<0.01 – 0.04
Number of samples	8	4	10	1	5	10	10	8	9
Dissolved organic carbon (mg/L)									
Median	14.5	8.3	8.5	0.5	0.3	0.3	0.7	0.4	0.3
Range	8.6 – 19	—	5.6 – 9.5	—	<0.1 – 2.6	<0.1 – 0.3	<0.1 – 18	0.3 – 0.4	<0.1 – 0.4
Number of samples	4	1	5	1	5	6	5	4	5
Dissolved iron (µg/L)									
Median	2,200	3,910	4,750	74	<50	<50	59	<50	<50
Range	273 – 5,400	—	4,200 – 6,940	—	<10 – 82	<10 – 62	<10 – 2,000	<3 - 55	<10 – 110
Number of samples	4	1	6	1	5	6	6	4	5
Dissolved oxygen (mg/L)									
Median	6.0	2.8	0.2	7.6	8.4	8.1	4.4	7.9	7.9
Range	0.6 – 10.8	1.3 – 8.3	<0.1 – 0.7	—	5.2 – 8.8	7.5 – 9.0	2.0 – 7.4	7.1 – 9.3	7.1 – 9.3
Number of samples	8	4	10	1	5	9	10	9	9
Excess N_2 (mg/L)									
Concentration[a]	nd	nd	2.6	nd	nd	nd	1.5[b]	nd	nd

[a] Concentrations of excess nitrogen were measured during January – February 1999.

[b] Excess N_2 value is for a sample collected from well JC-4, which is similar in depth and location along the field edge to well JC-6 (figs. 3, 4).

Table A3. Summary of analytical data (December 1997 – February 1999) for water samples collected at site 4 in the Neuse River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; <, less than; P, phosphorus; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	JP-1	JP-2	JP-6	JP-4	JP-5	Streambed piezometer	Stream
Nitrate (mg/L as N)							
Median	<0.01	7.6	3.0	<0.01	0.05	0.01	0.7
Range	<0.01 – 0.06	5.2 – 8.2	0.42 – 7.9	<0.01 – 0.05	<0.01 – 0.51	<0.01 – 0.05	0.1 – 1.7
Number of samples	11	12	10	12	7	9	10
Ammonia (mg/L as N)							
Median	<0.01	<0.01	<0.01	0.03	<0.01	0.2	0.16
Range	<0.01 – 0.05	<0.07 – 0.18	<0.01 – 0.04	<0.01 – 0.07	<0.01 – 0.06	0.07 – 1.9	<0.01 – 1.0
Number of samples	11	12	10	12	7	9	10
Dissolved phosphorus (mg/L as P)							
Median	0.98	<0.01	<0.01	0.60	0.10	0.75	0.12
Range	0.58 – 1.0	<0.01 – 0.06	<0.01 – 0.03	0.38 – 0.67	0.06 – 0.28	0.13 – 1.7	0.05 – 0.23
Number of samples	11	12	10	12	7	9	10
Dissolved organic carbon (mg/L)							
Median	0.3	0.5	0.6	0.3	1.8	0.5	6.8
Range	<0.1 – 0.4	<0.1 – 0.6	<0.1 – 1.5	<0.1 – 0.5	1.6 – 3.1	<0.1 – 2.9	4.7 – 9.4
Number of samples	7	7	6	7	3	5	6
Dissolved iron (µg/L)							
Median	2,060	<50	<50	695	<50	1,230	315
Range	520 – 2,100	<10 – 1,900	<50 - 50	530 - 940	<50 – 593	440 – 2,900	200 – 870
Number of samples	7	7	6	8	3	5	6
Dissolved oxygen (mg/L)							
Median	0.3	7.2	1.1	0.2	1.0	0.3	7.8
Range	0.1 – 3.7	6.5 – 8.5	0.4 – 3.0	<0.1 – 7.1	<0.1 – 9.0	<0.1 – 3.7	4.7 – 12.9
Number of samples	11	12	9	9	8	10	10
Excess N_2 (mg/L)							
Concentration[a]	nd	1.0	nd	nd	1.1	2.4	nd

[a] Concentrations of excess N_2 were measured during February 1999.

Table A4. Summary of analytical data (April 1998–May 1999) for water samples collected at site 2 in the Tar-Pamlico River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; <, less than; P, phosphorus; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	PM-1	PM-2	PM-4	PM-3	Streambed piezometer 2S	Stream
Nitrate (mg/L as N)						
Median	5.5	9.4	6.8	0.03	2.0	3.8
Range	2.3 – 7.8	7.7 – 11.0	6.0 – 9.0	0.01 – 4.9	0.01 – 8.1	2.3 – 5.4
Number of samples	6	6	5	5	6	6
Ammonia (mg/L as N)						
Median	<0.01	<0.01	<0.01	0.09	0.02	<0.01
Range	<0.01 – 0.19	<0.01 – 0.04	<0.01 – 0.04	<0.01 – 0.24	0.01 – 0.16	<0.01 – 0.02
Number of samples	6	6	5	5	6	6
Dissolved phosphorus (mg/L as P)						
Median	<0.01	<0.01	<0.01	<0.01	0.04	<0.01
Range	<0.01 – 0.02	<0.01 – 0.01	<0.01 – 0.01	<0.01 – 0.02	0.01 – 0.05	<0.01 – 0.04
Number of samples	6	6	5	5	6	6
Dissolved organic carbon (mg/L)						
Median	1.5	1.7	1.2	15.0	2.0	3.0
Range	0.5 – 1.7	0.7 – 1.8	0.4 – 1.4	4.9 – 19.0	1.3 – 2.2	2.3 – 3.6
Number of samples	5	5	5	5	4	6
Dissolved iron (µg/L)						
Median	85	<50	250	5,100	106	<50
Range	<50 - 820	<50 – 140	73 – 270	220 – 7,000	<50 – 670	<50 – 230
Number of samples	6	6	5	5	6	6
Dissolved oxygen (mg/L)						
Median	0.2	2.0	1.4	<0.1	<0.1	9.2
Range	0.1 – 1.7	0.2 – 6.6	1.1 – 3.7	<0.1 – 1.0	<0.1 – 0.4	5.6 – 10.5
Number of samples	6	6	5	5	7	8
Excess N_2 (mg/L)						
Concentration[a]	5.1	0.8	3.5	2.8	7.2	nd

[a] Concentrations of excess N_2 were measured during February 1999.

Table A5. Summary of analytical data (June–July 1998) for water samples from the stream transect at site 2 in the Tar-Pamlico River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Site	Date	Nitrate (mg/L as N)	Ammonia (mg/L as N)	Dissolved phosphorus (mg/L as P)	Dissolved organic carbon (mg/L)	Dissolved iron (µg/L)	Dissolved oxygen (mg/L)	Excess N_2 (mg/L)[a]
PM-4	07/30/98	9.0	0.04	<0.01	1.3	260	3.7	nd
PM-3	07/30/98	0.05	0.24	<0.01	7.3	3,600	1.0	nd
LBS	07/01/98	4.0	<0.01	0.04	1.9	200	<0.1	nd
LBI	07/01/98	5.8	<0.01	0.04	1.3	<50	1.3	nd
1S	06/30/98	7.2	<0.01	0.02	2.2	<50	0.4	2.5
1I	06/30/98	<0.01	1.6	0.08	2.8	<50	0.2	4.9
2S	06/30/98	8.1	0.02	0.03	2.2	<50	0.4	7.2
2I	06/30/98	<0.01	3.2	0.25	3.6	230	<0.1	nd
2D	06/30/98	0.02	0.13	0.02	1.6	2,400	<0.1	nd
3S	06/30/98	11.0	0.04	0.04	2.0	<50	0.3	nd
3I	06/30/98	0.38	0.2	0.03	1.7	1,000	nd	nd
RBS	07/01/98	16.0	0.03	0.04	1.7	<50	0.8	nd
RBI	07/01/98	7.1	<0.01	0.05	2.0	<50	0.1	nd
Seep1	06/30/98	2.0	0.44	0.04	4.0	990	1.4	nd
Seep2	06/30/98	2.0	0.09	0.04	4.0	110	1.3	nd
Seep3	06/30/98	5.8	0.02	0.05	2.6	<50	2.0	nd
Stream	06/30/98	5.0	0.02	0.04	2.7	<50	6.9	nd

[a] Concentrations of excess N_2 were measured during February 1999.

Table A6. Summary of analytical data (November 1997–March 1999) for water samples collected at site 3 in the Neuse River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than; —, not applicable; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	TB-2	TB-1	TB-9	TB-6	TB-5	TB-10	P2	TB-3	Streambed piezometer	Stream
Nitrate (mg/L as N)										
Median	0.50	4.4	4.8	5.4	<0.01	5.4	0.81	0.02	0.04	0.87
Range	<0.01 – 1.6	3.9 – 4.9	4.7 – 4.9	5.3 – 5.6	<0.01 – 0.04	5.0 – 5.8	0.02 – 6.8	<0.01 – 0.05	<0.01 – 5.5	<0.01 – 1.7
Number of samples	10	11	2	2	9	9	10	10	10	10
Ammonia (mg/L as N)										
Median	0.03	<0.01	0.02	0.02	0.03	<0.01	0.02	0.04	0.53	0.44
Range	<0.01 – 0.07	<0.01 – 0.06	<0.01 – 0.02	<0.01 – 0.03	<0.01 – 0.06	<0.01 – 0.03	<0.01 – 14.0	<0.01 – 0.07	<0.02 – 4.6	0.04 – 2.9
Number of samples	10	11	2	2	9	9	10	10	10	10
Dissolved phosphorus (mg/L as P)										
Median	0.05	0.04	0.09	0.04	0.03	0.02	0.02	0.05	0.48	0.04
Range	0.01 – 0.07	<0.01 – 0.09	0.07 – 0.11	0.01 – 0.06	<0.01 – 0.05	<0.01 – 0.07	<0.01 – 1.5	<0.01 – 0.1	<0.01 – 0.95	0.01 – 0.47
Number of samples	10	10	2	2	9	9	10	10	10	10
Dissolved organic carbon (mg/L)										
Median	0.6	1.2	0.6	<0.1	0.6	0.3	5.8	0.4	3.7	8.1
Range	0.1 – 0.7	0.1 – 1.8	—	—	<0.1 – 1.3	<0.1 – 0.4	3.6 – 9.4	0.1 – 0.9	1.1 – 8.6	6.3 – 10.0
Number of samples	6	6	1	1	5	5	6	5	6	6
Dissolved iron (µg/L)										
Median	<50	53	<10	<50	<50	<50	168	730	5,200	920
Range	<50 – 77	<10 – 82	—	—	<50 – 55	<50 – 62	39 – 2,000	240 - 1,100	1,300 – 15,000	490 – 1,100
Number of samples	6	6	1	1	5	5	6	6	6	6
Dissolved oxygen (mg/L)										
Median	0.8	1.8	1.4	4.4	1.9	4.7	1.0	0.5	1.0	5.4
Range	0.1 – 8.0	0.8 – 2.7	0.9 – 2.0	4.4 – 4.5	0.3 – 4.0	3.0 – 5.5	0.3 – 5.7	0.1 – 1.3	0.4 – 2.8	3.0 – 11.6
Number of samples	10	11	2	2	9	9	10	10	7	9
Excess N_2 (mg/L)										
Concentration[a]	nd	1.0	nd	nd	nd	nd	nd	nd	3.7	nd

[a] Concentrations of excess N_2 were measured during March 1999.

Table A7. Summary of analytical data (January 1999–October 2003) for water samples collected at site 5 in the Neuse River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than; —, not applicable; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	L2M	L2D	L3	L4S	L4D	L6	L6D	L8S	L8D	L11S
Nitrate (mg/L as N)										
Median	6.2	1.0	0.05	19.2	20.0	41.3	0.12	11.5	6.5	5.2
Range	5.6 – 6.2	0.15 – 1.3	<0.02 – 0.07	17.9 – 27.1	8.5 – 27.4	32.4 – 56.1	<0.01 – 0.25	9.4 – 12.0	3.3 – 9.3	2.6 – 19.6
Number of samples	3	13	3	6	24	19	16	7	7	12
Ammonia (mg/L as N)										
Median	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Range	<0.04 – 0.06	<0.02 – 0.04	<0.04 – 0.04	<0.02 – 0.05	<0.02 – 0.4	0.02 – 0.56	0.01 – 0.04	<0.04	<0.02 – 0.04	<0.04
Number of samples	3	13	3	6	19	14	11	7	7	12
Dissolved phosphorus (mg/L as P)										
Median	<0.01	0.02	0.08	0.18	0.02	0.02	<0.01	0.05	0.70	0.02
Range	<0.01	0.01 – 0.03	0.01 – 0.14	0.08 – 0.31	<0.02 – 0.04	0.01 – 0.03	<0.02	0.03 – 0.06	0.59 – 0.78	0.02 – 0.03
Number of samples	3	10	2	6	12	8	6	6	6	7
Dissolved organic carbon (mg/L)										
Median	0.8	0.5	<0.3	1.4	1.0	2.0	0.3	0.4	0.4	0.6
Range	--	0.1 – 0.8	<0.3	1.1 – 2.0	0.7 – 1.4	0.6 – 3.2	<0.1 – 0.4	0.2 – 0.6	0.3 – 0.7	<0.1 – 0.7
Number of samples	1	8	3	6	9	8	7	7	7	9
Dissolved iron (µg/L)										
Median	26	408	5,320	23	122	38	701	12	10	<10
Range	14 – 27	170 – 1,500	4,800 – 5,690	9 – 29	21 – 2,500	5 – 286	535 – 1,050	6 – 54	6 – 112	<10 – 20
Number of samples	3	13	3	6	15	14	11	7	7	12
Dissolved oxygen (mg/L)										
Median	5.5	0.6	0.2	4.2	3.1	1.3	0.3	6.7	1.9	4.0
Range	5.3 – 7.2	0.3 – 1.5	0.1 – 0.7	2.5 – 5.4	0.7 – 6.5	0.5 – 6.0	0.1 – 1.2	3.8 – 8.6	1.2 – 5.3	1.4 – 5.8
Number of samples	3	13	3	6	24	19	16	7	7	12
Excess N_2 (mg/L)										
Concentration[a]	nd	2.1	1.8	nd	nd	nd	3.6	<1	1.9	0.4

Table A7. Summary of analytical data (January 1999 – October 2003) for water samples collected at site 5 in the Neuse River basin, North Carolina. — Continued

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than; —, not applicable; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	L11D	L15	L15S	L15M	L15D	L18D	L24	L70S	L70D
Nitrate (mg/L as N)									
Median	7.7	12.6	3.6	9.9	2.8	0.5	<0.05	89.8	19.4
Range	4.3 – 9.3	11.6 – 26.6	0.2 – 8.1	9.3 – 12.6	0.8 – 4.2	0.25 – 1.5	<0.05	80.5 – 96.3	16.2 – 19.9
Number of samples	8	3	4	3	9	5	2	4	4
Ammonia (mg/L as N)									
Median	<0.04	<0.04	0.08	<0.04	<0.04	<0.02	0.04	<0.04	0.04
Range	<0.04	<0.04	<0.04 – 0.37	<0.04 – 0.06	<0.01 - <0.04	<0.04	0.03 – 0.05	0.02 – 0.06	0.02 – 0.04
Number of samples	8	3	4	3	9	5	2	4	4
Dissolved phosphorus (mg/L as P)									
Median	0.05	0.02	0.04	<0.01	0.02	0.15	0.06	<0.01	<0.01
Range	0.04 – 0.07	0.02	0.01 – 0.10	<0.01	0.01 – 0.14	0.10 – 0.17	--	<0.01	<0.01
Number of samples	7	2	4	3	8	4	1	3	3
Dissolved organic carbon (mg/L)									
Median	0.4	0.7	6.1	1.1	0.3	0.4	3.2	2.6	0.7
Range	<0.1 – 0.6	0.7 – 1.5	4.0 – 8.2	--	<0.1 – 0.6	<0.1 – 0.6	2.6 – 3.7	2.5 – 2.6	0.7
Number of samples	8	3	2	1	7	5	2	3	3
Dissolved iron (µg/L)									
Median	<10	21	912	35	49	21	1,484	46	116
Range	7 – 14	20 – 21	87 – 3,300	21 – 159	19 – 260	7 – 112	158 – 2,810	40 – 100	102 – 211
Number of samples	8	3	4	3	9	4	2	4	4
Dissolved oxygen (mg/L)									
Median	4.4	1.6	2.4	1.9	1.1	2.2	0.8	6.8	0.7
Range	3.7 – 4.7	1.2 – 1.7	1.0 – 4.1	1.8 – 2.4	0.3 – 2.3	1.6 – 2.6	0.5 – 1.0	3.8 – 11.0	0.5 – 0.8
Number of samples	8	3	4	3	9	4	2	4	4
Excess N_2 (mg/L)									
Concentration[a]	<1	nd	nd	nd	7.0	nd	nd	nd	nd

Table A7. Summary of analytical data (January 1999–October 2003) for water samples collected at site 5 in the Neuse River basin, North Carolina. — Continued

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than; —, not applicable; µg/L, microgram per liter; nd, no data; N_2, nitrogen gas]

Statistical measure	GR-148	GR-149	GR-151	GR-152	GR-153	S2	S4	S7
Nitrate (mg/L as N)								
Median	<0.05	<0.05	<0.05	<0.05	<0.05	3.8	0.10	3.6
Range	<0.05	<0.05	<0.02 – 0.05	<0.05	<0.06	<0.02 – 9.0	<0.02 – 1.0	<0.02 – 8.6
Number of samples	2	2	9	9	7	46	40	44
Ammonia (mg/L as N)								
Median	0.21	0.30	0.60	0.2	1.61	1.32	0.07	0.07
Range	0.13 – 0.30	0.29 – 0.30	0.10 – 9.42	0.05 – 15	1.47 – 2.17	0.07 – 6.8	<0.01 – 0.87	0.02 – 0.43
Number of samples	2	2	9	9	7	45	40	43
Dissolved phosphorus (mg/L as P)								
Median	0.18	0.12	0.87	0.89	0.78	<0.02	0.17	<0.02
Range	0.02 – 0.34	0.11 – 0.13	0.83 – 1.15	0.77 – 3.5	0.67 – 0.89	<0.01 – 0.15	<0.02 – 0.49	0.01 – 0.27
Number of samples	2	2	5	5	2	45	40	43
Dissolved organic carbon (mg/L)								
Median	3.2	4.3	2.2	2.7	8.5	7.2	15.5	5.5
Range	2.6 – 3.7	3.0 – 5.6	1.1 – 9.4	2.0 - 18	8.5 – 17.3	3.0 – 24	9.3 – 23	1.6 – 29
Number of samples	2	2	5	4	3	29	28	25
Dissolved iron (µg/L)								
Median	10,200	8,185	90	44	6,210	492	1,050	420
Range	6,100 – 14,300	6,970 – 9,400	15 – 1,070	19 – 18,900	5,700 – 11,300	110 – 5,440	151 – 5,180	67 – 5,900
Number of samples	2	2	9	9	7	43	40	41
Dissolved oxygen (mg/L)								
Median	1.1	0.3	0.2	0.2	0.1	6.2	3.1	5.2
Range	--	--	0.1 – 1.0	0.2 – 0.4	0.1 – 0.4	0.1 – 10.5	0.1 – 11.4	0.4 – 9.8
Number of samples	1	1	9	8	7	46	37	44
Excess N_2 (mg/L)								
Concentration[a]	2.1	nd	nd	nd	nd	nd	nd	nd

[a] Concentrations of excess N_2 were measured during May-June 1999.

Table A8. Summary of analytical data (March–October 2006) for water samples collected along the buffer transect at site 5 in the Neuse River basin, North Carolina.

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; —, not applicable; <, less than; µg/L, microgram per liter]

Statistical measure	L6	PT1-1A	PT1-1B	PT1-1C	PT1-2A	PT1-2B	PT1-2C	PT1-3A
Nitrate (mg/L as N)								
Median	41.9	18.8	16.0	8.5	26.4	26.0	25.2	6.8
Range	37.1 – 51.6	17.4 – 19.4	12.2 – 19.7	7.7 – 11.2	26.0 – 27.3	25.6 – 27.5	24.5 – 29.9	6.4 – 14.6
Number of samples	3	3	3	3	3	3	3	3
Ammonia (mg/L as N)								
Median	0.08	0.29	0.03	0.03	0.02	0.02	0.01	0.03
Range	0.06 – 0.12	<0.04 – 0.36	0.02 - <0.04	0.02 - <0.04	0.02 - <0.04	0.01 - <0.04	0.01 - <0.04	0.01 – 0.03
Number of samples	3	3	3	3	3	3	3	3
Dissolved phosphorus (mg/L as P)								
Median	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Range	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Number of samples	3	3	3	3	3	3	3	3
Dissolved organic carbon (mg/L)								
Median	3.3	1.3	0.7	0.7	0.9	0.8	0.9	3.7
Range	--	--	--	--	--	--	--	--
Number of samples	1	1	1	1	1	1	1	1
Dissolved iron (µg/L)								
Median	45	10	<6	4	7	5	5	41
Range	--	--	--	--	--	--	--	--
Number of samples	1	1	1	1	1	1	1	1
Dissolved oxygen (mg/L)								
Median	0.2	3.4	4.3	3.2	6.3	6.8	6.3	1.4
Range	0.1 – 0.3	3.2 – 3.7	3.8 – 4.8	2.7 – 4.0	5.4 – 6.4	5.7 – 6.8	5.5 – 6.5	1.1 – 2.5
Number of samples	2	3	3	3	3	3	3	3

Table A8. Summary of analytical data (March–October 2006) for water samples collected along the buffer transect at site 5 in the Neuse River basin, North Carolina. — Continued

[mg/L, milligram per liter; N, nitrogen; P, phoshporus; —, not applicable; <, less than; µg/L, microgram per liter]

Statistical measure	PT1-3B	PT1-3C	PT1-3D	PT1-4A	PT1-5B	S2	S7
Nitrate (mg/L as N)							
Median	1.7	<0.06	<0.06	1.6	<0.06	6.1	2.1
Range	0.16 – 1.8	0.04 – 0.59	<0.06	<0.06 – 2.3	<0.06	2.0 – 10.7	1.1 – 9.6
Number of samples	3	3	3	3	3	28	27
Ammonia (mg/L as N)							
Median	<0.04	0.07	<0.04	0.06	0.06	0.76	0.06
Range	0.01 – 0.06	0.06 – 0.09	0.02 – 0.06	<0.04 – 3.33	0.05 – 0.06	0.09 – 2.38	<0.02 – 0.59
Number of samples	3	3	3	3	3	28	27
Dissolved phosphorus (mg/L as P)							
Median	0.01	0.50	0.61	0.02	0.81	0.05	0.08
Range	0.01	0.41 – 0.65	0.59 – 0.63	0.02 – 0.64	0.69 – 0.93	0.01 – 0.29	0.01 – 0.42
Number of samples	3	3	3	3	3	28	27
Dissolved organic carbon (mg/L)							
Median	0.7	1.1	0.3	12.8	1.1	14.9	14.8
Range	--	--	--	--	--	--	--
Number of samples	1	1	1	1	1	1	1
Dissolved iron (µg/L)							
Median	485	3,240	1,380	15,400	2,460	305	284
Range	--	--	--	--	--	--	--
Number of samples	1	1	1	1	1	1	1
Dissolved oxygen (mg/L)							
Median	1.4	3.1	1.5	1.3	4.8	5.7	5.6
Range	0.7 – 2.1	2.5 – 3.9	0.7 – 2.3	1.3 – 2.4	4.0 – 5.5	5.3 – 6.1	5.5 – 5.8
Number of samples	3	3	3	3	2	2	2

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