Identifying Riparian Sinks for Watershed Nitrate using Soil Surveys

A. E. Rosenblatt, A. J. Gold,* M. H. Stolt, P. M. Groffman, and D. Q. Kellogg

ABSTRACT

The capacity of riparian zones to serve as critical control locations for watershed nitrogen flux varies with site characteristics. Without a means to stratify riparian zones into different levels of ground water nitrate removal capacity, this variability will confound spatially explicit *source–sink* models of watershed nitrate flux and limit efforts to target riparian restoration and management. We examined the capability of SSURGO (1:15 840 Soil Survey Geographic database) map classifications (slope class, geomorphology, and/or hydric soil designation) to identify riparian sites with high capacity for ground water nitrate removal. The study focused on 100 randomly selected riparian locations in a variety of forested and glaciated settings within Rhode Island. Geomorphic settings included till, outwash, and organic/alluvial deposits. We defined riparian zones with "high ground water nitrate removal capacity" as field sites possessing both >10 m of hydric soil width and an absence of ground water surface seeps. SSURGO classification based on a combination of geomorphology and hydric soil status created two functionally distinct sets of riparian sites. More than 75% of riparian sites classified by SSURGO as organic/alluvium–hydric or as outwash–hydric had field attributes that suggest a high capacity for ground water nitrate removal. In contrast, >85% of all till sites and nonhydric outwash sites had field characteristics that minimize the capacity for ground water nitrate removal. Comparing the STATSGO and SSURGO databases for a 64 000-ha watershed, STATSGO grossly under-represented critical riparian features. We conclude that the SSURGO database can provide modelers and managers with important insights into riparian zone nitrogen removal potential.

Our understanding of watershed export of nitrogen (N) is beset by uncertainties surrounding the role of *sinks*—areas within a watershed that are capable of removing N before it can be delivered to receiving waters. In watersheds ranging from local (i.e., 1000 ha) to continental (i.e., the Mississippi Basin) scales, researchers have found that riverine discharges account for less than one-third of the anthropogenic input of N to the watershed (Jordan et al., 1997; Howarth et al., 1996). Nitrate in subsurface flow often constitutes the majority of nonpoint source N loading to streams (Lowrance et al., 1997; Correll, 1997). Nitrate can be retained or removed through soil and plant processes from ground water, streams, and riparian zones that border surface waters.

Riparian zones can serve as critical control points for nitrogen flux within a watershed (Hill, 1996; Gilliam et al., 1997; Hedin et al., 1998). In many watersheds, ground water recharge from upland areas moves through riparian zones before discharging as baseflow to streams (Correll, 1997; Winter et al., 1998). Dramatic changes in riparian zone ground water quality have been observed over short distances, particularly if the water table within the riparian zone approaches the surface and encounters anaerobic soils with high accumulations of organic carbon. There is great interest in incorporating riparian zone N processing in watershed-scale models of N dynamics. Riparian zones display great variability in their water table dynamics and patterns of subsurface carbon and nitrogen removal capacity (Simmons et al., 1992; Nelson et al., 1995; Correll, 1997; Lowrance, 1998). Watershed-scale models of nitrogen dynamics may benefit from the inclusion of data on the extent and variation of characteristics that affect nitrogen retention by riparian zones. As with all proposed enhancements to watershed modeling, this endeavor requires an assessment of the accuracy of the spatial data available to depict key properties (Wagenet and Hutson, 1996; Whittemore and Beebe, 2000). Currently, a number of watershed scale models use the State Soil Geographic Database (STATSGO) as a source of input data for total maximum daily load (TMDL) assessments (USEPA, 2000). STATSGO has a scale of 1:250 000 with minimum line widths that equate with field widths in excess of 60 m and minimum mappable polygons (i.e., the minimum size of a soil unit that can be delineated on a map) greater than 600 ha (Soil Survey Staff, 1997). This scale is quite coarse relative to the size of many riparian zone features.

There is great interest in developing relationships between riparian nitrogen removal capacity and visually obvious (i.e., mappable) field attributes. Pinay et al. (1995) suggest that geomorphic features can provide insight into riparian zone denitrification capacity. Lowrance et al. (1997) used STATSGO to classify riparian nutrient retention functions in different geomorphic regions of the Chesapeake Basin and the Delmarva Peninsula. In that area, certain geomorphic regions are dominated by level riparian zones with high water tables, conditions that have been found to generate substantial ground water nitrate removal (Correll, 1997). In previous work, we have found substantial ground water nitrate removal in riparian zones with hydric soils (Simmons et al., 1992; Nelson et al., 1995; Gold et al., 1998). The hydric soil designation was developed to enhance wetland classification and is now linked to specific soil series with high water tables (Soil Survey Staff, 1993). Dramatic declines in dissolved oxygen concentrations and substantial increases in ground water nitrate removal capacity often occur within the first several meters of hydric soils (Simmons et al., 1992; Nelson et al., 1995). We have also observed little ground water nitrate removal in nonhydric riparian soils that develop in re-

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Abbreviations: PD, poorly drained soil; SSURGO, Soil Survey Geographic database; STATSGO, State Soil Geographic database; USGS, U.S. Geological Survey; VPD, very poorly drained soil.

sponse to deep water tables and often occur in settings adjacent to deeply incised streams.

The presence of hydric soils in riparian zones does not assure retention of N from upland sources. Another source of variation in riparian ground water nitrate removal occurs where ground water emerges in surface *seeps* at the upland boundary of hydric soils and traverses the riparian zone as surface runoff. In this type of setting, Hill (1996) found minimal ground water nitrate removal due to insufficient retention and interaction of nitrate-laden ground water with biologically active portions of the root zone. Unlike surface seeps, upwelling of deep ground water directly into the stream is difficult to recognize from visual observations. Areas dominated by upwelling may have limited riparian ground water nitrate removal potential, since ground water flowpaths traverse riparian zones at depths well below the biologically active, upper zone of hydric soils (i.e., <1–2 m) (Devito et al., 2000; Hill et al., 2000). Seeps and upwelling are a function of structure and may be related to other mappable features, such as geomorphology of the site.

Riparian attributes conducive to substantial ground water N removal often occur in narrow strips less than 30 m from the stream (Nelson et al., 1995). Several studies have found that most reduction of ground water nitrate concentration occurs within the first 10 to 15 m of a riparian forest (Lowrance et al., 1984; Peterjohn and Correll, 1984; Jacobs and Gilliam, 1985). Thus, accurate assessment of the role of riparian zones in the flux of nitrogen at the watershed scale may require high resolution data that may not be displayed at the STATSGO map scale. The Soil Survey Geographic (SSURGO) digital, georeferenced soil survey (Soil Survey Staff, 1997) database is at much finer scales (1:15 840–1:31 680) than STATSGO. In a previous study (Gold et al., 1989), we found that soil survey data at a scale of 1:15 840 provided an accurate assessment of surficial geology. Line widths on SSURGO maps equate with actual field widths of 4 to 8 m. Both STATSGO and SSURGO soil databases contain spatially explicit information on hydric soil status and geomorphology; however, the SSURGO data set affords greater detail for identifying these attributes at the riparian scale.

Here we present the results of an intensive field reconnaissance study that examined the relationship between selected field (i.e., groundtruthed) characteristics of riparian zones (i.e., hydric soil widths, presence of surface seeps) and SSURGO map classifications. Our goal was to determine the efficacy of using SSURGO data to improve our ability to classify the ground water N removal capacity of riparian zones for use in watershed modeling, protection, and restoration efforts.

METHODS

Description of the Study Area

The study sites were located on first- and second-order streams in the 64 000-ha Pawcatuck River Watershed in southern Rhode Island. Based on hydrographic data, digitized from 1:24 000 U.S. Geological Survey (USGS) 7.5 minute topographic quadrangle maps (Rhode Island Geographic Information System, 1988), first- and second-order streams comprise 70% of the total stream length in the drainage network. The soil parent materials in the watershed are comprised primarily of glacial till, glacial outwash, and organic and alluvial deposits (Rector, 1981). Soil orders found within the watershed include Inceptisols, Histosols, and Entisols.

Glacial tills are unstratified deposits of sand, silt, clay, and boulders that are located on gently sloping uplands and higher-gradient drumlins (Wright and Sautter, 1988). Tills can be either ablation (loose) or basal (dense). Hydraulic conductivity values for Rhode Island tills range from 4×10^{-3} to 1×10^{-2} cm s^{-1} in ablation tills to $<1 \times 10^{-4}$ cm s^{-1} in basal tills (Rector, 1981). Soils developed from dense basal till generally have higher hydraulic conductivity in the upper horizons (above the dense till layer) resulting in perched water table systems and shallow ground water flow. Streams in till areas usually have a high gradient due to the relative position of till on the landscape. Floodplains are uncommon in till settings. Glacial outwash deposits are stratified layers of sand and gravel deposited by glacial meltwater streams. They typically occur in valleys commonly referred to as outwash plains (Rector, 1981). Hydraulic conductivity values of Rhode Island outwash soils can range from 1×10^{-3} to 1×10^{-2} cm s^{-1} (Rector, 1981). Streams in outwash are at low gradients and often have low flow velocities. Organic soils have extremely high water holding capacities and high water tables for a significant portion of the year. Alluvial soils occur as floodplains where sand and silt is deposited by streams during flooding. Both organic and alluvial deposits are usually found on flat areas of the landscape having low gradients (Wright and Sautter, 1988).

Site Selection

We randomly located approximately 1500 orthogonal site lines on the 362 km of first- and second-order streams in the watershed using a digitized, georeferenced USGS 1:24 000 topographic hydrography coverage (Rhode Island Geographic Information System, 1988) that meets Federal Geographic Data Committee standards. The orthogonal site lines were added graphically to all first- and second-order streams on the digital stream coverage by on-screen digitizing, at approximately 250-m intervals. Each site line was assigned a unique identification number. Using a random number generator, sites were randomly selected. Less than 10% of potential sites were discarded after screening for landowner permission to enter private property. In total, 100 randomly generated sites were selected and used for field data collection.

Field reconnaissance maps were developed for each of the 100 sampling sites using ArcView 3.1 software (Environmental Systems Research Institute, 1998). These maps incorporated 1995 digital orthophotography (1:12 000 scale) as a backdrop to the orthogonal site lines. Using the reconnaissance maps, sites were pinpointed through orienting methods using obvious landscape features such as road intersections and farm fields as points of reference. A measuring tape and compass were used to determine exact site locations.

We used the SSURGO digital spatial database for Rhode Island developed in 1996 (USDA, 1998) to compare soil map unit attributes with field results. We corrected the Rhode Island SSURGO data set to parallel current requirements for SSURGO certification standards. Since 1998, all new SSURGO databases contain a hydrography data layer (hydrolines) digitized from the original soil survey report. Rhode Island SSURGO does not have a separate hydrography layer. To overcome this limitation, we used the USGS digitized hydrolines during site location. Sites were then visually matched to the hydrolines in the original soil survey report to determine the exact SSURGO riparian soil map unit for use in determining a site's SSURGO categorization in analysis.

The SSURGO database classified the 100 study sites into 25 different soil map units. We compared the distribution of soil parent material and hydric status of the SSURGO designated map units at the study sites with the distribution of those attributes in the soil map units found along the entire length of riparian corridors of all lower-order streams of the study area. Hydric soils formed in till, outwash, or organic/alluvium comprised 69% of the undisturbed soils based on SSURGO data of a 30-m buffer of the lower-order streams throughout the entire study area. Within the 100 sites selected for this study, the SSURGO database classified 73% as hydric soils, suggesting that the sites were reasonably representative of the overall watershed.

Site Vegetation and Stream Classification

The riparian sites were forested and displayed no recent signs of cutting or disturbance. In most hydric soils the dominant overstory tree was red maple (*Acer rubrum* L.), with sweet pepperbush (*Clethra alnifolia* L.), highbush blueberry (*Vaccinium corymbosum* L.), sphagnum moss (*Sphagnum* sp.), skunk cabbage [*Symplocarpus foetidus* (L.) Salisb. ex W.P.C. Barton], and cinnamon fern (*Osmunda cinnamomea* L.) commonly comprising understory species. In the upland portions of the riparian sites, white pine (*Pinus strobus* L.), red oak (*Quercus rubra* L.), white oak (*Quercus alba* L), and red maple were the dominant tree species, with bullbrier (*Smilax rotundifolia* L.), cinnamon fern, sweet pepperbush, and *Lycopodium* sp. as the common understory species. All sites met the Riverine Lower Perennial system and subsystem classification as defined for the National Wetlands Inventory (Cowardin et al., 1979).

Site Characterization

At each site, six transect lines were delineated into the riparian forest. These transects were perpendicular to the stream channel with three on each side of the stream (specified as left and right banks determined from the direction of stream flow). On each bank, the three transects were placed 7.5 m apart and extended in parallel 30 m away from the stream channel (Fig. 1). Thus, each site encompassed an area 15 m (along the stream) × 60 m (perpendicular to the stream). The top of the stream bank was used to define the stream channel edge.

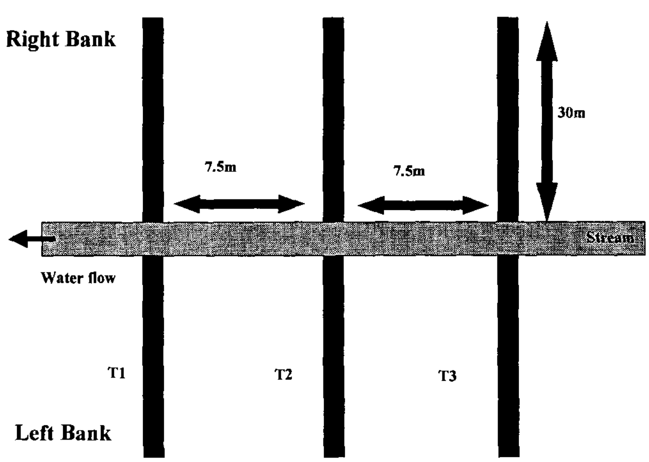

Fig. 1. Plan view of a site layout. Each site consisted of a left and right bank, determined from the direction of stream flow. Each bank contained three transects, 7.5 m apart and 30 m long. The three transects extended parallel to one another and perpendicular to the stream, beginning at the top of the stream bank.

Along each transect we used a soil auger to determine the depth to hydromorphic features, which include both redoximorphic features and features related to the accumulation of organic matter. Based on these features, soil drainage class boundaries of VPD/PD, PD/SPD, SPD/MWD (VPD, very poorly drained; PD, poorly drained; SPD, somewhat poorly drained; and MWD, moderately well drained) and hydric soil boundaries were delineated along each transect line within the first 30 m from the stream bank.

On each stream bank the width of each soil drainage class and the hydric soil widths from the three transects were averaged to create a set of mean drainage class widths and mean hydric soil widths per bank. Transect averages were used for all direct comparisons with the digitally derived SSURGO data for the same cross-section. Transects were located along straight stream reaches, rather than meanders, in order to minimize intrasite variability. By averaging the three transects per bank we hoped to account for some of the spatial error associated with the width of the digitized site line.

For each site, we recorded the presence or absence of seeps. Ground water surface seeps, also referred to as lateral springs (Downes et al., 1997), occur at the base of sloping lands within certain riparian zones of the study area. The upslope edge of such seeps is easily identified by distinct vertical faces usually 15 to 30 cm in height where mineral soil materials are exposed. Immediately upslope of the seepage face, the soils are mineral and nonhydric, while organic soil materials typically occur at the base of the seepage face. These seeps generate surface water at the bottom of the exposed mineral face for either the entire year or during the spring and fall, when water tables are elevated. Defined rivulets often emanate from the seepage face, but do not exist above the seep, suggesting that the surface water observed is not the result of upland runoff, but rather from ground water emerging at the seepage face.

Statistical Analyses

We examined the symmetry of left and right banks of the sites using a *t* test and found that within a site, the hydric soil widths of adjacent banks were not independent at the $p <$ 0.05 level. As a result, a data set was created that used only one bank per site by selecting a random bank from each site for all statistical comparisons. This was done by assigning a random number to each of the 100 sites. If the random number was even, then the right bank was used, and if the random number was odd, then the left bank was used in all statistical comparisons.

For the following attribute categories, each field site was placed into a particular class based on the characteristics of the SSURGO soil map unit identified through the digital site line:

(i) SSURGO slope classes: A, 0 to 3%; B, 0 to 8%; C, 3 to 15%; or D, 15 to 25%.
(ii) SSURGO geomorphic class: All sites were classified as either till, outwash, or organic/alluvium based on the soil map unit's description of the soil parent material.
(iii) SSURGO hydromorphic class: Each site was classified as either hydric or nonhydric using the hydric soils designation of the soil map unit (Soil Survey Staff, 1991).
(iv) SSURGO hydrogeomorphic classes: Both the hydric status and SSURGO geomorphic classification were assigned to a riparian soil map unit. Hydrogeomorphic settings are either till–hydric, outwash–hydric, organic/alluvium, till–nonhydric, or outwash–nonhydric.

Within each SSURGO category we used analysis of variance (ANOVA) to test the equality of means of field-measured hydric soil width between category classes. Where there was significance, Tukey's Honest Significant Difference (HSD) test was used to test for differences between classes (Ott, 1993). In addition, within each SSURGO category, we used Chi Square analyses to examine differences in the occurrence of observed surface seeps between category classes. All statistical analyses were performed on Statistica for Windows (StatSoft, 1999). Significant differences for all statistical analyses are reported at $p < 0.05$.

Several of the classes found in different SSURGO categories are interrelated. Within the soil units of the study area all organic/alluvium soil units are also classified as hydric soils. In addition, within the 100 study sites, all soil map units classified as hydric also were classified as SSURGO Slope Class A (0–3%), and 96% of all A slope classes were mapped hydric.

High Capacity Ground Water Nitrate Removal Riparian Sites

Based on past research findings (Lowrance et al., 1984; Peterjohn and Correll, 1984; Jacobs and Gilliam, 1985; Hill, 1991, 1996) we defined "high capacity ground water nitrate removal riparian sites" based on the co-occurrence of >10 m of groundtruthed hydric soil width and an absence of surface seeps. We examined the proportion of sites with those features within each soil survey category class. We then explored the effects of map scale on the depiction of soil map units in the riparian zone with high capacity for ground water nitrate removal. We compared the STATSGO and SSURGO databases within the entire 64 000 ha of the study area. We used the attribute files of each database to depict selected soil map units that bordered the entire stream network of the digitized, georeferenced USGS 1:24 000 topographic hydrography coverage (Rhode Island Geographic Information System, 1988). The extent and pattern of stream reaches bordered by these queried soil map units were then obtained.

RESULTS

Hydric Soil Width and SSURGO Categorizations

The mean field width of hydric soils in the 100 riparian sites was 14.2 m, with a standard deviation of 12.6 m and a bimodal distribution. Hydric soil width was minimal (less than 3 m) on 32% of the sites and extensive (>27 m) on 31% of the sites. A number of the soil survey categorization schemes proved useful for stratifying the data into distinct classes. Mean hydric width varied significantly with slope class, hydromorphic class, geomorphic class, and hydrogeomorphic class.

SSURGO Slope Classes

The mean hydric width of the A slope class was significantly higher than the other three slope classes (Table 1). Hydric soil widths >10 m were found on more than 65% of the A slope class compared with less than 10% on each of the other slope classes.

Geomorphic Classes

Significant differences in mean hydric width were noted between SSURGO geomorphic classes. The organic/alluvium class had significantly greater mean hydric widths than either till or outwash classes (Table 2). More than 85% of organic/alluvium sites had >10 m of hydric soils present. Till and outwash settings did not differ significantly in mean hydric width. All SSURGO organic soil map units are listed as hydric soils, and within the study area, all alluvial soils are listed as hydric. Thus, all SSURGO organic/alluvium settings are classified as hydric soil.

Table 1. Goundtruthed riparian zone attributes of different SSURGO slope classes. Values obtained from 100 riparian sites located on lower-order streams.

	Groundtruthed site attributes			
SSURGO slope class†	Hydric soil width‡	Sites w/>10 m hydric width	Sites w/no seeps	Sites w/>10 m hydric width and no seeps
		% within class		
A: 0–3% n = 76§	17.8 (12.0)a¶	67a	68a	49a
B: 0–8% n = 10	2.1 (2.9)b	0b	70a	0b
C: 3–15% n = 11	3.8 (8.8)b	9b	82a	0b
D: 15–35% n = 3	2.9 (2.5)b	0b	33a	0b

† Class determined from the SSURGO database associated with the digitally located soil map unit corresponding to each field site.
‡ Values are means (standard deviation in parentheses).
§ n corresponds to the number of groundtruthed field sites within the particular SSURGO slope class.
¶ Values within a column followed by different letters were significantly different ($p < 0.05$).

Hydromorphic Classes

Great differences were found in the hydric width of sites classified as hydric vs. nonhydric. The mean groundtruthed hydric width of sites mapped by SSURGO as hydric was significantly and substantially higher than sites mapped as nonhydric (Table 3). Groundtruthed hydric soil widths >10 m occurred on 70% of sites classified as hydric compared with 4% of the sites classified as nonhydric.

Hydrogeomorphic Classes

The mean hydric widths of all three hydric hydrogeomorphic classes were significantly different than the two

Table 2. Groundtruthed riparian zone attributes of different SSURGO geomorphic classes. Values obtained from 100 riparian sites located on lower-order streams.

	Groundtruthed site attributes			
SSURGO geomorphic class†	Hydric soil width‡	Sites w/>10 m hydric width	Sites w/no seeps	Sites w/>10 m hydric width and no seeps
		% within class		
Till n = 51§	10.6 (12.2)a¶	37a	47a	10a
Outwash n = 28	13.9 (11.4)a	54a	89b	50b
Organic/ alluvium n = 21	23.4 (10.5)b	86b	95b	86c

† Class determined from the SSURGO database associated with the digitally located soil map unit corresponding to each field site.
‡ Values are means (standard deviation in parentheses).
§ n corresponds to the number of groundtruthed field sites within the particular SSURGO geomorphic class.
¶ Values within a column followed by different letters were significantly different ($p < 0.05$).

Table 3. Groundtruthed riparian zone attributes of different SSURGO hydromorphic classes. Values obtained from 100 riparian sites located on lower-order streams.

SSURGO hydromorphic class†	Groundtruthed site attributes			
	Hydric soil width‡	Sites w/>10 m hydric width	Sites w/no seeps	Sites w/>10 m hydric width and no seeps
		% within class		
Hydric n = 73§	18.3 (11.9)a¶	70a	68a	51a
Nonhydric n = 27	3.1 (6.0)b	4b	70a	0b

† Class determined from the SSURGO database associated with the digitally located soil map unit corresponding to each field site.
‡ Values are means (standard deviation in parentheses).
§ n corresponds to the number of groundtruthed field sites within the particular SSURGO hydromorphic class.
¶ Values within a column followed by different letters were significantly different ($p < 0.05$).

nonhydric classes (Table 4). However, the till–hydric setting had a substantially lower proportion of sites with groundtruthed hydric soil width >10 m than the organic/alluvium and outwash–hydric classes.

Variation within Hydric Soils

Substantial variation was observed in the proportion of poorly drained (PD) and very poorly drained (VPD) soils that constituted the hydric soil width of the study sites. However, this variation was largely explained by geomorphic classes or by the drainage class designation of the SSURGO map unit (Fig. 2). In sites mapped by SSURGO as till, we found that the hydric soil width was predominately composed of PD soils. This finding agreed with the SSURGO drainage class designation of the till sites. Hydric soils of the SSURGO till sites were entirely composed of one soil map unit, an undifferentiated group dominated by PD soil series. Sites designated by SSURGO as organic/alluvium soils were dominated by VPD soils and 81% of the organic/alluvium sites were designated as VPD soil map units by SSURGO. Both PD and VPD soils occurred frequently within the hydric soils of sites mapped as outwash; however, the drainage class of the SSURGO map unit for the site usually agreed with the dominant (i.e., >70% of the hydric width) drainage class found through field observation.

Table 4. Groundtruthed riparian zone attributes of different SSURGO hydrogeomorphic classes. Values obtained from 100 riparian sites located on lower-order streams.

SSURGO hydrogeomorphic class†	Groundtruthed site attributes			
	Hydric soil width‡	Sites w/>10 m hydric width	Sites w/no seeps	Sites w/>10 m hydric width and no seeps
		% within class		
Till–hydric n = 34§	14.4 (12.5)a¶	53a	38a	15a
Outwash–hydric n = 18	19.7 (10.0)ab	83b	80c	78b
Organic/alluvium n = 21	23.4 (10.5)b	86b	95c	86h
Till–nonhydric n = 17	3.0 (7.2)c	6c	65b	1a
Outwash–nonhydric n = 10	3.3 (3.1)c	0c	94c	1a

† Class determined from the SSURGO database associated with the digitally located soil map unit corresponding to each field site.
‡ Values are means (standard deviation in parentheses).
§ n corresponds to the number of groundtruthed field sites within the particular SSURGO hydrogeomorphic class.
¶ Values within a column followed by different letters were significantly different ($p < 0.05$).

Seeps and SSURGO Classification

Seeps were found on 31% of the sites. No significant differences were found in the occurrence of seeps between different slope classes (Table 1) or between hydromorphic classes (Table 3). Significant differences were found in the proportion of seeps between different geomorphic classes (Table 2) and hydrogeomorphic classes (Table 4). Approximately half of the till class sites had surface seeps, while seeps were infrequently found on sites in the other geomorphic classes. In the hydrogeomorphic category, the occurrence of seeps in the till–hydric class was significantly and markedly higher than the other classes.

Riparian Classes with High Ground Water Nitrate Removal Capacity

The hydrogeomorphic classes stratified the field data into two distinct groups. Most sites classified as hydric–outwash and organic/alluvium contained both >10 m hydric soils and a lack of seeps (Table 4). In contrast, most sites classified as nonhydric or as hydric till had either minimal hydric widths or contained ground water surface seeps. None of the other categorization schemes separated the field sites into such widely divergent groups based on a co-occurrence of attributes that suggest high ground water nitrate removal capacity.

Depicting High Ground Water Nitrate Removal Capacity Riparian Zones

Figure 3 compares STATSGO with SSURGO to illustrate the effects of different map scales on the identification of stream reaches bordered by riparian zones with either the outwash–hydric or organic/alluvium soil survey classes. Figure 3 depicts the drainage network of streams within the watershed of the Chipuxet River, a fourth-order stream that flows into the Pawcatuck River. Using the SSURGO database (Fig. 3b), we found riparian zone soils with potentially high ground water nitrate removal capacity throughout the drainage network. In contrast, with the STATSGO database (Fig. 3a), riparian zones with potentially high ground water nitrate removal capacity only occurred along higher-order streams at the most downgradient portions of the stream network. We found striking differences between STATSGO and SSURGO at the watershed scale. Whereas soil map units with potentially high ground water nitrate removal bordered 39.2% of the entire drainage network of the Pawcatuck Watershed using the SSURGO database, only 2% of the drainage network was bor-

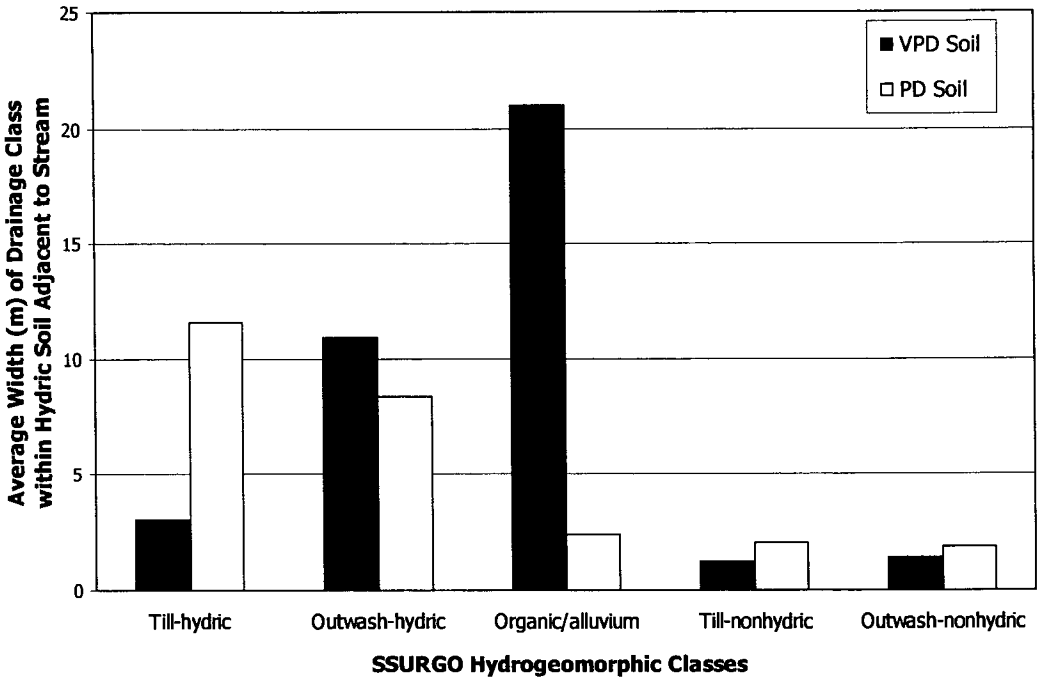

Fig. 2. Average width of very poorly drained (VPD) and poorly drained (PD) soils along lower-order streams in different hydrogeomorphic classes at 100 randomly selected sites in the Pawcatuck River Watershed, Rhode Island.

dered by STATSGO map units with potentially high ground water nitrate removal capacity.

DISCUSSION

In glaciated regions the structure of riparian zones associated with lower-order streams can be quite variable. Based on our field data, the 100 study sites displayed a bimodal distribution of hydric soil widths. In addition, approximately one-third of the riparian sites contained surface seeps, which may dramatically reduce riparian ground water nitrate removal capacity. Given the variability in these site attributes, we expect that the riparian zones would display comparable variability in their functional capacity for ground water nitrate removal. Without a means to stratify riparian zones

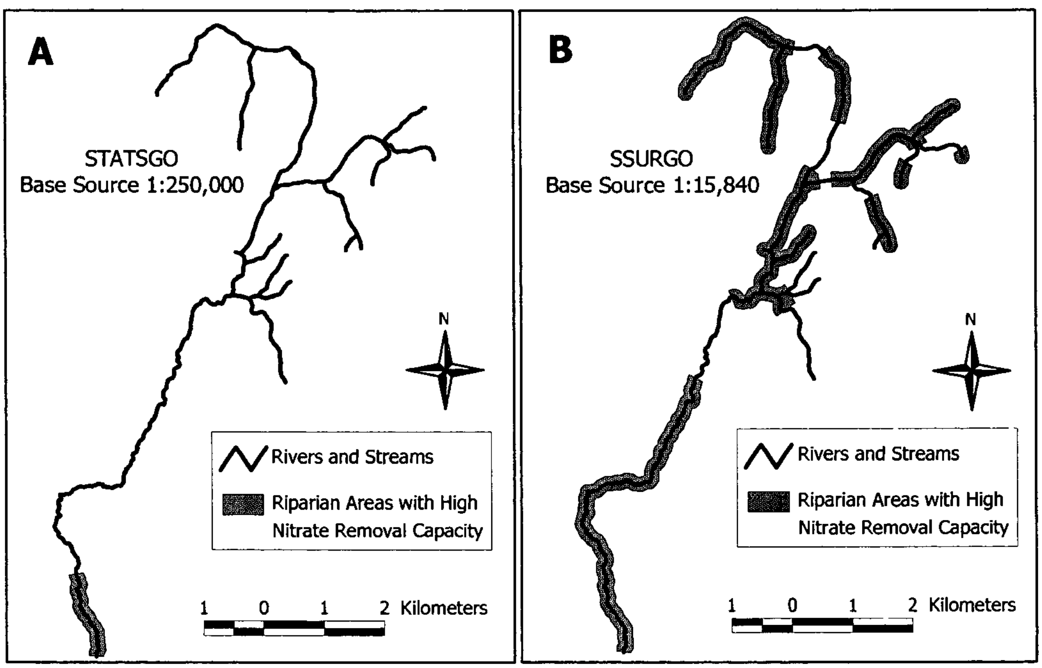

Fig. 3. Comparison of riparian areas with high ground water nitrate removal capacity using different spatial databases on an identical fourth-order stream network within the Pawcatuck Watershed of Rhode Island. High ground water nitrate removal capacity riparian areas consist of soil map units classified as either outwash–hydric or organic/alluvium.

into different levels of ground water nitrate removal capacity, this variability will confound spatially explicit *source–sink* models of watershed nitrate flux and limit efforts to target riparian restoration and management to locations that maximize nitrate retention.

Based on our research, SSURGO can be a valuable tool to watershed managers and modelers in the identification of riparian corridors with high potential for ground water nitrate removal. At the scale of SSURGO, the hydric soil classification was capable of resolving much of the variation in hydric soil width noted in riparian sites, while the geomorphic classification separated sites based on the occurrence or absence of surface seeps. By aggregating individual map units into functional soil classes, we enhance our ability to extend insights from the site scale to the watershed scale (Bouma et al., 1996).

Classifying riparian soils based on a combination of geomorphology and hydric soil status created two functionally distinct sets of riparian soil classes:

(i) Those soil classes that predominately represent sites with conditions that suggest ground water flow through a functionally significant width of hydric soils. These classes include soil map units classified as outwash–hydric and organic/alluvium.

(ii) Those soil classes where ground water nitrate removal may be constrained by either minimal hydric soil width (till–nonhydric or outwash–nonhydric classes) or by surface seepage and rapid flow across the riparian zone (till–hydric class).

Riparian sites classified by SSURGO as organic/alluvium–hydric or as outwash–hydric soil classes have a high potential for ground water nitrate removal. A substantial majority of these sites have groundtruthed hydric soil widths > 10 m and no surface seeps. Given the slow rate of ground water flow along stream reaches bordered by these hydrogeomorphic riparian classes, ground water from neighboring uplands will be subjected to lengthy retention times in soils that have been found to have high nitrate transformation rates (Simmons et al., 1992; Nelson et al., 1995). Riparian sites with soils classified as nonhydric (i.e., till–nonhydric and outwash–nonhydric) are expected to have low potential for ground water nitrate removal. More than 85% of these nonhydric sites have groundtruthed hydric soil widths of <5 m (median <1 m). Given these narrow widths of hydric soils, ground water retention in soils with high nitrate transformation rates would be limited, minimizing the capacity for removal.

Our data suggest that sites classified as till–hydric may have lower ground water nitrate removal potential than other riparian sites classified as hydric soils. Less than 40% of the till–hydric sites had hydric soil widths >10 m and many sites contained ground water seeps, which can short-circuit ground water retention in riparian hydric soils (Hill, 1991). These seeps reflect the subsurface flow processes generated by the physical geography of till settings. Till often contains fragipans or highly compact layers that restrict vertical infiltration and generate perched water tables and lateral subsurface flowpaths (Veneman and Bodine, 1982; Pickering and Veneman, 1984; Stolt et al., 2001). In addition, riparian zones in till settings are usually located at toeslope landscape positions and the change in slope associated with hydric riparian sites in till reduces the hydraulic gradient of the ground water. The combination of shallow restrictive layers and marked change in hydraulic gradient induces surface seepage (Winter et al., 1998) and minimizes subsurface flow and nitrate transformation within the anaerobic, carbon-rich hydric soils that border the stream.

The differences we observed in drainage class patterns within the hydric soils of different geomorphic classes may also have implications for ground water nitrate removal capacity. Because PD soils dominated the hydric soils of till sites, we expect these locations to be subject to lower water tables or shorter periods of high water tables than the hydric soils of organic/alluvium sites that are largely composed of VPD soils. Accumulations of organic matter and anaerobic conditions within PD till hydric soils are more likely to be limited to the upper portions of the soil, whereas the VPD organic/alluvium soils appear to generate anaerobic conditions and accumulation of organic carbon deeper into the profile and may contain a more extensive zone of favorable conditions for ground water denitrification. The observed agreement between SSURGO drainage class and the field-observed drainage class of hydric soils suggests that SSURGO could be also be a useful database to parameterize more site-specific riparian biogeochemical models such as the Riparian Ecosystem Management Model (REMM) (Lowrance et al., 2000). In addition, the differences in saturation between hydric soils of different hydrogeomorphic classes should have implications for other riparian functions, such as habitat restoration and conservation biology.

Obtaining spatial data at scales relevant to the functional patterns of ecosystem processes is a major challenge in watershed modeling (Groffman and Wagenet, 1994; Wagenet and Hutson, 1996; Addiscott and Tuck, 1996). Our field data demonstrate that the SSURGO spatial database can capture much of the pattern and extent of riparian zones with characteristics that indicate a high capacity to serve as sinks for watershed nitrate. Equally important, our field data demonstrate that STATSGO data can substantially misrepresent the structure and ground water nitrate removal capacity of riparian zones in lower-order streams of heterogeneous landscapes, such as the glaciated northeastern USA. STATSGO failed to display the pattern of critical soil features along streams. Clearly, much of this disparity results because the STATSGO database is compiled by generalizing more detailed soil survey maps. Over the entire 64 000-ha study area, STATSGO distributed the soils among 11 map units and only one of those units is dominated by hydric soils. In contrast, SSURGO uses 79 soil map units to describe the same area, of which six are either hydric outwash or organic/alluvium classes.

Our study demonstrates the value of field-validated SSURGO riparian classification schemes for watersheds with diverse riparian zone structure. The SSURGO database is increasingly being used for county scale decision-making (Fernandez et al., 1993) and is expected to be available for more than half the USA in the next several years.

Although a SSURGO-based classification scheme advances our ability to identify riparian zones with high ground water nitrate removal capacity, our study also points out important research gaps. Given the sizeable proportion of hydric riparian zones with surface seeps, we need further work to clarify the fate of nitrate in these riparian settings. Hill (1991), working in Canada, reported minimal riparian nitrate removal where surface seeps fostered overland flow across wetland soils to the stream. In contrast, Downes et al. (1997) reported substantial riparian nitrate removal in a similarly described setting in New Zealand.

Approximately 50% of the sites we classified as high ground water nitrate removal capacity riparian zones (>10 m hydric soil width and no seeps) were characterized by hydric soils in outwash. Along higher-order streams, deep (>5 m) outwash deposits occur in glacial meltwater valleys (Johnston and Dickerman, 1985) and nitrate-laden ground water may move below the upper, biologically active portions of the saturated zone, limiting ground water nitrate removal (Devito et al., 2000). However, within the headwaters of glaciated watersheds, where most lower-order streams occur, outwash deposits are likely to be shallow. To advance the usefulness of the SSURGO database for classifying riparian ground water nitrate removal capacity, additional work is needed to determine the extent of interaction between ground water flowpaths and the biologically active zones in the ground water of outwash–hydric riparian sites (Hill et al., 2000).

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REFERENCES

Addiscott, T.M., and G. Tuck. 1996. Sensitivity analysis for regional-scale solute transport modeling. p. 153–162. *In* D.L. Corwin and K. Loague (ed.) Applications of GIS to the modeling of non-point source pollutants in the vadose zone. SSSA Spec. Publ. 48. SSSA, Madison, WI.

Bouma, J., H.W.G. Booltink, and P.A. Finke. 1996. Use of soil survey data for modeling solute transport in the vadose zone. J. Environ. Qual. 25:519–525.

Correll, D.L. 1997. Buffer zones and water quality protection: General principles. p. 7–20. *In* N.E. Haycock et al. (ed.) Buffer zones: Their processes and potential in water protection. Quest Environ., Harpenden UK.

Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31. U.S. Fish and Wildlife Serv., Washington, DC.

Devito, K.J., D. Fitzgerald, A.R. Hill, and R. Aravena. 2000. Nitrate dynamics in relation to lithology and hydrologic flow path in a river riparian zone. J. Environ. Qual. 29:1075–1084.

Downes, M.T., C. Howard-Williams, and L.A. Schipper. 1997. Long and short roads to riparian zone restoration: Nitrate removal efficiency. p. 244–254. *In* N.E. Haycock et al. (ed.) Buffer zones: Their processes and potential in water protection. Quest Environ., Harpenden, UK.

Environmental Systems Research Institute. 1998. ArcView 3.1. ESRI, Redlands, CA.

Fernandez, R.N., M. Rusinkiewicz, L. Morais da Silva, and C.J. Johannsen. 1993. Design and implementation of a soil geographic data base for rural planning and management. J. Soil Water Conserv. 48:140–145.

Gilliam, J.W., J.E. Parsons, and R.L. Mikkelson. 1997. Nitrogen dynamics and buffer zones. p. 54–61. *In* N.E. Haycock et al. (ed.) Buffer zones: Their processes and potential in water protection. Quest Environ., Harpenden, UK.

Gold, A.J., P. Jacinthe, P.M. Groffman, W.R. Wright, and R.H. Puffer. 1998. Patchiness in groundwater nitrate removal in a riparian forest. J. Environ. Qual. 27:146–154.

Gold, A.J., S. Tso, P.V. August, and W.R. Wright. 1989. Using soil surveys to delineate stratified drift deposits for groundwater protection. J. Soil Water Conserv. 44:232–234.

Groffman, P.M., and R.J. Wagenet. 1994. Advances and pitfalls in expressing land qualities at different scales. Proc. 15th World Congr. Soil Sci. 6a:662–681.

Hedin, L.O., J.C. von Fischer, N.E. Ostrom, B.P. Kennedy, M.G. Brown, and G.P. Robertson. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil–stream interfaces. Ecology 79:684–703.

Hill, A.R. 1991. A groundwater nitrogen budget for a headwater swamp in an area of permanent ground water discharge. Biogeochemistry 14:209–224.

Hill, A.R. 1996. Nitrate removal in stream riparian zones. J. Environ. Qual. 25:743–755.

Hill, A.R., K.J. Devito, S. Campagnolo, and K. Sannugadas. 2000. Subsurface denitrification in a forest riparian zone: Interactions between hydrology and supplies of nitrate and organic carbon. Biogeochemistry 51:193–223.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Zhu Zhao-Liang. 1996. Regional nitrogen budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35:75–139.

Jacobs, T.J., and J.W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. J. Environ. Qual. 14:472–478.

Johnston, H.E., and D.C. Dickerman. 1985. Hydrology, water quality, and groundwater development alternatives in the Chipuxet groundwater reservoir, Rhode Island. Water Resour. Investigation Rep. 84-4254. U.S. Geol. Survey, Providence, RI.

Jordan, T.E., D.L. Correll, and D.E. Weller. 1997. Effects of agriculture on discharges of nutrients from Coastal Plain watersheds of Chesapeake Bay. J. Environ. Qual. 26:836–848.

Lowrance, R. 1998. Riparian forest ecosystems as filters for nonpoint-source pollution. p. 113–141. *In* M.L. Pace and P.M. Groffman (ed.) Successes, limitations, and frontiers in ecosystem science. Springer, New York.

Lowrance, R., L.S. Altier, J.D. Newbold, R.R. Schnabel, P.M. Groffman, J.M. Denver, D.L. Correll, J.W. Gilliam, J.L. Robinson, R.B. Brinsfield, K.W. Staver, W. Lucas, and A.H. Todd. 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environ. Manage. 21:687–712.

Lowrance, R., L.S. Altier, R.G. Williams, S.P. Inamadar, J.M. Sheridan, D.D. Bosch, R.K. Hubbard, and D.L. Thomas. 2000. REMM: The riparian ecosystem management model. J. Soil Water Conserv. 55:27–34.

Lowrance, R., R. Todd, J. Fail, Jr., O. Hendrickson, Jr., R. Leonard, and L. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. Bioscience 34:374–377.

Nelson, W.M., A.J. Gold, and P.M. Groffman. 1995. Spatial and temporal variation in groundwater nitrate removal in a riparian forest. J. Environ. Qual. 24:691–699.

Ott, R.L. 1993. An introduction to statistical methods and data analysis. 4th ed. Duxbury Press, Belmont, CA.

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology 65:1466–1475.

Pickering, E.W., and P.L.M. Veneman. 1984. Moisture regimes and morphological characteristics in a hydrosequence in central Massachusetts. Soil Sci. Soc. Am. J. 48:113–118.

Pinay, G., C. Ruffinoni, and A. Fabre. 1995. Nitrogen cycling in two riparian forest soils under different geomorphic conditions. Biogeochemistry 30:9–29.

Rector, D.D. 1981. Soil survey of Rhode Island. USDA Soil Conserv. Serv. in cooperation with the Rhode Island Agric. Exp. Stn., Washington, DC.

Rhode Island Geographic Information System. 1988. Hydrolines (rivers and streams with stream attributes). RIGIS, Rhode Island Dep. of Environ. Manage.–Planning–GIS, Providence.

Simmons, R.C., A.J. Gold, and P.M. Groffman. 1992. Nitrate dynamics in riparian forests: Groundwater studies. J. Environ. Qual. 21:659–665.

Soil Survey Staff. 1991. Hydric soils of the United States. Misc. Publ. 1491. USDA Soil Conserv. Serv., Washington, DC.

Soil Survey Staff. 1993. Soil survey manual. USDA Handbook 18. USDA, Washington, DC.

Soil Survey Staff. 1997. National soil survey handbook. Title 430-VI. U.S. Gov. Print. Office, Washington, DC.

Statsoft. 1999. Statistica for Windows. Statsoft, Tulsa, OK.

Stolt, M.H., B.C. Lesinski, and W. Wright. 2001. Micromorphology of seasonally saturated soils in carboniferous glacial till. Soil Sci. 166:406–414.

USEPA. 2000. BASINS 2.0 fact sheet. USEPA, Washington DC.

USDA. 1998. SSURGO: Soil survey geographic data base for State of Rhode Island. USDA, NRCS, NCSS Natl. Cartogr. and Geospatial Center, Fort Worth, TX.

Veneman, P.L.M., and S.M. Bodine. 1982. Chemical and morphological soil characteristics in a New England drainage-toposequence. Soil Sci. Soc. Am. J. 46:359–363.

Wagenet, R.J., and J.L. Hutson. 1996. Scale-dependency of solute transport modeling/GIS applications. J. Environ. Qual. 25:499–510.

Whittemore, R.C., and J. Beebe. 2000. EPA's BASINS model: Good science or serendipitous modeling? J. Am. Water Resour. Assoc. 36:493–499.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and surface water: A single resource. Circ. 1139. U.S. Geol. Survey, Denver, CO.

Wright, W.R., and E.H. Sautter. 1988. Soils of the Rhode Island landscape. Agric. Exp. Stn. Bull. 429. Univ. of Rhode Island Agric. Exp. Stn. in cooperation with the USDA Soil Conserv. Serv., Washington, DC.