

## Statistical Evaluation of Effects of Riparian Buffers on Nitrate and Ground Water Quality

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### ABSTRACT

A study was conducted to statistically evaluate the effectiveness of riparian buffers for decreasing nitrate concentrations in ground water and for affecting other chemical constituents. Values for pH, specific conductance, alkalinity, dissolved organic carbon (DOC), silica, ammonium, phosphorus, iron, and manganese at 28 sites in the Contentnea Creek Basin were significantly higher ( $p < 0.10$ ) in old (>20 yr) discharging ground water draining areas with riparian buffers compared with areas without riparian buffers. No differences in chloride, nitrate nitrogen, calcium, sodium, and dissolved oxygen concentrations in old ground water between buffer and nonbuffer areas were detected. Comparison of samples of young (<20 yr) discharging ground water samples from buffer and nonbuffer areas indicated significantly higher specific conductance, calcium, chloride, and nitrate nitrogen in nonbuffer areas. Riparian buffers along streams can affect the composition of the hyporheic zone by providing a source of organic carbon to the streambed, which creates reducing geochemical conditions that consequently can affect the chemical quality of old ground water discharging through it. Buffer zones between agricultural fields and streams facilitate dilution of conservative chemical constituents in young ground water that originate from fertilizer applications and also allow denitrification in ground water by providing an adequate source of organic carbon generated by vegetation in the buffer zone. Based on the median chloride and nitrate values for young ground water in the Contentnea Creek Basin, nitrate was 95% lower in buffer areas compared with nonbuffer areas, with a 30 to 35% reduction estimated to be due to dilution and 65 to 70% due to reduction and/or denitrification.

ESTABLISHING riparian vegetative buffers has been recommended as a means of decreasing nitrate concentrations and other nutrients in subsurface and surface runoff from cultivated fields in the Neuse River Basin in North Carolina (Gilliam et al., 1997). The basis of this recommendation is supported by many studies (e.g., Peterjohn and Correll [1984]; Lowrance et al. [1984]; Jacobs and Gilliam [1985]) that demonstrate the effectiveness of buffers in decreasing nitrate concentrations in ground water. However, these and other studies did not include many different sites distributed over a wide geographical area. Although many studies have been conducted at the field scale and have shown that nitrate reduction can occur beneath forested riparian buffers, no statistical comparisons of *multiple* buffered and unbuffered areas have been made to determine if riparian buffers significantly decrease ground water nitrate nitrogen concentrations at a broader geographical scale.

Evidence suggests that the presence of vegetation in a riparian buffer, per se, is not required to effect nitrate

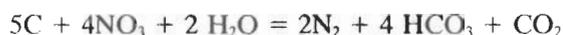
reduction in ground water and that many processes are responsible. McMahon and Bohlke (1996) reported that nitrate reduction in floodplain deposits and bed sediment beneath a Colorado stream was due to denitrification and mixing in the hyporheic zone. Spruill et al. (1997) reported low nitrate nitrogen (all nitrate concentrations in this paper will be reported as nitrate nitrogen) concentrations (median < 0.05 mg L<sup>-1</sup>) in shallow ground water throughout the Outer Coastal Plain of the Albemarle-Pamlico Drainage Basin. The low nitrate nitrogen concentrations were attributed to the presence of DOC in ground water, which acts as an electron donor for denitrifying bacteria that are present in the aquifer. Although many studies indicate that denitrification or plant uptake can significantly reduce nitrate in ground water as it passes beneath riparian buffers, Speiran (1996) identified several factors, independent of the presence of vegetation, which may account for low nitrate concentrations in ground water. The factors associated with nitrate reduction at several sites in the Coastal Plain of Virginia include (i) organic content of the soil through which recharge moves vertically, (ii) hydraulic and organic carbon content of aquifer materials through which ground water moves laterally, and (iii) dilution by low-nitrate waters from deep underlying aquifers or other sources.

Because riparian buffers do not always decrease nitrate concentrations in ground water, questions persist regarding their effectiveness. High concentrations of nitrate nitrogen (>3 to 4 mg L<sup>-1</sup>) have been documented in ground water flowing beneath riparian buffers. Speiran (1996) reported nitrate nitrogen concentrations in excess of 5 mg L<sup>-1</sup> in ground water beneath a riparian zone with coarse-grained low-carbon sediments in the Virginia Coastal Plain. Hamilton et al. (1993), in a study of the Delmarva Peninsula, reported that high nitrate nitrogen concentrations occur at depth in an aquifer recharged from agricultural fields far upgradient from the discharge area. Much of this deep ground water flows beneath riparian buffers before discharging to streams. Bohlke and Denver (1995) concluded that low nitrate nitrogen concentrations in a stream in Maryland were due to nitrate reduction in ground water passing through a subsurface calcareous glauconitic formation located directly beneath a stream rather than due to the buffer zone. They reached this conclusion upon observing high nitrate nitrogen concentrations (9.0 mg L<sup>-1</sup>) in a stream draining an adjacent watershed, which also had riparian buffers, but in which the subsurface formation was well beneath the streambed.

Denitrification and/or nitrate reduction, based on results from several studies referred to in this paper, usu-

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ally is associated with the presence of organic carbon in the soil, aquifer sediments, or water. Organic carbon is required by heterotrophic bacterial denitrification according to the following reaction (Korom, 1992):



Although less commonly discussed in the literature, other mechanisms of denitrification also are possible. For example, where carbon occurs at low concentrations or is not present, nitrate can be reduced by autotrophic reduction whereby iron and other elements can act as electron donors (Korom, 1992). Vegetative uptake of nitrate in ground water also is possible, but is considered to be much less important in decreasing nitrate concentrations in buffer zones than denitrification (Gilliam et al., 1997).

Organic carbon availability, therefore, is considered to be a major requirement for bacterial reduction of nitrate. Pfenning and McMahon (1996) reported that the denitrification potential of riverbed sediments for discharging ground water in Colorado was organic-carbon limited. Obenhuber and Lowrance (1991) reported that nitrate nitrogen concentrations in microcosms that decreased from 12.17 to 5.84 mg L<sup>-1</sup> in response to additions of organic carbon were due to biological denitrification. Nitrate nitrogen concentrations were low in ground water flowing beneath low-transmissivity, organic-carbon-rich sediments in an agricultural field on the eastern shore of Virginia well before passing beneath a riparian buffer (Speiran, 1996), indicating denitrification. Gilliam (1991) reported that nitrate nitrogen concentrations in shallow ground water in the lower Coastal Plain of North Carolina (also referred to as the outer Coastal Plain) are generally low because sufficient organic matter exists in soils in this area to microbially reduce nitrate. Gilliam and Skaggs (1981) reported that water-borne nitrate losses from cultivated organic soils were low (<1 kg ha<sup>-1</sup>) compared with water-borne nitrate losses (40 kg ha<sup>-1</sup>) from cultivated sandy soils with little organic carbon. The low nitrate losses in drainage waters in the lower Coastal Plain were attributed to denitrification in soils having high organic matter. Nitrate nitrogen concentrations greater than 3 mg L<sup>-1</sup> were not found in shallow ground water having more than 2 to 3 mg L<sup>-1</sup> of DOC in the Coastal Plain of the Albemarle-Pamlico Drainage Basin of North Carolina and Virginia (Spruill et al., 1997). Even though nitrogen loading rates were the same for other agricultural areas where corn (*Zea mays* L.) was grown (about 168 kg ha<sup>-1</sup> of nitrogen), the median nitrate nitrogen concentration in shallow ground water of the outer Coastal Plain, which had median DOC concentrations of about 5 mg L<sup>-1</sup>, was low or not detectable (detection level = 0.05 mg L<sup>-1</sup>). This phenomenon was attributed to the presence of saturated soils and DOC and the resulting extensive denitrification throughout the shallow aquifer in the outer Coastal Plain.

The primary purpose of this study was to determine statistically whether the presence of riparian buffers, 30-m-wide or more and composed of lowland hardwood vegetation (typically sweet gum [*Liquidambar styraciflua* L.], cypress [*Taxodium distichum* L.], black willow

[*Salix nigra* Marshall], willow oak [*Quercus phellos* L.], tupelo [*Nyssa sylvatica* L.]), is associated with lower nitrate nitrogen concentrations in discharging ground water that has passed beneath the riparian buffer. The terms riparian buffer, buffer, and vegetative buffer are used interchangeably throughout this paper and refer to this definition. If other mechanisms are important in decreasing nitrate concentrations in ground water (for example denitrification processes that occur in aquifer sediments independent of the presence of a riparian buffer), then the presence of buffers should have no statistically discernible effect on nitrate nitrogen concentrations. Additional chemical constituents also were included in the analysis to discern possible effects of riparian buffers on water quality.

The terminology for ground water in this paper refers to the terms *young* and *old* ground water. *Young* ground water refers to ground water that has traveled from recharge to discharge areas over a period of days to 20 yr in shallow aquifers or the upper meter of an aquifer. *Old* ground water refers to ground water aquifer that has traveled from recharge to discharge areas over a period of more than 20 yr in deep aquifers or deep portions of a shallow aquifer. This terminology is primarily for conceptual purposes and is intended only to reflect relative age of discharging ground water. As will be noted later in this paper, in upland settings with short distances (and therefore with brief ground water travel times) between the ground water divide and the stream, for example, the oldest ground water may be younger than 20 yr old.

## STUDY AREA

The study area is located in the Contentnea Creek Drainage Basin (2538 km<sup>2</sup>) between Wilson and Hookerton, North Carolina, in the Coastal Plain (Fig. 1). Contentnea Creek is a tributary of the Neuse River in the Albemarle-Pamlico Basin. Contentnea Creek has been identified as a major source of both nitrogen and phosphorus loads in the Neuse River Basin (Spruill et al., 1995). More than 50% of land in the basin is used for agriculture, with most of the remaining area forested (36%) or wetland (9%) (McMahon and Lloyd, 1995). Soil types in the basin range from well-drained to moderately drained soils on uplands to poorly drained soils in stream valleys (McMahon and Lloyd, 1995).

Ground water typically provides 50% or more of the streamflow in the Coastal Plain (McMahon and Lloyd, 1995) and it is thought that most ground water discharge is from shallow aquifer systems. A typical Coastal Plain water budget presented in Giese et al. (1997) estimated that of 1270 mm of precipitation received annually over most of the Coastal Plain, on the average, 840 mm is evapotranspired, 300 mm percolates to ground water, and about 130 mm leaves the watershed as surface runoff. Approximately 270 mm discharges to streams from the unconfined shallow aquifers, and the remaining 30 mm recharges deep, confined aquifers. Therefore, about 70% of the annual runoff is from shallow ground water, which emphasizes the importance of ground water's effects on water quality of receiving streams.

Principal shallow aquifers in the study area include the surficial aquifer and Yorktown aquifer. The surficial aquifer is composed of unconsolidated fine sand, silt, clay, and soil residuum with coarser grained sediments occurring in relict beach ridges or alluvium (Winner and Coble, 1996). Thickness of the surficial aquifer in the study area ranges from 3 to 6 m.

The surficial aquifer overlies the Yorktown confining unit, which averages about 8 m in thickness throughout the Coastal Plain where it occurs (Winner and Coble, 1996), and may be absent in the southeastern portion of the study area and in stream valleys in the area. The Yorktown aquifer underlies the Yorktown confining unit, where it is present, and is about 6 m thick. Based on information presented in Giese et al. (1997), average hydraulic conductivity of the surficial and Yorktown aquifers ranges between 6 and 9 m d<sup>-1</sup>, representative of a clean fine to medium sand (Heath, 1983). Depth to the water table in the study area ranges from a few tenths of a meter in discharge areas near streams to approximately 2 m below land surface in upland recharge areas.

## METHODS

Potential ground and surface water sampling sites were selected by overlaying a digital coverage of a map of Contentnea Creek and its principal tributary streams on digital map layers showing roads and land use.

Land-use information was obtained from 30-m multiple-resolution land characteristics (MRLC) data obtained between 1990 and 1993. Land-use divisions used in this analysis were pasture, crop, and forest. Only streams with bridge crossings were included as potential sites for this study. A 30-m zone was delineated along both sides of each stream using geographic information (GIS) software to determine the presence or absence of a buffer next to the streams. Where forested land occurred on both sides of the stream, sites were classified as buffer sites. Remaining sites with no forested areas on both sides of the stream were classified as nonbuffer sites. Final selection included more than 200 potential sites of buffer and nonbuffer categories. After assigning sequential numbers to each site-selection pool, 14 sites having 30-m lowland hardwood forest buffers and 14 sites having no hardwood buffer between the agricultural area or pasture and the stream were randomly selected (Fig. 1).

Information on the percentage of organic carbon in soils adjacent to each sampling site was obtained from the Map Unit Interpretation Record (MUIR) attribute data associated with the USDA's Natural Resources Conservation Service SURRGO (USDA, 1995) database for Greene County, Wilson County, and Wayne County, North Carolina. The percentage of stream with riparian buffer upstream from each sampling site was computed by dividing the stream length upstream with riparian buffers by the total stream length (including all tributaries) upstream.

Ground and surface water samples were collected at all 28 sites during baseflow conditions when flow is assumed to be entirely from ground water. Ground water was sampled by using a minipiezometer, placed near the center of the stream so that the screen interval was between 0.3- and 0.6-m beneath the streambed. Samples collected near the center of the stream are considered to be representative of old ground water discharging to the stream (Fig. 2). The water level was then measured by using a manometer (Winter et al., 1988) to verify that the gradient was upward and that ground water was discharging to the stream. Virtually all streams in Contentnea Creek were observed to be gaining streams during the low-flow sampling period in 1997. After verifying that the ground water-surface water gradient was positive, samples were collected from the minipiezometer with a peristaltic pump connected by a flexible polytetrafluoroethylene line attached to the slip-on connection of the 8-cm stainless steel screen. A water sample from the stream was collected in the centroid of flow, also with a peristaltic pump, and filtered. The stream samples were considered to represent primarily young shallow ground water that discharged rapidly along short flowpaths to the stream (Fig. 2). All samples for this study were collected

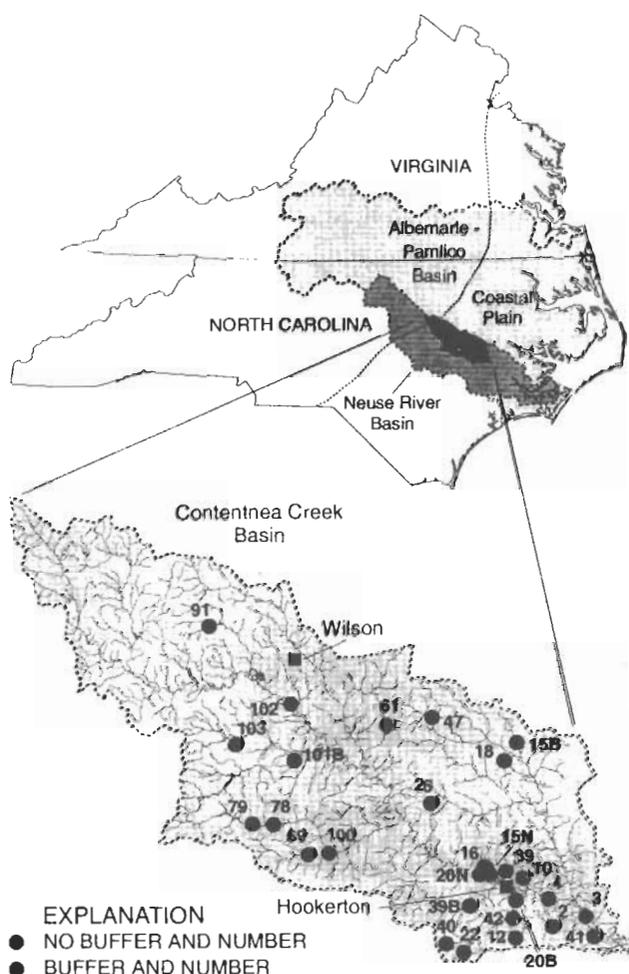


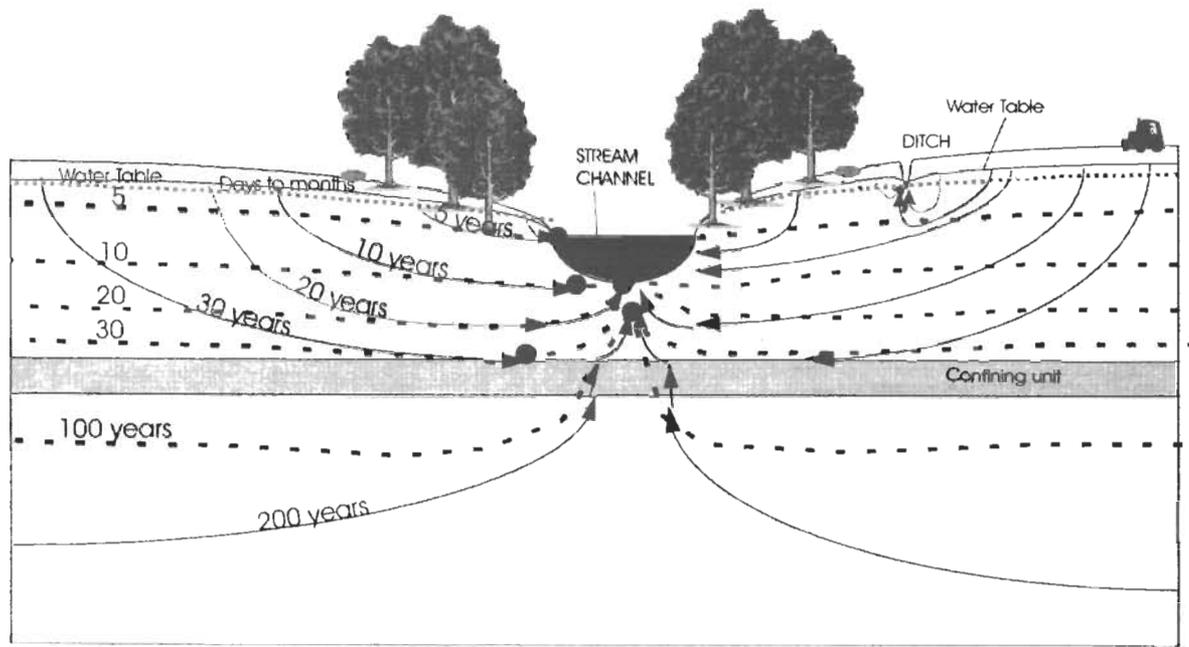
Fig. 1. Location of study area, sampling sites, and site numbers shown in Table 1.

during low-flow conditions in September and October of 1997 by pumping the samples through a 0.45- $\mu$ m disposable capsule filter. Field measurements were made for specific conductance, temperature, pH, and dissolved oxygen. Samples were analyzed for dissolved nutrients (dissolved ammonium nitrogen, nitrate nitrogen, Kjeldahl nitrogen, and phosphorus), silica, iron, manganese, chloride, and organic carbon. The North Carolina Department of Natural Resources Water Quality Laboratory in Raleigh, North Carolina analyzed all samples. Data from piezometer and stream samples are presented in Table 1.

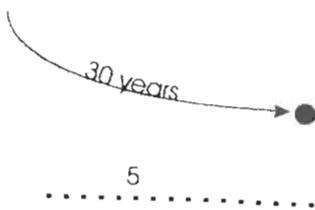
Nonparametric statistical tests were used for the analysis because of small sample size and because of skewed data distributions. A nonparametric two-sample Mann-Whitney test (Conover, 1980) was used to determine if differences in water quality were associated with buffers in old ground water samples and young ground water samples. Differences were considered significant at  $p < 0.10$ . The Spearman rho (Conover, 1980) correlation analysis was used to discern relationships between various chemical constituent concentrations and other variables.

## RESULTS AND DISCUSSION

Results and discussion of this paper are subdivided, in the interest of clarity, under the subheadings *young* and *old* ground water, as defined above. Riparian buffers can act directly on shallow or young ground water



#### EXPLANATION:



Flow path of water moving from recharge to discharge area. Years indicated show the time before present that water was recharged to reach the point shown.

Dashed lines indicate age of ground water at this depth below water table. Number indicates age in years.

Fig. 2. Conceptual view of young and old ground water discharging to a stream.

through vegetative uptake and assimilation and through generation of carbon to fuel denitrification and other redox reactions in ground water moving directly beneath the buffer zone (Correll, 1996). Correll (1996) notes that the effectiveness of buffers is thought to be greatest where ground water passes just beneath a riparian buffer but is limited where ground water is too deep and cannot interact with vegetation in the riparian buffer. Either the water table can be too deep or ground water that moves along deep flow paths or at the base of shallow aquifers can be too deep for the riparian buffer to have a discernible effect (illustrated by older flow paths depicted in Fig. 2).

This study provides evidence that riparian buffers affect old ground water that has bypassed the physical riparian buffer. Correll (1996) cited several studies that demonstrate that significant organic matter is supplied to stream channels by vegetated buffers. The importance of riparian vegetation in providing a carbon source to streams for water quality management also has been noted by Hill (1996). As will be shown in the following section, riparian vegetation appears to affect ground water quality at the watershed scale by supplying carbon

to stream sediments through which the old ground water must pass. Riparian buffers also may affect shallow ground water through simple dilution, a potentially important effect of buffers that is often overlooked.

#### General Oxidation-Reduction Relationships between Selected Constituents

Before discussing results of this study pertaining to buffer effects on old and young ground water, study data can be pooled to illustrate overall importance of oxidation-reduction phenomena. Chemical effects on ground water quality by riparian buffers and hyporheic zones of streams appear to be related to oxidation-reduction reactions, with organic carbon supplied by growing vegetation and/or soil organic carbon providing the primary driving agent for creating reducing conditions. By pooling all data from both shallow and deep ground water, it is possible to observe several interesting consistent relationships (Fig. 3). A Lowess smooth line, a nonparametric graphical smoothing technique (Helsel and Hirsch, 1992), is used to show trends in the data.

Because dissolved iron concentration is a good indica-

tor of oxidation–reduction conditions, it was chosen to illustrate relationships with other chemical constituents. Concentrations of most constituents are positively correlated with increasing concentrations of dissolved iron (Fig. 3) and negatively correlated with nitrate nitrogen. Dissolved calcium, manganese, and specific conductance did not exhibit positive or negative correlations (Fig. 3).

Nitrate nitrogen concentrations decrease below  $0.1 \text{ mg L}^{-1}$  when iron is present at  $1000 \text{ } \mu\text{g}$  or greater; these data show that ground water in buffer areas usually is reduced and will tend to have low nitrate nitrogen. Specific conductance is highly correlated to calcium and probably reflects calcium mineral solubility as a function of pH, with lower pH values reflective of oxidized conditions and higher pH values associated with reduced conditions. Calcium and manganese concentrations and specific conductance reach a minimum when iron concentrations range between  $2000$  and  $10\,000 \text{ } \mu\text{g L}^{-1}$  (Fig. 3). Surprisingly, no striking pattern in dissolved oxygen concentrations was detected across the entire range of iron solubility, although concentration appears to decrease from  $2$  to  $1 \text{ mg L}^{-1}$  under more reduced conditions. The occurrence of measurable oxygen under these conditions is not easily explained, although it is possible that methane or hydrogen sulfide could cause inaccurate readings of dissolved oxygen. Chloride also had no striking pattern, although, like calcium and manganese, it reached a minimum concentration at between  $1000$  and  $10\,000 \text{ } \mu\text{g L}^{-1}$ . Although it is beyond the scope of this paper, the extremely high iron concentrations observed ( $>50\,000 \text{ } \mu\text{g L}^{-1}$ , Table 1) are noteworthy and cannot be readily explained at near neutral pH with alkalinities over  $100 \text{ mg L}^{-1}$ . However, iron is highly correlated to DOC (Spearman rho correlation =  $0.79$ ,  $p < 0.001$ ) and it is possible that it occurs as a colloid or organic complex. Data from buffer sites dominate the reducing half, or right hand side, of each graph shown in Fig. 3.

#### Effects of Riparian Buffers on Nitrate and Chemical Quality of Old Discharging Ground Water

Graphical comparisons, using (i) boxplots of observed concentrations of selected chemical constituents and (ii) results of the two-sample comparisons between ground water discharging to streams at sites according to presence or absence of forested buffers in old discharging ground water, are shown in Fig. 4.

Statistically significant differences in values of pH, specific conductance, DOC, alkalinity, silica, ammonium, total Kjeldahl nitrogen (KN), phosphorus, iron, and manganese in discharging ground water were associated with the presence of buffers, with highest concentrations occurring in areas having buffers. The presence of buffers affected concentrations of many chemical constituents in discharging ground water, as indicated in Fig. 4, although there was no statistically significant effect on median nitrate nitrogen concentrations. Even though high nitrate nitrogen concentrations did occur in the nonbuffer areas, as indicated in Fig. 4, this phe-

nomenon is probably because these nonbuffer areas were located along first order streams where the old ground water is not much older than the young ground water. All elevated nitrate nitrogen concentrations occurred in small first or second order streams that had no riparian buffer. However, because the median concentration was not affected by a few large nitrate nitrogen values, no statistically significant difference was detected in this sample. Reasons for this will be discussed in the section on young ground water. As has been demonstrated in two recent studies (Speiran, 1996; Spruill et al., 1997), nitrate nitrogen reduction and denitrification can occur independent of the presence of riparian buffers within aquifers having sufficient organic carbon that can act as an electron donor. Therefore the null hypothesis that nitrate nitrogen concentrations are not statistically different between old ground water from buffer areas and ground water from nonbuffer areas discharging to streams is accepted at  $\alpha = 0.10$  ( $p = 0.74$ ). It is concluded that riparian buffers do not significantly affect nitrate nitrogen concentrations in discharging older ground water from long flow paths. I suggest that old ground water does not have very high nitrate nitrogen concentrations in the Contentnea Creek drainage. This result is consistent with observations by Gilliam (1991) that deep ground water typically does not have concentrations greater than a few milligrams per liter. Denitrification can and does take place at places within the aquifer away from riparian buffer zones along streams (Speiran, 1996). If old ground water were to have high nitrate nitrogen concentrations, however, the potential for denitrification is clearly present, as shown in Fig. 4 for many other chemical constituents.

Concentrations of several other chemical constituents are associated with and affected by the presence of riparian buffers. Data collected during this study indicate that ground water in streambed sediments in discharge zones along a stream, compared with recharge areas, has elevated concentrations of a variety of chemical constituents, possibly due to chemical characteristics of fluvial deposits beneath the stream channel. These fluvial deposits form a unique chemical matrix that can be distinguished from aquifer material located beneath and away from the stream channel or riparian zone. Based on observations from sampling and coring work currently (1999) being conducted in the Contentnea Creek Drainage and other areas in the North Carolina Coastal Plain, there is often a layer of black, fine-grained sediments that often extends from a few tenths of a meter to  $1 \text{ m}$  or more beneath streambeds in the drainage basin. Significantly higher concentrations of most of the measured chemical constituents occurred in ground water from areas with riparian buffers compared with ground water from areas having no buffer (Fig. 4), and most are associated directly (pH, alkalinity, Kjeldahl nitrogen, ammonium, iron, and manganese) or indirectly (phosphorus and silica) with oxidation–reduction processes. Dissolved sulfate was not analyzed, although these stream sediments would release hydrogen sulfide ( $\text{H}_2\text{S}$ ), as was evident from the odor one noticed while walking on the streambed at most buffer sites. This

Table 1. Site and chemical data for piezometer and stream samples collected in September and October 1997. Site numbers are shown in Fig. 1. All analyses performed by the North Carolina Department of Environment and Natural Resources Water Quality Laboratory.

Site	Type†	pH	D.O.‡ mg L <sup>-1</sup>	S.C.§ µS cm <sup>-1</sup>	DOC	ALK#	CL**	Si‡‡	NH <sub>4</sub> -N§§ mg L <sup>-1</sup>	KJDL-N	NO <sub>3</sub> -N###	P	Ca	Fe	Mn	Na
Piezometer samples																
2	B	6.68	1.29	660	32	230	15	21	14	16	0.05	0.37	35	97 000	510	5.3
3	N	5.98	1.33	207	5	70	11	6	0.09	0.2	0.01	0.07	25	15 000	45	3.8
4	N	4.91	1.46	116	5	10	7	4	0.07	0.2	0.01	0.03	6.3	1 100	49	2.3
10	N	5.61	3.6	230	5	4	15	17	0.1	0.1	0.02	0.15	16	6 000	98	4.5
12	N	5.76	1.58	195	16	42	20	14	2	2.2	0.02	0.22	12	6 400	39	8
15	B	6.86	0.9	634	16	210	16	17	6.8	7.7	0.04	0.83	69	49 000	300	15
15	N	5.56	1.9	122	12	49	8	16	0.16	0.5	0.01	0.07	4.5	480	39	12
16	N	6.03	0.45	193	6	56	12	11	0.51	0.6	0.02	0.10	23	2 200	43	6.3
18	N	5.13	1.3	93	5	4	18	14	0.09	0.2	0.04	0.12	2.7	3 900	24	6.1
20	N	6.81	1.21	746	28	240	9	26	36	45	0.02	7.00	39	42 000	1 900	3
20	N	5.27	2.09	166	5	2	13	5	0.04	0.2	6.1	0.02	16	50	48	3.4
22	N	4.18	1.98	273	5	1	22	7	0.03	0.1	15	0.01	19	55	78	5.3
26	N	5.83	1.18	118	5	36	10	15	0.87	0.9	0.02	0.35	3.4	8 200	30	7.5
39	B	5.06	0.86	238	5	2	9	13	0.01	0.1	0.16	0.01	27	100	130	5.9
39	N	5.38	0.9	164	5	16	18	8	0.12	0.4	0.01	0.01	12	850	34	6.7
40	B	5.57	0.67	100	5	28	7	19	3.3	5.2	0.01	0.75	8.3	3 000	21	3.6
41	N	4.85	1.22	215	5	2	19	5	0.14	0.7	8.9	0.01	21	79	64	2.6
42	N	5.79	1.7	219	5	16	14	7	0.06	0.2	6.7	0.04	21	190	44	7.9
47	B	5.60	1.34	132	28	30	13	12	1.9	3	0.01	0.17	6.1	9 400	82	5
61	B	6.36	2.24	224	22	50	12	8	6.4	6.4	0.03	0.99	10	17 000	270	4.5
69	B	6.55	1.46	146	7	24	12	10	0.32	0.4	0.01	0.56	8.6	4 300	69	5.6
78	B	5.53	0.96	179	14	42	30	33	2.3	2.3	0.02	0.37	7.2	13 000	270	10
79	B	6.34	1.28	579	8	160	57	35	2.7	3.4	0.01	0.37	64	12 000	260	21
91	B	1.54	1.54	28	5	28	16	7	0.08	0.2	0.48	0.01	9	600	210	3.3
100	N	6.43	2.00	200	5	78	4	22	3.6	3.8	0.07	1.40	11	5 800	110	13
101	B	5.92	1.45	244	14	60	7	36	9.5	12	0.03	0.62	10	25 000	400	3
102	B	6.54	1.88	442	13	100	22	30	8.6	9.9	0.02	0.74	24	24 000	1 800	24
103	B	5.83	1.01	271	29	68	18	15	3.6	3.9	0.02	0.1	13	30 000	330	11

Continued next page.

Table 1. Continued.

Site	Type†	pH	D.O.‡	S.C.§	DOC¶	ALK#	CL††	SI‡‡	NH <sub>3</sub> -N§§	KJDL-N¶¶	NO <sub>3</sub> -N##	P	Ca	Fe	Mn	Na
mg L <sup>-1</sup>																
µS cm <sup>-1</sup>																
Stream samples																
2	B	6.46	0.89	210	23	22	11	10	0.01	0.7	0.01	0.09	15	1700	220	6.9
3	N	5.96	1.52	158	5	17	10	5	0.11	0.3	2.3	0.03	9.3	310	54	4.7
4	N	6	0.87	21.1	6	24	17	9	0.39	0.5	1.6	0.04	11	210	59	6.2
10	N	6.1	3	178	6	24	14	7	0.5	0.8	0.08	0.04	15	1800	88	4.2
12	N	6.4	2.63	128	9	27	13	4	0.05	0.5	0.01	0.24	8.6	1200	38	2.7
15	N	6.87	1.17	142	16	61	10	5	0.13	0.4	0.01	0.18	9	2800	99	6.3
15	B	5.75	0.65	140	9	51	13	11	0.03	0.2	0.01	0.1	7.4	1900	69	10
15	N	6.71	2.03	203	6	44	18	7	0.24	0.5	1.7	0.01	27	140	11	6.4
18	N	5.9	2.94	128	5	12	17	10	0.07	0.4	0.01	0.23	8.4	160	53	6.7
20	B	6.95	0.6	144	11	110	8	6	0.19	0.4	0.01	0.05	20	4900	510	4.1
20	N	6.15	3.08	188	5	11	18	6	0.09	0.1	4.9	0.05	50	50	100	3.2
22	N	4.33	242	242	5	2	29	5	0.09	0.3	11	0.01	18	440	45	5
25	N	6.16	3.04	141	5	15	17	6	0.36	0.5	0.33	0.48	12	1100	56	4.1
39	B	5.89	4.5	97	15	15	12	11	0.44	0.6	0.01	0.11	4.4	910	29	6.5
39	N	6.2	2.67	223	7	39	16	7	0.14	0.4	0.03	0.11	19	6500	220	8.6
40	B	6.07	0.88	101	17	24	12	9	0.01	0.4	0.03	0.11	7.2	1600	55	6
41	N	6.5	3.18	193	5	29	17	2	0.09	0.3	1.1	0.03	21	280	45	4.1
42	N	6.13	2.8	200	5	22	18	6	0.09	0.3	1.5	0.06	16	71	68	9
47	B	6.01	0.66	119	26	24	11	3	0.15	0.5	0.01	0.12	7.9	4000	140	6.1
61	B	6.3	1.85	123	19	37	10	5	0.11	0.6	0.01	0.12	9.5	5700	210	4.5
69	B	6.11	5.1	102	11	27	12	5	0.09	0.4	0.34	0.09	6.8	2100	70	5.7
78	B	6.34	3.64	85	11	29	11	9	0.26	0.4	0.23	0.12	8.9	3100	260	5.6
79	B	6.45	2.3	111	11	32	12	8	0.22	0.5	0.11	0.07	9.4	2700	150	5.7
91	B	6.45	6.56	111	12	17	10	6	0.17	0.4	0.09	0.02	3.9	740	39	4.9
100	N	6.48	98	98	11	20	12	8	0.14	0.5	0.41	0.07	6.5	960	25	6
101	B	6.21	3.12	84	14	17	12	5	0.12	0.4	0.01	0.05	3.8	890	23	4.8
102	B	7.38	4.73	208	9	39	22	21	0.29	0.8	2.2	0.08	6.4	390	97	26
103	B	6.15	2.43	127	12	20	19	8	0.1	0.4	0.27	0.01	9.2	400	49	8.4

† B, buffer; N, no buffer.  
 ‡ Dissolved oxygen.  
 § Specific conductance at 25°C.  
 ¶ Dissolved organic carbon (detection limit for piezometer samples is 5 mg L<sup>-1</sup>).  
 # Alkalinity, as calcium carbonate.  
 †† Chloride.  
 †‡ Silica.  
 §§ Ammonia, as nitrogen.  
 ¶¶ Kjeldahl nitrogen.  
 ## Nitrate plus nitrite (detection limit for piezometer samples is 0.01 mg L<sup>-1</sup>).

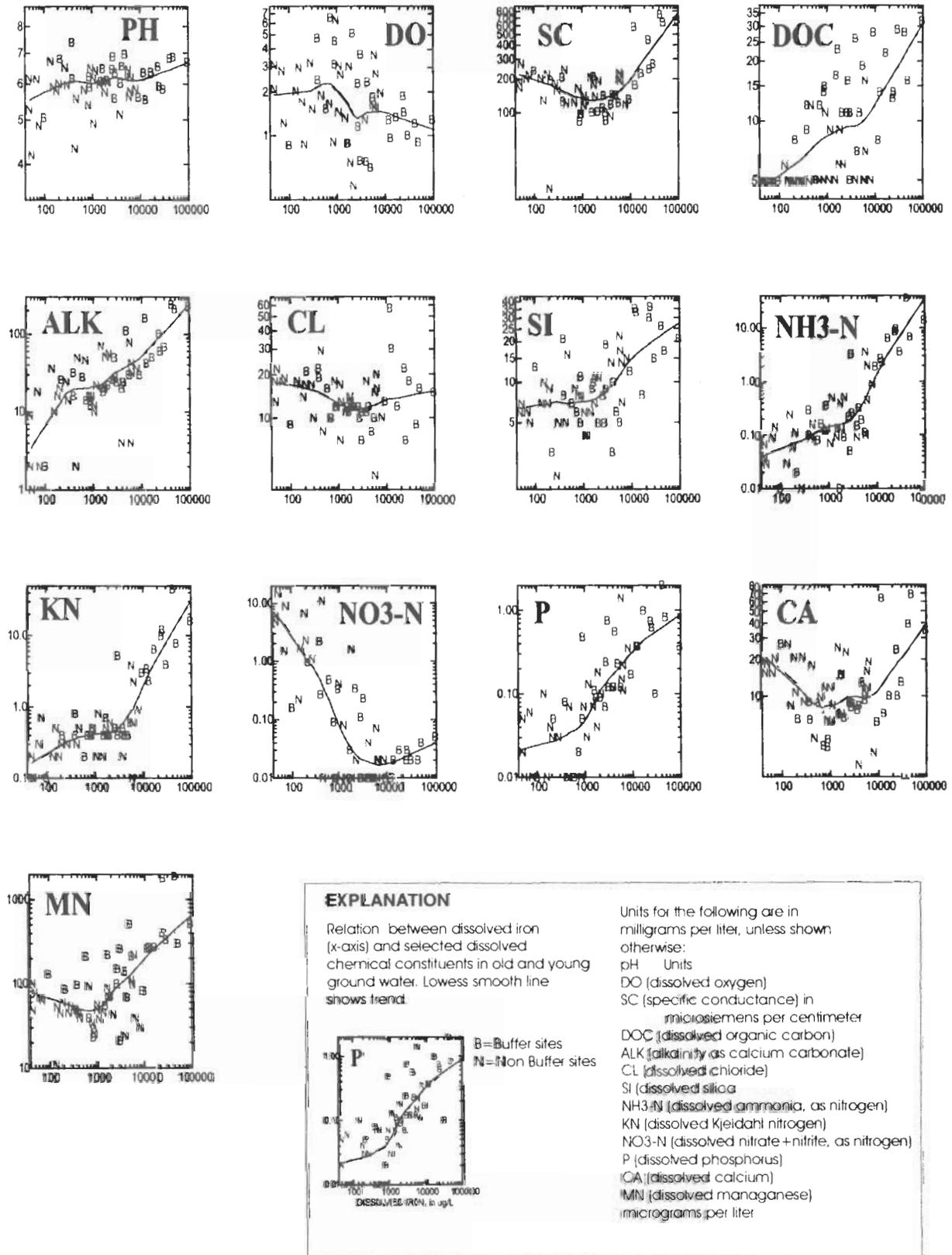


Fig. 3. Relationship between dissolved iron and selected chemical constituents in discharging ground water.

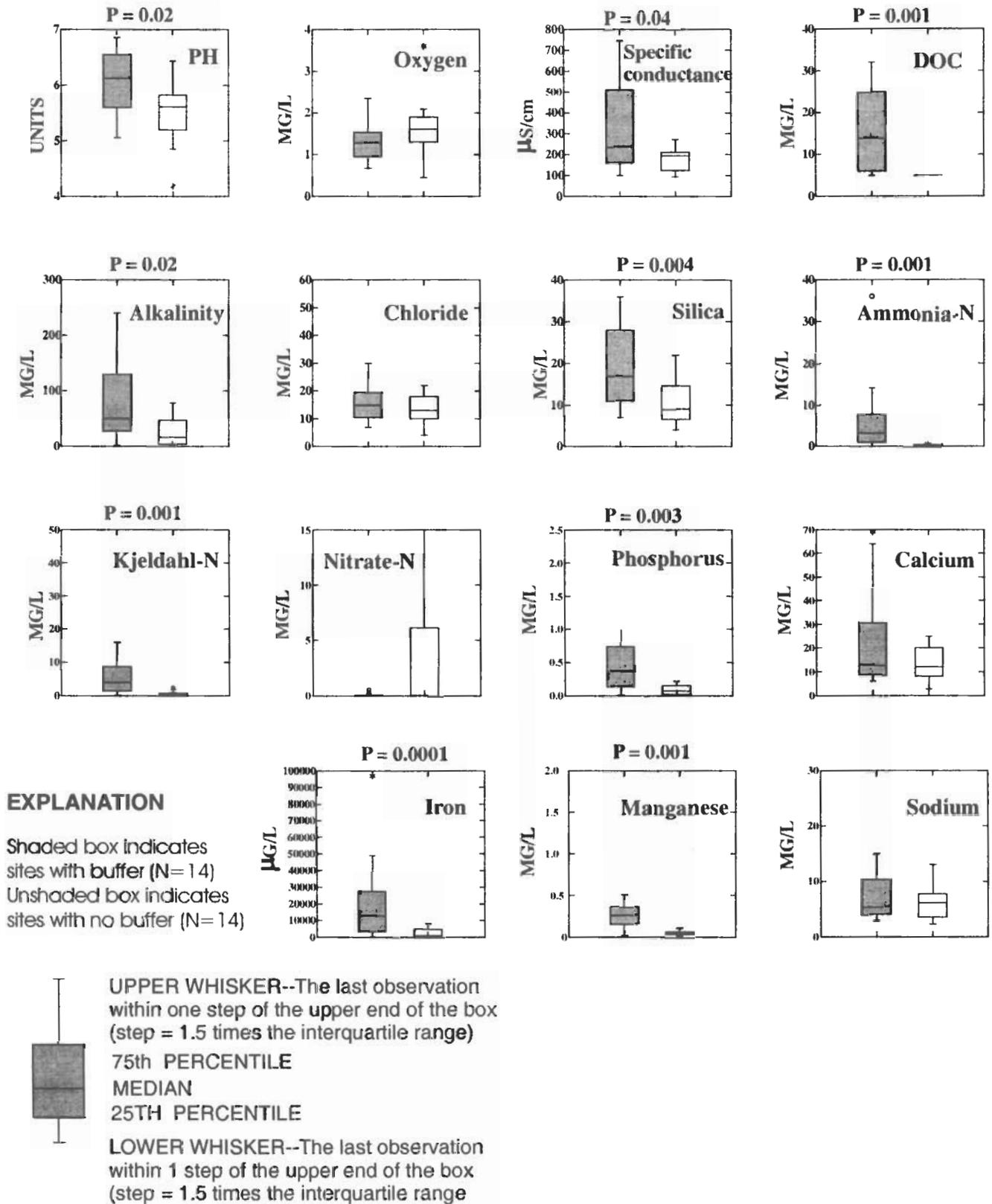


Fig. 4. Boxplots showing ground water quality differences associated with riparian buffers. Chemical constituents that were significantly different at  $\alpha = 0.10$  are indicated by the probability value shown above each box.

observation implies low sulfate concentrations in discharging ground water, elevated  $\text{H}_2\text{S}$ , and potentially elevated  $\text{N}_2$ ,  $\text{CH}_4$ , and  $\text{CO}_2$ .

High concentrations of chemical constituents in discharging ground water in streams with riparian buffers can be partially explained as a result of ground water of a particular composition moving through a new reaction medium, the sediment and organic material beneath and adjacent to the stream. This area beneath and adjacent to the stream has been referred to as the *hyporheic zone* by several authors (Triska et al., 1989; Harvey and Bencala, 1993; Stanford and Ward, 1993). Much of this research has been conducted in forested mountain stream environments of the western United States. The hyporheic zone of streams studied in the Contentnea Creek basin, and probably for most higher order streams in the Coastal Plain where stream gradients are low (less than  $1.6 \text{ m km}^{-1}$ ), are likely to have relatively greater amounts of organic carbon content in the stream bed and floodplain deposits compared with high-energy mountain stream environments with predominantly gravel and cobble streambeds. Even in comparing the organic carbon content of streambeds in the higher gradient Piedmont with streams in the lower gradient Coastal Plain, organic carbon concentrations in sediments of the Piedmont streams generally were less than 2% compared with more than 2.5 to 10% in Coastal Plain streams of the Albemarle–Pamlico Drainage (Woodside and Simerl, 1996). Concentrations of organic carbon in bed sediments of less than 2 mm for reservoirs and Coastal Plain streams ranged from 8 to  $180 \text{ g kg}^{-1}$ , with most greater than  $10 \text{ g kg}^{-1}$ . Streams of the inner Coastal Plain, including Contentnea Creek where this study was conducted, had bottom sediment organic carbon concentrations of about  $20 \text{ g kg}^{-1}$ . In contrast, most streams draining the Piedmont had less than  $6 \text{ g kg}^{-1}$  organic carbon for the <2-mm size fraction (Woodside and Simerl, 1996).

The organic carbon content of the streambed appears to exert a major effect on discharging ground water chemistry. Hill and Sanmugas (1985) found that nitrate loss rates were significantly correlated with water-soluble carbon content of the sediment as well as with organic carbon, total nitrogen, and sediment ammonium for three rivers in Ontario. Ground water samples collected in the Contentnea Creek Basin were characterized by reducing conditions in ground water from buffer sites, as indicated by elevated iron, manganese, and ammonium concentrations and low nitrate nitrogen concentrations (Table 1). Geochemically reducing conditions are probably caused by decaying organic material in the streambed and floodplain deposits. The origin of this organic material is vegetation and organic debris from streambank buffer areas and vegetation growing upstream within the watershed. The thickness of the organic streambed material can be rather thin, but functional, even in sandy upland drainages, if some vegetative material is present in the watershed.

The development and geochemical importance of a hyporheic zone and its geochemical importance in controlling discharging ground water quality is conceptually

depicted in Fig. 5. In an upland watershed with few or no riparian trees to generate organic carbon, the development of a hyporheic zone can be minimal because little organic material accumulates (Fig. 5A). In a watershed with substantial forested stream buffers, however, organic material can accumulate in the streambed (Fig. 5B) and, as it decays, creates reducing conditions. Under such conditions, oxidized compounds, as well as sorbed trace elements, undergo reduction and are released into solution, elevating their concentrations in ground water that flows through these materials. Some of these chemical constituents, particularly organic nitrogen and ammonia, probably phosphorus, and possibly silica may be released into solution from decaying organic materials. Geochemical processes that may take place are illustrated in Fig. 5C.

Conceptually, the hyporheic zone is an important consideration when attempting to model mass transport in a ground water–surface water system, because the streambed sediment can significantly change the chemical quality of ground water before it discharges to a stream by elevating concentrations of some chemical constituents and reducing others. Jacobs and Gilliam (1985) also note loss of nitrate nitrogen in water discharging to ditches draining agricultural fields. This nitrate loss was attributed to organic detritus in bottom sediments of the ditch. Concentrations of several constituents can be higher in buffer areas than typical ground water concentrations from the surrounding aquifer. As demonstrated by results from the two-sample tests, highest concentrations of several constituents (i.e., ammonium and carbon) occurred in discharging ground water from areas having buffers (Fig. 4). The median dissolved concentration of ammonium in ground water from buffer sites was about  $3.5 \text{ mg L}^{-1}$ , with one site producing a sample with almost  $40 \text{ mg L}^{-1}$  (Fig. 4). This concentration contrasts with the typical ammonium concentration for shallow ground water from the Coastal Plain of the Albemarle–Pamlico Drainage of less than  $0.2 \text{ mg L}^{-1}$  (Spruill et al., 1997, 1998). The median DOC concentration in ground water collected from buffer areas was approximately  $12 \text{ mg L}^{-1}$ , well above the median concentration for ground water in both the inner (about  $2 \text{ mg L}^{-1}$ ) and outer Coastal Plain (about  $5 \text{ mg L}^{-1}$ ) of the Albemarle–Pamlico Drainage (Spruill et al., 1997).

Concentrations of several other constituents also are elevated in discharging ground water from areas with buffers. Iron and manganese often occur in ground water under reducing conditions as ferrous or manganous ions released from iron oxyhydroxides on deposited sediment in the stream channel. Other sorbed compounds or metals (not measured in this study) can be released from the solid sediment surfaces as iron and manganese enter into solution. Phosphate (as  $\text{H}_2\text{PO}_4$ ) and silica (as silicic acid,  $\text{H}_4\text{SiO}_4$ ), which are sorbed onto oxyhydroxide surfaces (Stumm and Morgan, 1981), can be transported on sediment eroded from uplands to the point of deposition on the streambed. After subsequent exposure to a reducing geochemical environment of the hyporheic zone, sorbed phosphorus can be released from

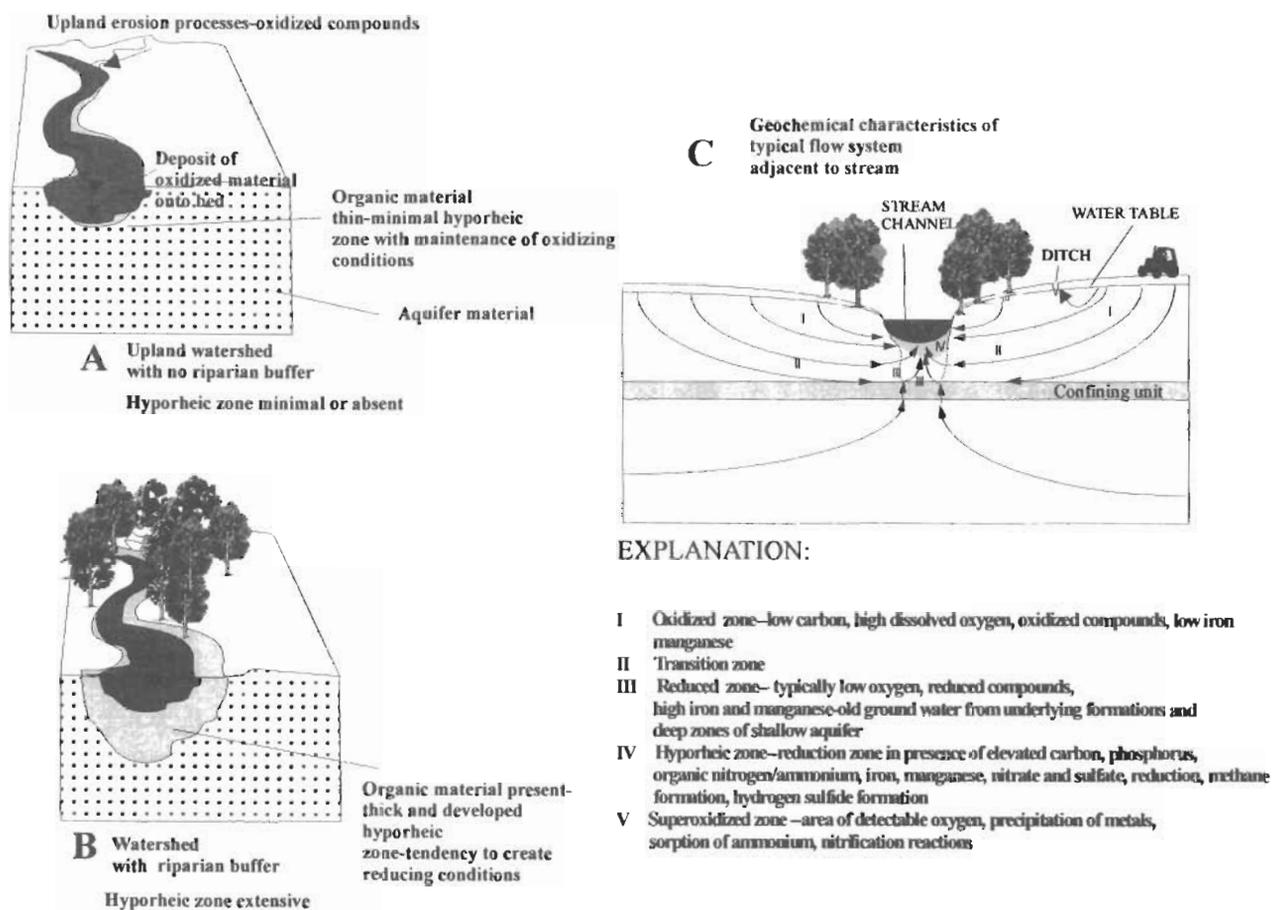


Fig. 5. Conceptual view of some watershed processes involved in creating a hyporheic zone of a stream.

the solid matrix of the hyporheic zone. This dissolution of phosphorus from sediment may partially explain the hyporheic zone ground water having a median dissolved phosphorus concentration of about  $0.5 \text{ mg L}^{-1}$  (Fig. 4), which is much higher than the median concentration of  $0.04 \text{ mg L}^{-1}$  for shallow ground water of the inner Coastal Plain (Spruill et al., 1998). As mentioned above, phosphorus and silica could also be released from decaying vegetation and organic material.

Elevated pH is correlated with high concentrations of ammonium, as indicated by a Spearman rho correlation ( $0.78, p < 0.001$ ) for data collected during this study (Table 1). Elevated specific conductance and alkalinity are also significantly correlated ( $p < 0.01$ ) with elevated ammonium as described above. The DOC present in ground water can be broken down to organic acids and ultimately oxidized to carbon dioxide ( $\text{CO}_2$ ), which increases the alkalinity of the ground water (Thurman, 1985, p. 15). These general reactions and processes are summarized and conceptually presented in Fig. 5C.

The effects of riparian buffers on the chemistry of old ground water discharging to a stream appears to be related to the relative dominance of riparian buffers at the watershed scale. High concentrations of many constituents are significantly correlated to percentage of stream length above the sampling point having a riparian buffer (Fig. 6). These results indicate that (i)

riparian buffers have a clear effect on specific redox-sensitive elements in old discharging ground water quality and (ii) the effect that riparian buffers have can occur at the watershed scale. Dissolved oxygen, chloride, nitrate nitrogen, calcium, and sodium are not significantly correlated to percentage of stream length with riparian buffers. These are the same constituents where significant differences were not detected between buffer and no buffer areas. Buffers did not affect concentrations of mostly conservative or nonredox sensitive ions (excepting nitrate) in old ground water discharging from long flow paths. Concentrations of nitrate nitrogen are low in old ground water probably because denitrification and/or dilution processes have occurred or because there simply was no nitrogen source at the time the water was recharged to the aquifer.

Complex processes can simultaneously occur at the sediment–surface water interface as ground water enters the channel. Ammonium in discharging ground water can be precipitated on the streambed upon exposure to more oxygenated water in the channel and sorbed onto clays or precipitated oxyhydroxides on the surface of the streambed, be taken up by biota, or undergo some nitrification. Although surface water ammonium concentrations do not appear to be affected by elevated ammonium in ground water from other Coastal Plain sites (Spruill et al., 1998), elevated concentrations of

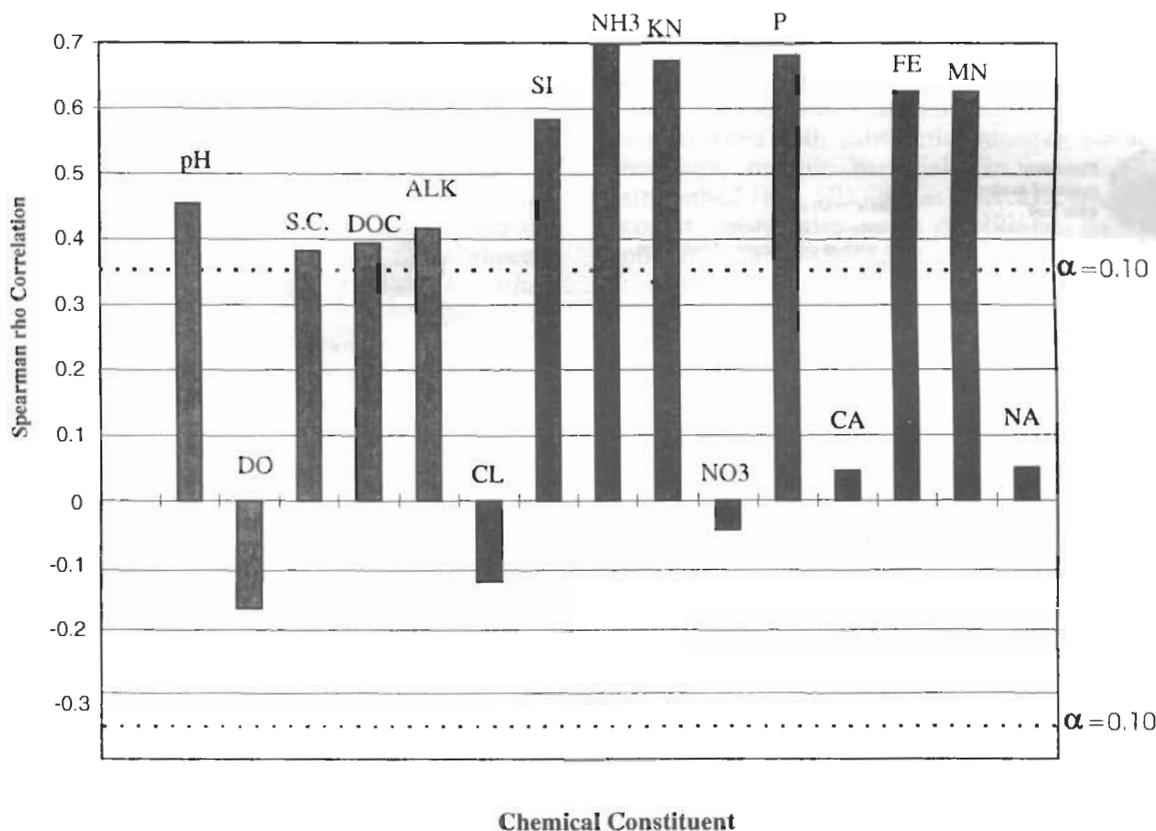


Fig. 6. Spearman  $\rho$  correlations between selected chemical constituents and percentage of stream length above sampling point. A  $\rho$  value above or below the value shown is required to be significant at  $\alpha = 0.10$ .

ammonium and some other constituents (for example phosphorus or silica) derived from the hyporheic zone could affect surface water concentrations. Spruill et al. (1998) detected a significant correlation between ground water and surface water phosphorus concentrations from samples collected from 30 streams in the Coastal Plain of the Albemarle–Pamlico drainage Basin. In that study, surface and ground water phosphorus concentrations were also highly correlated at buffer sites ( $\rho = 0.69$ ,  $p = .001$ ), indicating that the hyporheic zone could elevate phosphorus concentrations in the receiving stream. The data also suggest that ground water passing through organic material in marshes and estuaries may be a source of dissolved ammonium, the preferred form of nitrogen for uptake by algae in the Neuse River estuary in North Carolina (Boyer et al., 1994). More research is needed for evaluating the role of the hyporheic zone on surface water quality, particularly in estuaries where ammonium may be soluble in brackish or saline water.

Streambed characteristics of buffered watersheds can be artificially or naturally simulated where trees do not exist. For sandy upland watersheds with little vegetation lining the banks, it is likely that the organic carbon content of the streambed will be low and the thickness of organic deposits thin or nonexistent. The potential for creating reducing conditions will be correspondingly low, as illustrated in Fig. 5A. However, in areas that have significant organic material buildup because of damming, beaver activity, water-control structures, or

simply very low hydraulic gradients, as occur in areas of the Coastal Plain, reducing conditions can be created. Spruill et al. (1998) reported that nitrate nitrogen was reduced in the streambed from  $15 \text{ mg L}^{-1}$  in discharging ground water located 1 m beneath the streambed to  $2 \text{ mg L}^{-1}$  in the stream. Even though no riparian buffer was present adjacent to the particular field studied, sufficient organic material derived from low bushes and brush and trees upstream was apparently trapped by a dam that is located downstream from the study area to create reducing conditions within the bed. These results suggest that streams that are regularly dredged or that have been channelized, as is common in agricultural areas, would have less capacity to reduce nitrate and could increase exported nutrients in ground water. Yarbrough et al. (1984) reported that channelized streams transported significantly higher nitrogen and phosphorus loads, possibly resulting from removal of organic material from the streambed.

Chemical constituents that are associated either with oxidizing conditions or leaching from anthropogenic or geologic sources, such as nitrate, calcium, sodium, and chloride, were not significantly different between buffer and nonbuffer areas in old discharging ground water (Fig. 4). Most of these constituents are mobile in the dissolved state and are not (with the exception of nitrate) directly involved in oxidation–reduction processes. Although there was no statistically significant difference in nitrate nitrogen concentrations between buffer and nonbuffer areas, the four highest nitrate ni-

trogen concentrations occurred in old discharging ground water in the nonbuffer areas (these were extreme cases: more than 60% of the stream length above the sampling point had no trees). Most of the nonbuffer sites were geographically clustered near Hookerton, North Carolina (Fig. 1) and were located in small upland tributary drainages of Contentnea Creek. Ground water collected from the high-nitrate sites indicated oxidizing conditions (low ammonium, iron, and manganese) and contained low DOC. These sites were located in first-order streams with short flow paths between recharge and discharge areas, indicating that position in the watershed is probably an important factor. Even though these samples were collected with a piezometer near the center of the channel, this ground water is probably dominated by young ground water from short flow paths. Information presented in Modica et al. (1997) indicates that most (80–100%) ground water discharging to streams in upland areas is likely to be young (<20 yr old). The ground water in these four samples was probably affected by rapid movement of contaminants in ground water from agricultural fields to the stream.

#### Effects of Riparian Buffers on Nitrate and Chemical Quality of Young Discharging Ground Water

Because surface water samples for this study were collected during baseflow conditions and no significant point sources were known to exist upstream from the sampling points, water in the channel is derived from ground water of both shallow and deep origin. Surface water samples were considered to be representative of primarily young ground water, even though they are known to be a composite mix of both old and young ground water. Chemical constituents in old discharging ground water (calcium, nitrate nitrogen, chloride, and sodium) that were not different between buffer and nonbuffer areas are significantly different in young ground water discharging in buffer and nonbuffer areas. Significant differences also exist between buffer and nonbuffer locations for pH, specific conductance, DOC, iron, and manganese in the young ground water samples, with highest concentrations of specific conductance, chloride, nitrate nitrogen, and calcium occurring in the nonbuffer areas (Fig. 7). Concentrations of pH, dissolved iron, manganese, and DOC were significantly lower in the nonbuffer areas.

Reasons why differences due to buffers were observed in the young ground water samples and not in the old ground water samples relate partially to how ground water discharges to a stream and how the samples were collected. During baseflow periods, surface water flow is derived from discharges from both shallow and deep aquifers or from deep zones of a shallow aquifer (Fig. 2). Because the minipiezometer was driven into the streambed of the stream, usually near the middle, the ground water sampled typically reflects the oldest water and longest flow paths (Fig. 2). Thus, ground water moving to the stream or ditch laterally may be under-represented or not represented at all. In the non-

buffer areas, it was common to find water standing or minimally flowing in agricultural ditches. This water is probably representative of short flow systems feeding laterally into the ditches (Fig. 2) with the majority (little or no flow contribution by deep aquifers) of flow contributed by young ground water in the sandy well-drained upland areas. This assumption is supported by studies of a hypothetical Coastal Plain stream discussed by Modica et al. (1997), who showed that most baseflow in upland drainages is primarily derived from young ground water. In these settings, water collected either from a minipiezometer or from the channel actually reflects young ground water, even though it represents the oldest ground water discharging in this upland setting.

The presence of higher concentrations of calcium, nitrate nitrogen, and chloride and high specific conductance observed in young ground water in the nonbuffer areas may indicate a large percentage of shallow ground water affected by agricultural chemicals and applied relatively near the discharge point. Because forested buffer areas allow recharge through undisturbed soil with no chemical applications (as opposed to cultivated soil), shallow ground water moving beneath a wide vegetative buffer (compared with no vegetative buffer) will normally be dilute in the upper portion of the saturated zone. Dilute recharge results in lower concentrations of several constituents, including nitrate and chloride, in shallow ground water in buffer areas. The lower concentrations of chloride and nitrate nitrogen in buffer areas in the surface water samples indicate that dilution, and not only denitrification within the buffer areas, may be responsible for observed lower concentrations of nitrate nitrogen in shallow ground water discharging from buffer areas.

As has been determined in previous studies, DOC appears to be a major factor in controlling nitrate nitrogen concentrations in ground and surface water. Both deep ground water and shallow ground water were negatively correlated with DOC. However, young ground water (as represented by stream samples) (Table 1) nitrate nitrogen concentrations were most strongly negatively correlated with DOC ( $-0.698$ ,  $p = 0.01$ ), with old ground water having a lower, but still significant, negative correlation with DOC ( $-0.514$ ,  $p = 0.05$ ). High concentrations of nitrate nitrogen ( $>3 \text{ mg L}^{-1}$ ) occurred only in the nonbuffer areas with low organic soil carbon ( $<3\%$ ). Where buffers were present, however, nitrate nitrogen concentrations were less than  $3 \text{ mg L}^{-1}$  (Fig. 8). These results suggest that shallow ground water moving near the water table just below the land surface in transmissive sandy aquifers through riparian buffer areas is probably denitrified because of adequate DOC availability for denitrifying microbes. Aquifers with low DOC concentrations will tend to have high nitrate nitrogen in areas where nitrogen is applied as a fertilizer. Streams draining well-drained aquifers having low levels of DOC in the ground water and little organic streambed material will tend to have elevated nitrate nitrogen concentrations.

Although the relative importance of dilution and de-

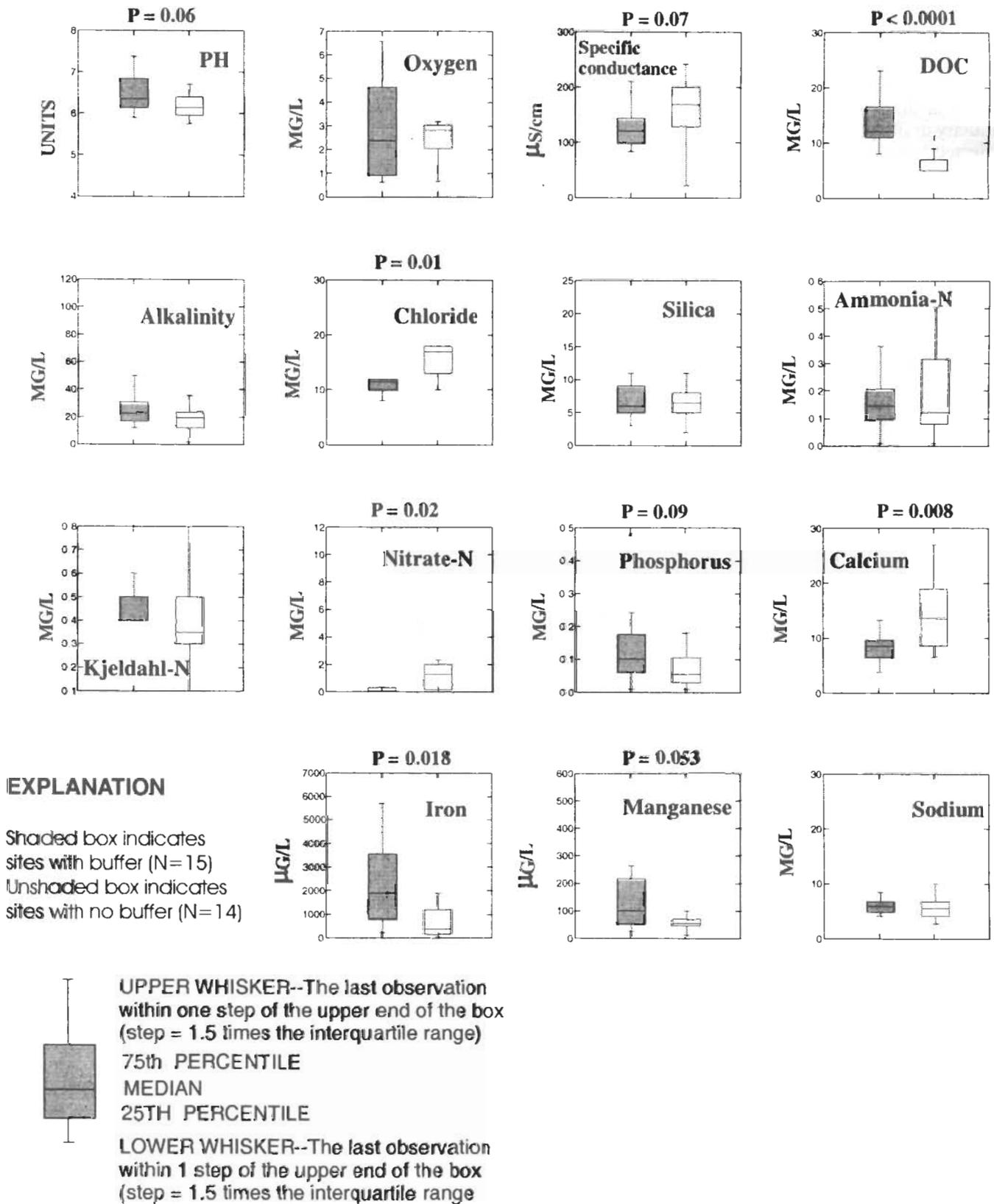


Fig. 7. Boxplots showing young ground water quality differences associated with forested buffers. Chemical constituents that were significantly different at  $\alpha = 0.10$  are shaded and the probability value is shown above each box.

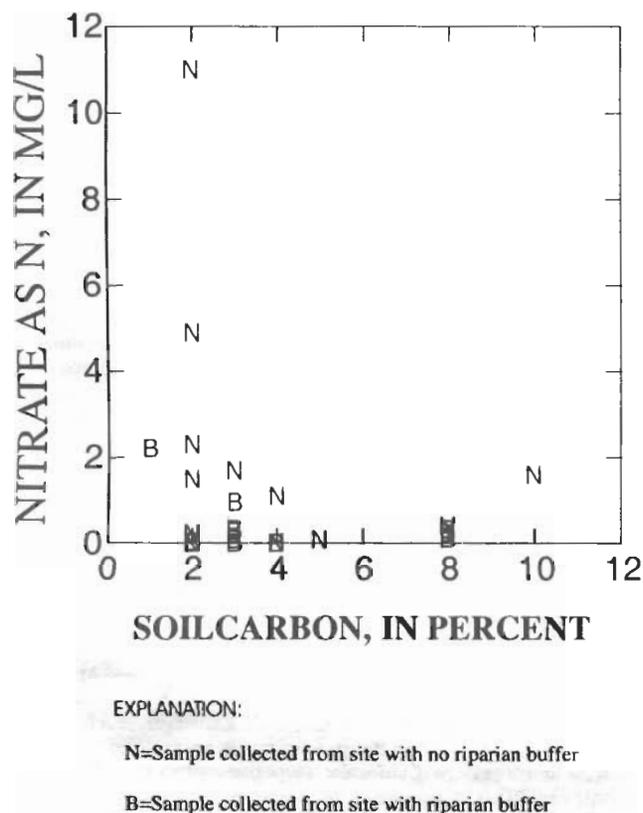


Fig. 8. Relationship of dissolved nitrate in young ground water with carbon content of soils adjacent to stream. Soil carbon data obtained from Natural Resource Conservation Service SURRGO data for Greene, Wilson, and Wayne Counties, North Carolina.

nitrification are difficult to measure, data from this study provides a basis for estimating the relative importance of both processes. The relative importance of these processes can be roughly determined by calculating the dilution for a conservative constituent, such as chloride, and comparing relative reduction of a nonconservative constituent, such as nitrate. If chloride concentrations from the young ground water in the buffer areas approximates typical chloride concentrations in shallow ground water that has moved from beneath agricultural fields and that has moved through riparian buffers (median of about  $11.5 \text{ mg L}^{-1}$ ; Fig. 7) and shallow ground water in the nonbuffer areas represents chloride concentrations under cultivated fields (about  $17.5 \text{ mg L}^{-1}$ ; Fig. 7), then the relative dilution taking place is  $(17.5 - 11.5)/17.5$ , or approximately 35%, through buffered areas. If dilution were also responsible only for the observed nitrate reduction in the young ground water, then the expected nitrate nitrogen concentration in buffer areas would be about  $1 \text{ mg L}^{-1}$  (a 35% reduction from the median  $1.5 \text{ mg L}^{-1}$  nitrate nitrogen concentration in shallow ground water from nonbuffer areas). However, nitrate nitrogen concentration in the shallow ground water of the buffer areas is only about  $0.06 \text{ mg L}^{-1}$  (Fig. 7), which is approximately a 95% reduction. Based on this simple analysis, then, about 30 to 35% of the decrease is due to dilution through riparian buffers and about 65 to 70% is due to other processes, presumably denitrification. Thus, a

riparian buffer can act on shallow ground water nitrate in two important ways: (i) by reducing nitrate through denitrification by providing a carbon source and (ii) by dilution by providing a contaminant-free recharge area.

## CONCLUSIONS

Riparian buffers can affect nitrate nitrogen concentrations and general ground water quality in two principal ways. First, riparian buffers can, at the watershed scale, affect old ground water discharging from long flow paths by increasing organic carbon buildup and debris on the streambed and creating a reducing reaction medium through which deep ground water must pass. Second, riparian buffers can affect young ground water discharging to streams by allowing dilution of chemical constituents along shallow flowpaths beneath the buffer zone before discharging to the stream and by generating organic carbon as DOC to drive denitrification and reduction reactions in the upper saturated zone beneath the buffer. Statistically, riparian buffers, both directly and indirectly, offer an effective way to reduce nitrate nitrogen concentrations in ground water and to improve water quality in streams. However, buffers may have increased concentrations of some elements, such as phosphorus, other forms of nitrogen, and silica, leading to increased concentrations of these elements in surface waters.

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