

GROUND-WATER NITRATE REMOVAL CAPACITY OF RIPARIAN ZONES
IN URBANIZING AND AGRICULTURAL WATERSHEDS

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ABSTRACT: We evaluated the relationship of dominant watershed land use to the structure and function of riparian zones with respect to nitrogen (N) dynamics. We focused on ground-water denitrification capacity, water table dynamics and the presence and pattern of organically-enriched deposits. We used the push-pull method (measurement of ¹⁵N-enriched denitrification gases derived from an introduced ground-water plume of ¹⁵N-enriched nitrate) to evaluate ground-water denitrification capacity on nine forested wetland riparian sites developed in alluvial or outwash parent materials in Southern New England. Three replicate sites were located in watersheds dominated by irrigated agriculture, suburban and forest. Soil morphology and water table dynamics were also assessed at each site. We found significantly lower mean annual water tables at sites within watersheds dominated by irrigated agriculture or suburban development versus forested watersheds. Water table dynamics were more variable at sites within suburban watersheds, experiencing greater extremes, especially during the summer. Ground-water denitrification capacity was significantly greater at sites within forested watersheds than at sites within watersheds dominated by irrigated agriculture. Because of the high degree of variability of sites within suburban watersheds, ground-water denitrification capacity was not significantly different from either forested or agricultural watersheds. The highly variable patterns of buried labile carbon and water tables at sites within both suburban and irrigated agricultural watersheds suggests that transport and depositional events are irregular, limiting the predictability of ground-water N dynamics in these riparian zones. Our results argue for effective source controls in urbanizing watersheds and in areas with irrigated agriculture.

KEY TERMS: riparian; ground water; nitrate; land use.

INTRODUCTION

Because ground-water hydrology plays a central role in the capacity of riparian zones to intercept and denitrify ground-water nitrate, any changes to hydrology may impact riparian function. Within suburban/urban watersheds impervious cover and storm drainage networks alter natural hydrologic flow paths and prevent infiltration and recharge to ground water, shifting water movement from ground-water flow to surface runoff (Schueler, 1994; Arnold and Gibbons, 1996). Surface runoff is diverted to storm-water systems, minimizing the potential for N transformations through interaction with upland and riparian ecosystems before entering streams, lakes and estuaries (Paul and Meyer, 2001; Gold et al., 2001). Reduced infiltration and recharge to ground water can lower riparian water tables, disconnecting ground water from biologically active surface soils. Within agricultural watersheds, high volume irrigation wells can also lower riparian water tables during the growing season. Lowered riparian water tables bring about long-term impacts on riparian hydrology and the quantity and quality of riparian soil organic matter (SOM).

While regional water tables in urbanizing watersheds tend to drop because of increased surface runoff, local conditions such as undersized or improperly located culverts may result in riparian flooding (Paul and Meyer, 2001), locally raising the water table from pre-development levels. In addition, locally high rates of sediment deposition may increase stream braiding, sustaining or raising riparian water tables. We hypothesize that riparian areas located in hydrologically-altered watersheds (i.e., irrigated agricultural and suburban/urban) will have higher spatial variability in ground-water denitrification rates than riparian areas in forested watersheds.

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To test this hypothesis we examined water table dynamics, soil morphology and ground-water denitrification capacity in riparian areas situated in watersheds dominated by irrigated agriculture or suburban/urban development as compared to those situated in watersheds dominated by forest (Kellogg et al., 2005).

Study Sites

Six riparian sites were located on first or second order streams throughout Rhode Island, USA:

- Ag1, Ag2 and Ag3 were within watersheds ranging in area from 47 to 590 ha, with 23 to 32% of the total area in agriculture, 19 to 42% forest and 2 to 5% impervious surface cover (ISC).
- Suburb1, Suburb2 and Suburb3 were within watersheds ranging in area from 30 to 206 ha and had ISC ranging from 35 to 46% of the total area, 0 to 2% agriculture, and 0 to 4% forest.

We compared these six sites located in developed watersheds to Forest1, Forest2 and Forest3 located within watersheds ranging in size from 90 to 1855 ha with 0% agriculture, 52 to 76% forest and ISC ranging from 1 to 3% described in detail by Kellogg et al. (2005). All sites were located on hydric soils with alluvial or glacial outwash parent materials. While the dominant land uses varied among watersheds, all riparian sites were forested, with the dominant species being red maple (*Acer rubrum* L.).

METHODS

Watershed boundaries were delineated by heads-up digitizing from geographically registered USGS 7.5-minute topographic quads. Land use within the watersheds was estimated using the MANAGE model (Joubert et al., 1996) based on statewide 1995 1:25,000 land use/land cover from the Rhode Island Geographic Information Systems (RIGIS) database. MANAGE aggregates some land use classifications and assigns ISC for each aggregate classification based on values developed for runoff calculations by USDA/NRCS (SCS, 1986). Changes in land use were noted by comparing aerial photographs taken in 1939 with those taken in 1995. Because the photos were not geo-referenced these changes could not be quantified.

At the six sites within developed watersheds a water table well was installed within the hydric soils of the riparian zone to a depth of approximately 1.75 m within 5 m of the stream. Similar water table wells had previously been installed at the sites within forested watersheds. Wells consisted of 3.8-cm i.d. PVC pipe with a pointed end cap and cover, slotted every 0.5 cm along the entire length. Water table wells were monitored at all nine sites monthly from January 2004 to August 2005. After levels were recorded wells were purged of two well volumes using a Masterflex L/S portable peristaltic pump (Cole Parmer, Vernon Hills, IL) and ground-water temperature recorded.

Mini-piezometers (0.8-cm o.d., 2-cm screen length; AMS, American Falls, ID) attached to gas-impermeable Teflon tubing were installed within 3 m of the stream. Mini-piezometer depth was guided by investigations of soil texture based on samples collected with a soil auger to determine permeable soil layers so that piezometers would be placed in layers conducting substantial ground-water flux. At four of the six sites, Ag2, Ag3, Suburb1 and Suburb2, three “shallow” mini-piezometers (50 cm to 90 cm below the soil surface) and three “deep” mini-piezometers (150 cm to 200 cm below the soil surface) were installed. Due to low saturated hydraulic conductivity within the upper meter at Ag1 and Suburb3, only 3 “deep” mini-piezometers were installed. All mini-piezometers were installed at least 2.5 m apart laterally.

At each of the sites a soil pit was dug in the hydric soil to a depth of approximately 1.5 m. Ground water was pumped from the pits at 600 L/min (Honda WP20X, American Honda Power Equipment Division, Alpharetta, GA), enabling soil characterization and sampling below the water table. Soil morphology was described using standard procedures. Soil samples were also obtained from auger borings to measure SOM content at the screened depth of each of the mini-piezometers approximately 1 m away laterally. To ensure the samples were not contaminated with carbon from surface soils, a small pit was dug and the sample collected when the depth of the pit was within one auger boring of the depth of the mini-piezometer. SOM content of soil samples was determined using the loss on ignition technique as described by Hanna (1964).

To estimate in situ ground-water denitrification capacity we used the push-pull method (Addy et al., 2002; Istok et al., 1997). We introduced a ground-water plume with ^{15}N -enriched $\text{NO}_3\text{-N}$ and a conservative tracer (SF_6) into each mini-piezometer. Following an incubation period of at least four hours the plume was extracted for analysis (Addy et al., 2002; Kellogg et al., 2005). Push-pull tests were performed twice during the autumn of 2004 because seasonally higher ground-water denitrification rates have been observed in this season (Kellogg et al.,

2005; Nelson et al., 1995). At least two weeks passed between the first and second denitrification push-pull tests, allowing time for any remaining plume to be flushed from the vicinity of the mini-piezometer. We based our denitrification capacity estimates on the second push-pull test to account for any microbial priming that would take place after initial exposure to elevated nitrate concentrations (Addy et al., 2002; Kellogg et al., 2005). Ambient, introduced and recovered ground-water samples were analyzed for temperature, dissolved oxygen (DO), dissolved organic carbon (DOC), NO₃⁻-N, dissolved SF₆, N₂, N₂O, ¹⁵N₂ and ¹⁵N₂O gases.

The Mann-Whitney U Test was used to compare water table heights and ground-water denitrification rates by dominant watershed land use. Spearman Rank Order correlations were used to determine significant correlations between ground-water denitrification capacity, ambient NO₃⁻-N concentrations, DO, temperature, depth, and SOM content. All statistical analyses were performed with STATISTICA 6.0 (StatSoft, Inc., Tulsa, OK). Statistical significance was set at $p < 0.05$ in all cases.

RESULTS

Buried organically-enriched layers were observed at all six sites and the three sites from forested watersheds monitored by Kellogg et al. (2005). Evidence of anthropogenic disturbance was noted at all sites within suburban watersheds where buried fragments of glass, plastic and other debris were found. For example, multiple buried graminoid layers (i.e., grasses, sedges or rushes) were recorded at Suburb2 from 0.37 to 1.24 m depth. Also at this site glass fragments were recovered to a depth of 0.27 m and plastic fragments were recovered down to 0.38 m suggesting that the upper 0.38 m were deposited over the last 50 to 60 years. The 1939 aerial photographs of this area show a large expanse of agricultural land that has since been converted to suburban development.

When grouped by dominant watershed land use, ambient nitrate was significantly higher at the suburban and agricultural sites than at the sites in forested watersheds, while not significantly different from each other. Ambient ground-water DO at the agricultural sites was significantly lower than at the suburban sites, though the DO at the sites in forested watersheds was not significantly different from the DO at sites in either agricultural or the suburban watersheds. Ambient DOC at the sites in forested watersheds was significantly higher than sites in either the agricultural or suburban watersheds. When all sites were taken together, DO and DOC were significantly correlated with ground-water denitrification capacity, though this pattern did not hold across the three watershed types when considered separately.

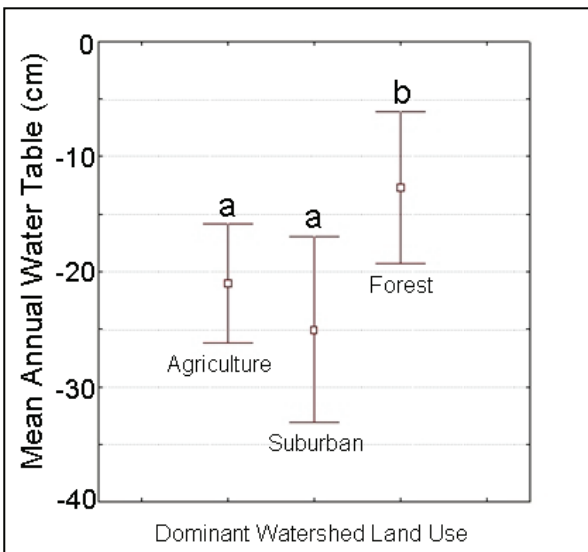


Figure 1. Mean Annual Water Table Depths (cm). Letters denote significant differences ($p < 0.05$).

Table 1. Summer Water Table Depths (cm): Lower (25%) and Upper (75%) Quartile Range

Dominant Watershed Land Use	Lower (25%) Quartile	Upper (75%) Quartile
Agriculture	18.9	47.9
Suburban	9.6	61.8
Forest	25.5	34.1

Water tables generally showed typical seasonal variation for forested riparian wetlands in the temperate northeast: highest in the winter and spring and lowest in summer and early autumn. All sites experienced occasional surface flooding in winter. During the summer months water tables occasionally dropped to more than 0.5 m below the soil surface at several of the sites. Mean annual water table depths were significantly deeper at

sites within both agricultural and suburban watersheds than at sites within forested watersheds, and not significantly different from each other (Figure 1). There were no significant differences in mean summer water table depths among the three watershed types, though variability was much higher in suburban and agricultural watersheds (Table 1), based on inter quartile ranges, with the suburban sites displaying a degree of “flashiness” in the water table.

In situ ground-water denitrification capacity measured in the shallow wells was not significantly different from that measured in deep wells so shallow and deep wells were pooled. The sites within forested watersheds had a significantly higher mean (\pm SE) in situ denitrification capacity ($64.3 \mu\text{g/kg soil/day} \pm 15.3$) than those within agricultural watersheds ($17.2 \mu\text{g/kg soil/day} \pm 6.0$), while the sites within suburban watersheds ($23.9 \mu\text{g/kg soil/day} \pm 12.7$) did not differ significantly from those in either forested or agricultural watersheds. At least 30% of samples from all watershed types displayed very low denitrification capacity; however high rates were most commonly observed in the forested watersheds (Figure 2). In situ ground-water denitrification rates within suburban watersheds displayed very high variability reflected in the long “tail” of the cumulative distribution function. Less than 10% of values observed in the suburban watersheds exceeded rates of $10 \mu\text{g/kg soil/day}$. In contrast, 70% of the values observed in forested watersheds exceeded that rate.

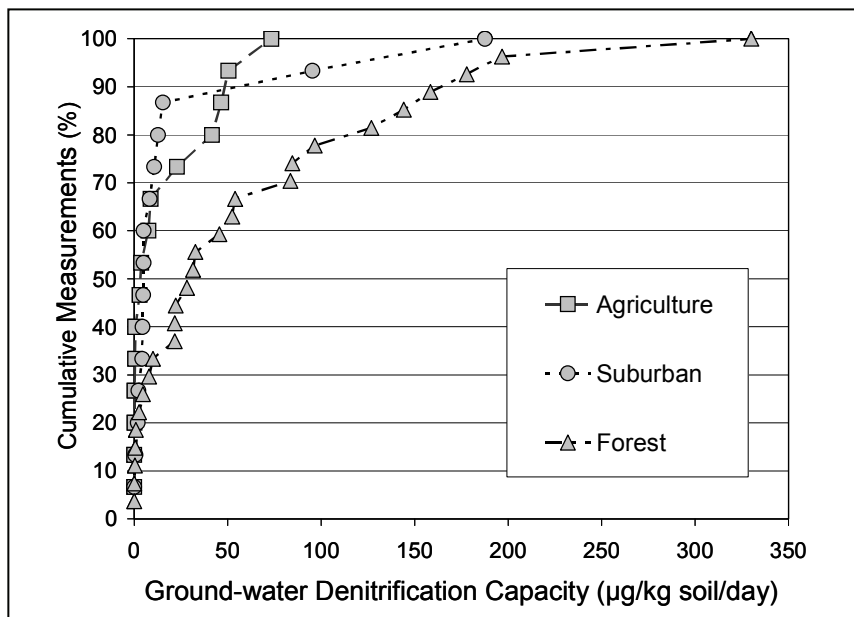


Figure 2. Cumulative Distribution of Ground-water Denitrification Capacity across Dominant Watershed Land Use Types. Each point represents one push-pull test: Agriculture ($n = 15$), Suburban ($n = 15$), Forest ($n = 27$).

DISCUSSION

Water table dynamics were more variable in developed watersheds, especially in summer, consistent with our hypothesis. Our study sites were located on low gradient streams which limited the extent of potential incisement and therefore, the degree to which the mean annual water table might drop at these sites. In addition to the low gradients, the stream bank soils consisted of erodible sands and silts with very low clay content (<5%), minimizing the development of steep stream banks. The suburban streams and riparian zones displayed substantial sedimentation and evidence of buried soils, similar to the findings of Walter and Merritts (2008). Past studies in urban areas (Groffman et al., 2002; Burt et al., 1999) have found incised steam channels, deeper riparian water tables and lower riparian ground-water denitrification. Those study sites were generally situated along higher gradient streams and with soils with somewhat higher clay content than our study sites.

The higher range of riparian water table elevation observed in the developed watersheds may be related to road culverts, sedimentation and irrigation as well as changes in watershed infiltration. At two suburban sites (Suburb1 and Suburb3) and two of the agricultural sites (Ag1 and Ag2), culverts were located less than 100 m downstream from the site. At several of these sites there was noticeable back-up behind culverts, restricting

stream flow and potentially locally raising the water table following runoff events. Lower average annual water tables at sites in agricultural watersheds corresponded to sites with some stream enlargement (i.e., deepening and/or widening) and/or irrigation in nearby agricultural areas.

Of the sites located in developed watersheds, the highest rate of denitrification capacity was observed at Suburb2 where buried layers of partially decomposed graminoid material were noted. The high rates of denitrification capacity and buried graminoid materials were only observed at shallow depths. Although the deep wells at this site were less than 4 meters away from the shallow wells, denitrification capacity was substantially lower in the deep wells. Paul and Meyer (2001) have described a spatial and temporal continuum of stream disturbance characteristics in urbanizing watersheds which is consistent with the high degree of variability in water table dynamics and ground-water denitrification capacity found within our suburban watersheds.

Most watersheds in Rhode Island have been subjected to human disturbance in the form of agriculture or urbanization in the past 200 years. Based on 1939 aerial photos, all the suburban and agricultural watersheds selected for this study have been subject to human disturbance for more than 65 years. This was confirmed by evidence found in the riparian soils of both the agricultural and suburban watersheds. All nine of the sites had buried organically-enriched soil horizons and the suburban sites also had buried glass and plastic fragments. These buried layers may be the result of flashy streams or upstream construction activities. The increased velocity associated with storm flows in urbanizing watersheds is capable of carrying and depositing large loads of mineral sediment and organic debris either in the stream channel itself or onto riparian areas.

CONCLUSION

Riparian zones in watersheds with irrigated agriculture or suburban development display an array of disturbances that restrict our ability to relate riparian ground-water denitrification capacity to generalized site or watershed characteristics. Conditions that favor ground-water denitrification, labile carbon and low DO, were found at sites within both suburban and agricultural watersheds, but did not occur in any consistent or predictable way. The highly variable patterns of buried labile carbon at sites within both suburban and agricultural watersheds suggests that transport and depositional events are irregular, limiting the predictability of N dynamics in riparian zones of disturbed watersheds. These results argue for effective source controls in urbanizing watersheds and in areas with irrigated agriculture.

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