

## LANDSCAPE ATTRIBUTES AS CONTROLS ON GROUND WATER NITRATE REMOVAL CAPACITY OF RIPARIAN ZONES<sup>1</sup>

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**ABSTRACT:** Inherent site factors can generate substantial variation in the ground water nitrate removal capacity of riparian zones. This paper examines research in the glaciated Northeast to relate variability in ground water nitrate removal to site attributes depicted in readily available spatial databases, such as SSURGO. Linking site-specific studies of riparian ground water nitrate removal to spatial data can help target high-value riparian locations for restoration or protection and improve the modeling of watershed nitrogen flux. Site attributes, such as hydric soil status (soil wetness) and geomorphology, affect the interaction of nitrate-enriched ground water with portions of the soil ecosystem possessing elevated biogeochemical transformation rates (i.e., biologically active zones). At our riparian sites, high ground water nitrate-N removal rates were restricted to hydric soils. Geomorphology provided insights into ground water flowpaths. Riparian sites located on outwash and organic/alluvial deposits have high potential for nitrate-enriched ground water to interact with biologically active zones. In till deposits, ground water nitrate removal capacity may be limited by the high occurrence of surface seeps that markedly reduce the time available for biological transformations to occur within the riparian zone. To fully realize the value of riparian zones for nitrate retention, landscape controls of riparian nitrate removal in different climatic and physiographic regions must be determined and translated into available spatial databases.

(KEY TERMS: watershed management; nonpoint source pollution; water quality; riparian zones; nitrate; wetlands.)

### INTRODUCTION

There is great interest in the role of riparian zones as sinks for watershed nitrate. Watershed nitrate loading poses a potential threat to the quality of coastal waters throughout the temperate zone of the Northern Hemisphere, from the Gulf of Mexico

(Rabalais *et al.*, 1996) to the Baltic Sea (Howarth *et al.*, 1996). Because nitrate is primarily transported to streams via ground water flow, biogeochemical transformations at the interface of streams and the land margin can have a large influence on the export of nitrate from watersheds (Hedin *et al.*, 1998; Lowrance, 1998). However, riparian zones display wide variation in their ground water nitrate removal capacity (Correll, 1997). Clearly, the age and species composition of the vegetated community will have profound effects on riparian nitrate dynamics (Haycock and Pinay, 1993; Osborne and Kovacic, 1993; Schultz *et al.*, 1995; Correll, 2000). However, the nitrate removal capacity of a riparian zone hinges on the interaction of nitrate-enriched ground water with components of the riparian zone that support removal processes, e.g., plant or microbial uptake or denitrification, the anaerobic conversion of nitrate to nitrogen gas. Site attributes, such as hydric status and geomorphology, can affect the interaction of nitrate-enriched ground water with portions of the soil ecosystem possessing elevated biogeochemical transformation rates (i.e., biologically active zones).

We suggest that factors controlling the innate nitrate removal capacity of riparian zones must be recognized and incorporated into any dialogue that seeks to integrate riparian zones into watershed scale nitrate management schemes. Lowrance *et al.* (1995) used the coarse scale (1:250,000) State Soil Geographic Database (STATSGO; Soil Survey Staff, 1997) to provide insights into riparian zone function for the major physiographic zones of the Chesapeake Bay

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watershed. In our research, we use a combination of laboratory and field studies to relate variability in groundwater nitrate removal to site attributes that are depicted in finer scale Geographic Information System (GIS) spatial data bases, such as the digital Soil Survey Geographic data base (SSURGO; USDA, 1995). SSURGO provides high resolution (1:15,840-1:31,680) information on a number of attributes related to riparian zone nitrate dynamics, including the geomorphology and soil wetness (i.e., hydric status). By linking site-specific studies of riparian ground water nitrate dynamics to spatial data, we can improve assessment and modeling of watershed nitrogen dynamics. Models are increasingly in demand to help estimate Total Maximum Daily Loads (TMDL; Whittemore and Beebe, 2000) and to target remediation efforts. Through the use of GIS analyses, we can target management, restoration and protection of stream reaches where riparian buffers can have a marked effect on watershed nitrate dynamics.

In this paper we have summarized 12 years of effort to focus on the relationship of site attributes to riparian ground water nitrate removal capacity. In addition we explore potential effects of recent and historic watershed alterations on the structure and nitrate retention functions of riparian zones.

We have examined the capacity of riparian nitrate removal from shallow ground water in the three major geomorphic settings of the glaciated Northeast – outwash, till, and organic/alluvial deposits. Glacial outwash consists of level or gently sloping stratified sands with high hydraulic conductivity; glacial till is composed of unstratified drift with low hydraulic conductivity and often occurs on sloping lands; and organic/alluvial deposits are created by wetland conditions and/or riverine processes. To help isolate the effects of physical setting on ground water nitrate removal, our studies focus on mature, forested riparian zones, dominated by a mix of red maple (*Acer rubrum* L.) and white oak (*Quercus alba* L.), with red maple more prevalent in wetter riparian soils. All of our studies were conducted at sites within Rhode Island.

#### HYDRIC SOILS AND GROUND WATER NITRATE REMOVAL

Water table dynamics and soil wetness are critical components in ground water nitrate removal. Several studies have found substantial ground water denitrification where the water table was within 1 m of the surface, but little denitrification when water tables are deeper in the soil profile (Simmons *et al.*, 1992; Starr and Gillham, 1993; Nelson *et al.*, 1995; Gold *et*

*al.*, 1998). When the water table is close to the surface, nitrate-enriched ground water passes through material that is relatively rich in organic carbon, which supports denitrification activity. Plant roots and living microbes capable of taking up nitrate are also more abundant in near-surface soils.

Soils developed under conditions of saturation, partial saturation, flooding or ponding often display *hydromorphic* characteristics – morphological indicators of anaerobic conditions in the upper part of the soil profile – such as mottles, iron concentrations and depletions, gleying, and organically enriched surface horizons (Bell *et al.*, 1992; Vepreskas, 1992; Rabenhorst *et al.*, 1998). The *hydric* soil designation applies to the set of soil series that display hydromorphic characteristics (Vepreskas, 1992; Rabenhorst *et al.*, 1998). From our research on riparian sites in New England, we have found that hydric status of soil is a useful indicator of water table dynamics. Nonhydric riparian soils occur where the seasonal high water table is greater than 60 cm from the soil surface. In riparian zones with hydric soils, the water table typically rises within 30 cm of the ground surface during much of the year.

Shallow water tables of hydric soils create a suite of conditions that promote denitrification. In particular, oxygen transfer from surface soils is restricted and aerobic decomposition of plant or alluvial derived organic matter is limited (Donahue *et al.*, 1983; Singer and Munns, 1991). In hydric soils, nitrate-enriched ground water may flow through reduced and carbon enriched surface soils (Figure 1a). Ground water nitrate flowing through nonhydric soils does not have the opportunity to interact with these reduced, organic laden materials (Figure 1b).

To examine ground water nitrate removal in hydric and nonhydric soils of riparian zones, we conducted *in situ* and mesocosm studies on four different outwash sites and one till site. In our *in situ* studies, we examined ground water nitrate removal by spiking the aquifer with a fixed ratio of bromide:nitrate (Simmons *et al.*, 1992; Nelson *et al.*, 1995). Bromide was used as a conservative, noninteractive tracer to characterize water flow and hydrodynamic processes (Sudicky *et al.*, 1983; LeBlanc *et al.*, 1991). Following ground water flow through a known volume of saturated soil, we sampled the introduced plume and obtained nitrate-N removal rates based on the ground water flux and changes in the ratio of bromide:nitrate. In the laboratory mesocosm studies (i.e., undisturbed saturated cores 15 cm in diameter and 40 cm long obtained from the saturated zone), we also used <sup>15</sup>N-enriched nitrate and observed denitrification gases that evolved during incubation and flow through the mesocosms (Gold *et al.*, 1998; Addy *et al.*, 1999).

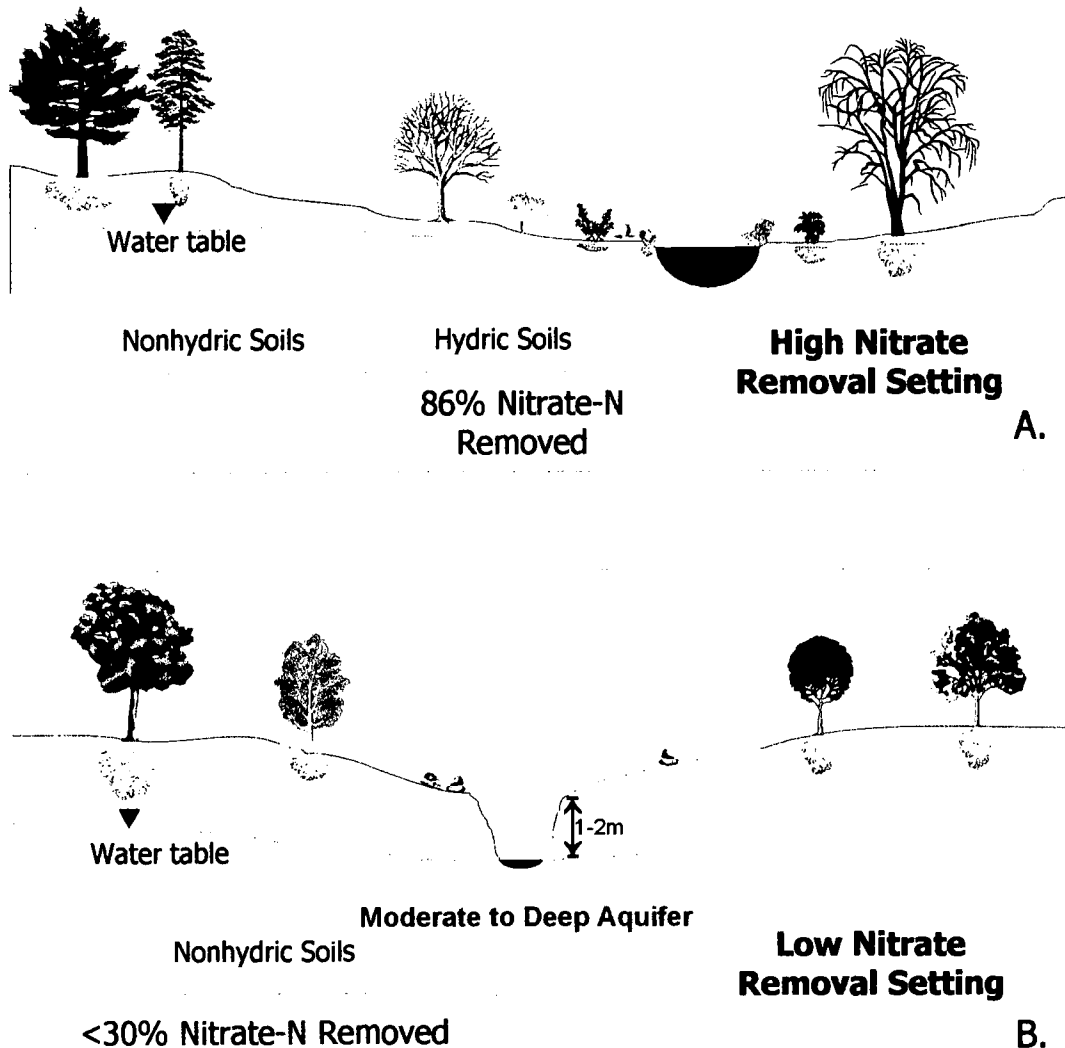


Figure 1. Hydric Soil Status and Nitrate-N Removal in Riparian Zones. In sites with hydric soils (A), ground water nitrate-N removal greater than 80 percent was noted. In contrast, in sites with steeper slopes and greater depth to water table (B), nonhydryc soils occurred and ground water nitrate-N removal was less than 30 percent. Data from Simmons *et al.* (1992).

Within these outwash and till sites, we observed large differences in ambient levels of dissolved oxygen and shallow ground water nitrate removal between hydric and nonhydryc soils. We found lower dissolved oxygen concentrations in shallow ground water of hydric soils than nonhydryc soils (Figure 2; Nelson *et al.*, 1995). High ground water nitrate-N removal was observed (Figure 2) in hydric soils and minimal ground water nitrate-N removal was found in nonhydryc soils (Simmons *et al.*, 1992; Hanson *et al.*, 1994; Nelson *et al.*, 1995; Gold *et al.*, 1998). Based on our mesocosm experiments, (Jacinithe *et al.*, 1998; Addy *et al.*, 1999) denitrification accounted for a substantial portion of the ground water nitrate-N removal rates in hydric soils (12 - 45  $\mu\text{g N kg/d}$ ) and was negligible

in the shallow ground water of nonhydryc soils (< 0.1  $\mu\text{g N kg/d}$ ).

#### GEOMORPHOLOGY AND RIPARIAN NITRATE REMOVAL CAPACITY

Our work and the work of colleagues in the southeastern U.S. demonstrate that hydric riparian zone soils can foster substantial removal of nitrate in the shallow ground water (Lowrance, 1992; Simmons *et al.*, 1992; Nelson *et al.*, 1995; Correll, 1997; Gilliam *et al.*, 1997; Gold *et al.*, 1998). Several important questions confound our ability to extend our observations

to the landscape or watershed scale. These questions hinge on the extent of interaction between nitrate-enriched ground water from upland sources and zones of high nitrate removal capacity within riparian zones. The geomorphology of a site may provide insights into several critical questions:

1. How do site conditions affect the depth of the biologically active zone of hydric riparian soils? Can we identify site attributes that enhance the potential for nitrate removal in situations where ground water flows at deeper depths (i.e., greater than 1 m)?

2. Can we identify soil and geomorphic settings where surface seeps bypass or "short-circuit" ground water interactions and nitrate removal within the biologically active portions of riparian soils?

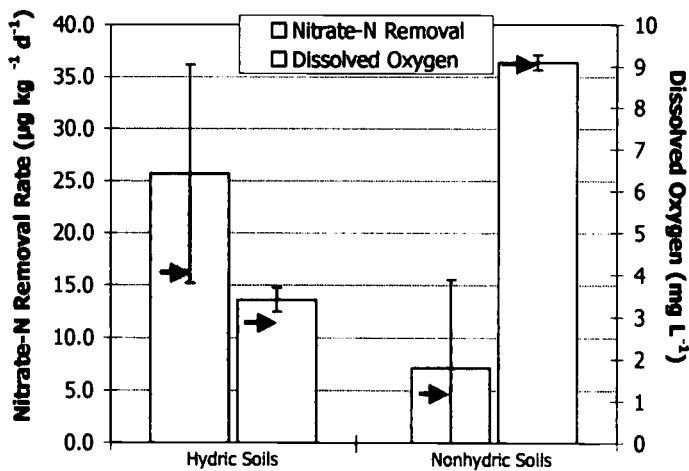


Figure 2. Dissolved Oxygen (DO) and Nitrate-N Removal Rate Vary by Hydric Soil Status in Riparian Zones. DO values are of 92 samples from Nelson *et al.* (1995). Nitrate-N removal rate values are from five sites included in Hanson *et al.* (1994), Nelson *et al.* (1995), Gold *et al.* (1998), and Addy *et al.* (1999). Annual mean is depicted by the length of each column, error bars represent standard error, and the arrows indicate the median value.

### Geomorphology and the Depth of the Biologically Active Zone

The ground water nitrate removal capacity of most soils is expected to be highest at the surface, where root density, organic matter and microbial activity are highest, and to decline rapidly with depth (Parkin and Meisinger, 1989; Groffman *et al.*, 1992). This upper zone of elevated ground water nitrate transformation rates is often termed the biologically active zone. The extent of interaction between nitrate-enriched ground water and the biologically active

zone is a key factor in the nitrate removal capacity of riparian zones. Hydric riparian soils appear to extend the depth of the biologically active zone. Within hydric soils we have consistently observed that root derived patches in the upper meter of ground water serve as hotspots of microbial activity and support high denitrification capacity (Jacinthe *et al.*, 1998; Addy *et al.*, 1999). In contrast, no patches were observed in the upper meter of ground water in non-hydric soils (Jacinthe *et al.*, 1998).

To explore the relationship of geomorphology with the depth of the biologically active zone within the ground water of hydric riparian areas, we have conducted field investigations on the occurrence and distribution of organically-enriched patches and horizons deep (i.e., up to 3 m) below the surface of hydric riparian soils. We have carefully examined the aquifer deposits at five different field sites using high capacity field pumps, observational pits, and coring. Based on the morphology of the upper 0.5 m of the solum and the landscape setting of the sites, three of the sites were initially classified as "outwash" and two of the sites were classified as "alluvial" deposits. In the two alluvial sites, we have observed layers of organic deposits 3 m below the water table. Surprisingly, organically-enriched layers of alluvial deposits and buried surface soils were also present below mineral soil deposits at all three "outwash" sites, suggesting that the depth of labile carbon and the depth of the biologically active zone might occur deeper into the aquifer than expected based on the surrounding geomorphology. Other riparian studies (Robertson *et al.*, 1991; Hill *et al.*, 2000; Devito *et al.*, 2000) have reported naturally occurring, organically-enriched deposits in the immediate vicinity of the stream and found substantial ground water nitrate removal within those deposits. Buried organic deposits may function similarly to artificial "denitrification walls," where sawdust-enriched trenches are constructed within the ground water to intercept and denitrify nitrate laden ground water (Schipper and Vojodic-Vukovic, 1998).

These buried deposits suggest that the geomorphology of hydric riparian zones may be strongly influenced by stream processes, highlighting their dynamic nature and reinforcing the fact that the effects of any watershed disturbance are concentrated and magnified within riparian zones. Our study area is prone to hurricanes that can violently and dramatically reshape stream channels and shorelines. A host of natural and human perturbations such as floods, land clearing, fires, and windthrow can result in events that alter a riparian zone through deposition of organic sediments or burial of organically-enriched surface horizons.

We are currently using laboratory and field studies to investigate the carbon lability, denitrification

potential, and ground water flow dynamics associated with these buried organically-enriched deposits. However, the occurrence of these buried horizons argues for the need to identify the types of site attributes, such as slope and hydric soil status, that reflect fluvial deposition of sediment and organic matter into riparian zones.

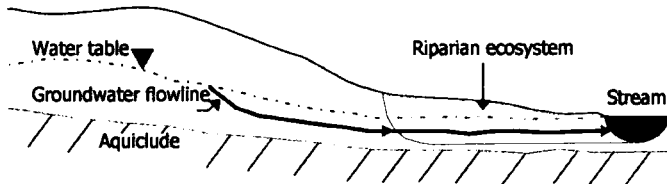
*Groundwater Flowpaths: Shallow vs. Deep Flow*

The extent of ground water nitrate removal within a riparian zone is tied to the flowpath and travel time through the riparian zone as well as the transformation rates along the flowpaths. Most of the riparian studies demonstrating high rates of ground water nitrate removal have been conducted in similar hydromorphic settings, i.e., shallow subsurface ground water flow through soil with relatively high levels of organic matter and roots, underlain by a shallow impermeable layer (Figure 3a; Hill, 1996). However, all ground water flow does not occur as

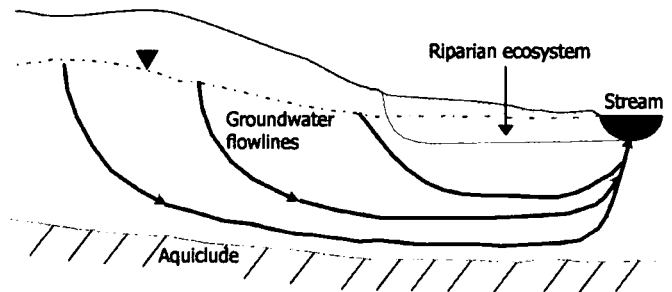
shallow subsurface flow. In deep outwash aquifers, a significant portion of the ground water recharge from distant sources may move deep below the riparian zone and upwell vertically to the stream, potentially “bypassing” the biologically active upper portions of hydric soils that consistently sustain high removal rates (Figure 3b; Hill, 1996).

These deep aquifers clearly present an important challenge for riparian researchers and reinforce the need to understand the relationship of ground water flowpaths with buried, organically-enriched layers in the near-stream vicinity and to understand the denitrification capacity of those layers (Hill *et al.*, 2000; Devito *et al.*, 2000). Geomorphology and stream order may govern whether ground water flow is shallow (Figure 3a) or deep (Figure 3b) within outwash deposits. For instance, outwash deposits are likely to be shallow within the headwaters of glaciated watersheds, where most lower order streams occur, promoting shallow ground water flow. These relationships between flowpaths, geomorphology, and stream order require further exploration.

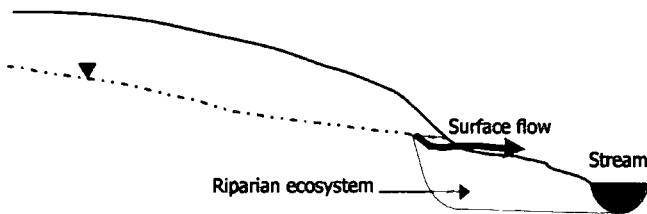
**A. Shallow Subsurface Groundwater**



**B. Deep Groundwater Bypass Flow**



**C. Groundwater Seep**



**D. Shoreline Alteration and Artificial Drainage**

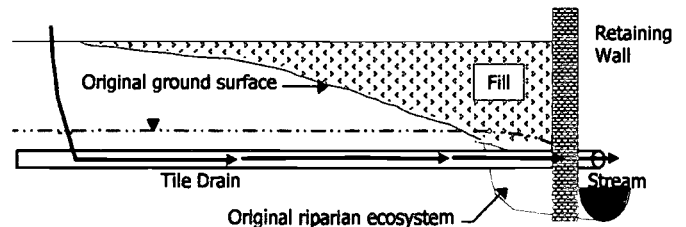


Figure 3. Ground Water Flowpaths Through Riparian Areas Can Control the Delivery of Nitrate-Enriched Ground Water to Streams. (A) Substantial interaction of ground water with biologically active zone in shallow aquifers. (B) Direct upwelling to streams in deep aquifers. (C) Bypass flow due to surface seeps. (D) Bypass flow due to filling and artificial drainage.

## Groundwater Flowpaths and Surface Seeps

The ground water nitrogen transformation capacity of hydric riparian soils can also be eclipsed if ground water “seeps” occur and dominate localized flow dynamics (Figure 3c). At seep locations, ground water emerges onto the ground surface and moves in small rivulets, traversing the riparian zone in a matter of hours, effectively bypassing the biologically active zone of riparian soils and lessening the retention time available for ground water nitrate removal to occur (Warwick and Hill, 1988). To examine the relationship of site characteristics to attributes affecting nitrate dynamics we conducted a detailed field reconnaissance at 100 randomly selected riparian locations in Rhode Island. At each site, we documented the geomorphology, width of hydric soils, and presence or absence of surface seeps (Rosenblatt *et al.*, 2001).

Surface seeps were found in over 85 percent of the “hydric” (defined in this study as hydric width greater than 10 m) riparian zones developed in till – potentially limiting their capacity for riparian ground water nitrate removal. In contrast, hydric riparian zones developed in outwash and organic/alluvial settings had few seeps (less than 11 percent), and hold considerable potential for ground water nitrate removal, particularly in those settings where nitrate-enriched ground water flow occurs within the upper portions of the aquifer.

### Groundwater Flowpaths: Impact of Human Disturbance

A variety of human activities can potentially reduce the capacity of riparian zones for ground water nitrate removal (Figure 3d). In artificially drained croplands, numerous studies have documented high ground water nitrate concentrations, where drainage networks bypass the biologically active portion of riparian aquifers (David *et al.*, 1997). This bypass flow can also occur in urbanized riparian zones, where streambanks are altered through filling and artificial drainage.

In addition to direct alterations of streambanks, urban and suburban watersheds can affect multiple aspects important to the ground water nitrate removal potential of riparian zones. Increased imperviousness and storm drains induce flashy overland flow events and stream channels often undergo down-cutting and bank erosion (Nanson *et al.*, 1981; Booth, 1990). The deeper stream channels in combination with a decline in ground water recharge can lower the depth to the water table in urbanized riparian zones –

functionally shifting hydric riparian settings to non-hydric settings and separating nitrate-enriched ground water from the biologically active portions of riparian soils.

For example, in a study of ecosystem properties along a rural-urban gradient in Baltimore, Maryland, Groffman *et al.* (2002) found riparian water table depths greater than 1 m in suburban and urban watersheds, while riparian water tables within an undisturbed, reference forested watershed were within 30 cm of the soil surface (Figure 4). All water table wells were located 5 m from the streambank in lowlands of first and second order streams. The mean water table in the Baltimore forested reference riparian area was similar to the mean water table in undisturbed hydric riparian sites in Rhode Island, while the Baltimore suburban and urban riparian sites displayed water table elevations comparable to the non-hydric riparian zones in Rhode Island. Overstory trees at all sites were similar and consisted of species associated with wetland settings, suggesting that hydrologic changes in the suburban and urban locations may have occurred over the last several decades.

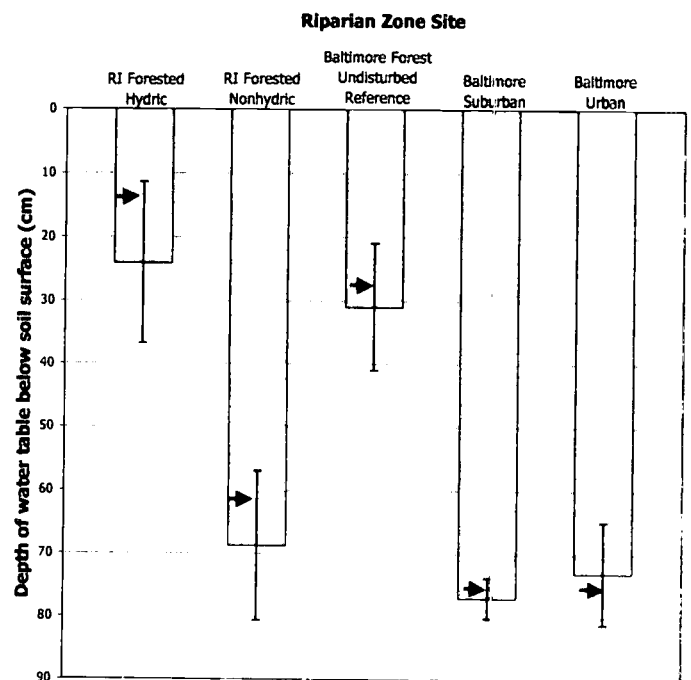


Figure 4. Depth of Water Table at Undisturbed and Disturbed Riparian Sites. RI data are water table depths at three hydric sites and three nonhydric sites included in Simmons *et al.* (1992) and Nelson *et al.* (1995). Baltimore Forest Undisturbed Reference and Urban data are water table depths from four wells at each of the respective sites (Groffman *et al.*, 2001 and unpublished data). Baltimore Suburban data are water table depths from four wells at each of two sites (Groffman *et al.*, 2001 and unpublished data). Annual mean is depicted by the length of each column, error bars represent standard error and the arrows indicate the median value.

Restoration of urban riparian zones must consider efforts to reverse the effects of urban hydrology on water table levels. Analysis of subsurface carbon sources in urban riparian zones should also be a priority. The dynamic hydrology of urban streams likely creates marked heterogeneity in floodplain sediments (including buried horizons) that could influence ground water denitrification – if ground water flow-paths can be directed through this media.

## CONCLUSION

We have used our investigations in the glaciated Northeast to illustrate the importance of soil wetness, geomorphology, and human alterations on the structural attributes that control riparian ground water nitrate removal capacity at the local and watershed scale. Discerning the various landscape controls of riparian ground water nitrate removal capacity in different climatic and physiographic regions is an essential element for effective management and evaluation strategies of watershed nitrate flux. As we refine our understanding of the influences of site attributes on riparian ground water nitrate removal capacity, we can identify and incorporate the necessary spatial data into management strategies and models that foster the protection and restoration of riparian zones and mitigate the effects of human disturbance on aquatic ecosystems.

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