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TESTING A SIMPLE FIELD METHOD FOR ASSESSING NITRATE REMOVAL IN RIPARIAN ZONES[1]

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ABSTRACT: Being able to identify riparian sites that function better for nitrate removal from groundwater is critical to using efficiently the riparian zones for water quality management. For this purpose, managers need a method that is quick, inexpensive, and accurate enough to enable effective management decisions. This study assesses the precision and accuracy of a simple method using three ground water wells and one measurement date for determining nitrate removal characteristics of riparian buffer zones. The method is a scaled-down version of a complex field research method that consists of a large network of wells and piezometers monitored monthly for over two years. Results using the simplified method were compared to those from the reference research method on a date-by-date basis on eight sites covering a wide range of hydrogeomorphic settings. The accuracy of the three-well, 1 day measurement method was relatively good for assessing nitrate concentration depletion across riparian zones, but poor for assessing the distance necessary to achieve a 90% nitrate removal and for estimating water and nitrate fluxes compared to the reference method. The simplified three-well method provides relatively better estimates of water and nitrate fluxes on sites where ground-water flow is parallel to the water table through homogeneous aquifer material, but such conditions may not be geographically widespread. Despite limited overall accuracy, some parameters that are estimated using the simplified method may be useful to water resource managers. Nitrate depletion information may be used to assess the adequacy of existing buffers to achieve nitrate concentration goals for runoff. Estimates of field nitrate runoff and buffer removal fluxes may be adequate for prioritizing management toward sites where riparian buffers are likely to have greater impact on stream water quality.

(KEY TERMS: Ground water; nitrate removal; riparian zone; riparian management; agricultural streams; Ontario.)

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INTRODUCTION

Riparian zones help mitigate the impact of agriculture on stream water quality by acting as nitrate sinks in the landscape (Hill, 1996; Dosskey, 2001; Puckett, 2004) and are widely recommended best management practices by federal and local agencies around the world (Welsch, 1991; Lowrance *et al.*, 1997; Naiman *et al.*, 2005). However, nitrate removal

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varies widely over time and space depending upon source size and hydrogeomorphic settings (Vidon and Hill, 2004a,b). Being able to quantify nitrate removal functions of riparian zones is critical for confirming the effectiveness of a buffer installation and for identifying locations where riparian buffers provide efficient protection of water quality vis-à-vis nitrate as riparian function can change substantially over small distances (Cooper, 1990; Haycock and Burt, 1993). Targeted placement and design of riparian buffers is also increasingly viewed as critical for achieving significant water quality improvement in watersheds (Dosskey *et al.*, 2005; Walter *et al.*, 2007).

Detailed numerical and conceptual models exist that enable the prediction of nitrate removal function in riparian zones (Welsch, 1991; Lowrance *et al.*, 1997, 2000; Hill, 2000; Altier *et al.*, 2002; Vidon and Hill, 2006). But these models are either too general for site-specific applications or are too complex for practical use by managers on many sites. Accurate site measurements can be costly and time-consuming. Many sampling wells in a three-dimensional flow net configuration (flow net method) and long sampling/monitoring periods may be required to properly account for the effects of complex ground-water flow patterns on nitrate removal (e.g., McDowell *et al.*, 1992; Haycock and Burt, 1993; Bosch *et al.*, 1996; Devito *et al.*, 2000; Hill *et al.*, 2000).

Land and water resource managers need a practical method for determining nitrate removal function of many sites to identify the best locations to preserve, augment, or install buffers for achieving water quality goals. Nitrate removal function has been assessed by the difference in ground water nitrate concentration between the upgradient edge and the stream edge of a riparian buffer (e.g., Jordan *et al.*, 1993; Correll *et al.*, 1997; Snyder *et al.*, 1998; Martin *et al.*, 1999) and by the distance through the riparian buffer found to completely deplete the input nitrate concentration (Lowrance, 1998). Fluxes of nitrate across the riparian zone must also be considered as a riparian zone may exhibit a large nitrate concentration reduction but very small fluxes, whereas another may display a smaller concentration reduction but receive very high nitrate loads and therefore be a larger nitrate sink at the watershed scale (e.g., Wigington *et al.*, 2003; Vidon and Hill, 2004b). Fluxes can be readily estimated from measurements of water table gradients and aquifer permeability taken in sampling wells (e.g., McDowell *et al.*, 1992). However, there is very little information in the literature documenting the efficacy of simplified research methods for assessing nitrate removal in riparian zones. For instance, it may be adequate to use only a few wells in a one-dimensional transect to assess nitrate removal functions for many types of riparian zones. It may also be enough to simply assess nitrate removal functions when nitrate fluxes entering the riparian zone are highest, but unnecessary to chart seasonal variation of nitrate loading and removal.

In this study, we assessed the precision and accuracy of a simplification of the flow net method that uses only three wells and one measurement date to assess nitrate removal characteristics of riparian buffer zones. Precision and accuracy were assessed by comparing nitrate input and removal estimates obtained by the simplified method (three-well approach) with estimates based on the reference flow net method on eight geomorphically different sites in order to correlate accuracy of the three-well approach with hydrogeomorphic patterns. We hypothesize that the accuracy of the simple approach may be relatively good for sites having one-dimensional ground-water flow (e.g., Lowrance *et al.*, 1984; Jacobs and Gilliam, 1985; Jordan *et al.*, 1993), but poorer for sites where flow patterns are increasingly complex (e.g., Schnabel *et al.*, 1993; Altman and Parizek, 1995; Correll *et al.*, 1997; Snyder *et al.*, 1998; Böhlke *et al.*, 2007). We interpreted the results to indicate how this simplified sampling method might be used to guide riparian management decisions for nitrate removal.

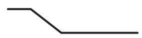
METHODS

Site Description

The eight sites selected for this study are located in Southern Ontario, within 100 km from Toronto, ON. The physical characteristics of the sites are shown in Table 1. Two of the riparian sites are located in large former glacial meltwater channels, bordered by extensive gravel terraces (Speed and Eramosa sites). At the gently sloping Speed site, soils are dominated by a coarse gravel deposit (0–3 m) that overlies substrates with low hydraulic conductivity (Ks) values of 10^{-6} cm/s that form a confining layer for ground-water flow (Vidon and Hill, 2004c). The upland at the Eramosa site is underlain by coarse gravel sediments that are 9–10 m thick along the steep valley slope at the crop field-riparian perimeter. At the slope base, 2.5 m of loamy sand and coarse gravel (Ks = 10^{-4} cm/s) thins rapidly downslope where a 1 m thick peat deposit with Ks values of 10^{-5} cm/s extends towards the river. Beneath the gravel and peat deposits, clay till forms a confining layer throughout the riparian zone (Vidon and Hill, 2004c).

The Road 10 and Boyne River riparian sites are located on the Alliston sand plain that forms an

TABLE 1. Physical Characteristics of the Test Sites in Southern Ontario, Canada.

Site Name	Topography Type	Riparian Width (m)	Upland Permeable Sediment depth (m)	Dominant Soil Texture	Vegetation	Slope Gradient**
Eramosa river (SGT)*		220	9-10	SL + G + P	SW	23.6%/<2% Overall: 5.7%
Boyne river (SP)		204	15	FS + P	SW	38.6%/< 2% Overall: 5.2%
Road 10 (SP)		30	6	S + LS	H	18.0%/< 1% Overall: 5.2%
Speed river (SGT)		66	2.8 to 3	G	H + HW	5.0%/< 1% Overall: 2.9%
Maskinonge (T)		45	2	LS + P	H + HW	13.1%/< 1% Overall: 5.1%
Ganatsekiagon (T)		25	1.4	CS	H	Overall: 13.2%
Highway 27 (T)		33	1.2	SL + LS	H + HW	20.1%/1–2% Overall: 11.3%
Vivian (TM)		37	0.9	SL + LS	H	Overall: 1%

Notes: Vegetation: HW, hardwood; SW, softwood; H, herbaceous. Soil texture: SL, sandy loam; LS, loamy sand; FS, fine sand; S, sand; CS, coarse sand; G, gravel; P, peat.
* The initials indicate geomorphology: SGT: Sand and Gravel Terraces, SP: Sand Plain, T:Till, TM: Till Moraine.
** The first value indicates the gradient of the steepest section of the riparian zone at the upland/riparian boundary and the second indicates the slope gradient of the remaining part of the riparian zone.

unconfined 9-12 m thick aquifer underlain by a thick sequence of silts and clays (Devito *et al.*, 2000). The Boyne River site is located in a valley incised approximately 10-12 m below the adjacent upland sand plain surface. Soils in the riparian zone are dominated by low conductivity peat deposits and fine sands (Ks = 10^{-3} cm/s), and are underlain by the regional clay at depths of approximately 6 m (Devito *et al.*, 2000). The Road 10 site has relatively flat topography and is dominated by sands (Ks = 10^{-3} cm/s) and loamy sands (Ks = 10^{-5} cm/s).

The other four riparian sites are located on glacial till (Maskinonge, Ganatsekiagon and Highway 27) or outwash silt (Vivian). The Maskinonge and Highway 27 riparian zones have a concave topography with level terrain near the streams. Loamy sand soils (0-2 m) dominate at the Maskinonge site where a dense silty sand till restricts subsurface flow at depth >2 m (Vidon and Hill, 2004c). At the Highway 27 site, a dense sandy loam till (Ks = 10^{-7} cm/s) forms a confining layer at a depth of 1.2 m. The soil above the confining layer is a sandy loam (Ks = 10^{-4} to 10^{-5} cm/s) near the field boundary changing to loamy sand and sands near the stream. The Ganatsekiagon site has a slightly convex topography and a slope that extends to the stream. The soil profile is composed of a coarse sandy ablation till with thin layers of gravel (Ks = 10^{-3} cm/s) over a dense basal till that restricts subsurface flow to depths <1.4 m in both the riparian zone and the adjacent upland. At the Vivian site, where the confining layer varies in depth between 0.9 and 1.5 m, sandy loam soils dominate between 0–0.5 m depth (Ks = 10^{-5} cm/s), while a loamy-sand mixed with gravel dominates between 0.5–0.9 m (Ks = 10^{-4} cm/s).

All of the riparian sites are located downslope from fertilized cropland (potatoes or corn). The Boyne and Eramosa riparian zones are forest sites dominated mainly by white cedar (*Thuja occidentalis* L.), while the other riparian sites are covered with an herbaceous plant community with scattered shrubs and deciduous trees. Recent research indicates that the impact of vegetation on nitrate removal relative to denitrification is negligible in many riparian zones (Devito *et al.*, 1996, 2000; Hill *et al.*, 2000; Sabater *et al.*, 2003; Vidon and Hill, 2004b). It is therefore unlikely that differences in vegetation cover between the eight test sites would contribute to differences in N removal.

Reference Method

The reference method consisted of a large network of wells and piezometers at each site. Between two and three transects consisting of six to eleven well and piezometer nests were installed at each site. Transects were 20–80 m apart and extended from the field edge to the stream. Each nest generally consisted in one well (5.1 cm ID PVC pipe perforated throughout its length) and at least three piezometers (1.27 cm ID PVC pipe with 20 cm long slotted ends) ranging in depth from 1.5 m at the Vivian site to 5.5 m at the Boyne site. Wells ranged in depth between 2–4 m. The entire network of wells and piezometers consisted in 61 wells and 223 piezometers distributed amongst the eight study sites (Vidon and Hill, 2004c).

For most of these sites, the field measurements and water sampling were performed monthly between March 2000 and September 2002. Soil hydraulic conductivities were determined for each soil horizon using piezometers screened at discrete intervals and the Hvorslev water recovery method (Freeze and Cherry, 1979). Three-dimensional ground-water flow paths were determined at each site, and the ground water and nitrate fluxes entering each riparian zone were calculated using Darcy's Law and the hydraulic gradient between adjacent equipotential lines. This approach takes into account spatial variations in soil hydraulic conductivity and complex flow paths including ground water upwelling, and provides detailed and accurate descriptions of ground water and nitrate flow through these riparian zones. The only exception was for the Boyne site where water fluxes were calculated using the water table gradient because flow was previously determined to be parallel to the ground surface (Hill *et al.*, 2000). From these field data, calculations were performed to determine reference values for nitrate concentration in ground water at the field edge, nitrate removal efficiency, distance to achieve a 90% nitrate removal, and the nitrate and ground water fluxes into each of the study sites during relatively high water table conditions. Data indicated consistent nitrate removal patterns between transects at each site. A detailed description of all calculations used in the reference method can be found in Vidon and Hill (2004a,c).

Simplified Method

The simplified methodology consisted of installing three ground-water monitoring wells (5.1 cm I.D. PVC pipes perforated throughout their length) on a transect perpendicular to streamflow across the riparian zone and to measure a limited number of hydraulic and water quality parameters in each well (Figure 1). The specific placement rules described here were necessary only for generating proper comparisons to the reference values, since the wells used in the simplified method were a subset of the wells used in the reference method. For other purposes, these placement rules should be considered as a flexible template that can be modified as needed for different sites. For this study, the three ground water wells were installed to depths of about 2-4 m into riparian sediments above the confining layer at each site. The first well (well 1) was located at the field edge or, for sites with a steep concave topography with seeps, at the slope bottom where seeps are observed. The second well (well 2) was installed approximately 10 m into the riparian zone from well 1. A distance of approximately 10 m was chosen because most nitrate removal often occurs in the first 10-20 m from the field edge in many riparian zones (Lowrance *et al.*, 1984; Peterjohn and Correll, 1984; Haycock and Pinay, 1993; Böhlke *et al.*, 2002). The third well (well 3) was installed near the stream. The depth of permeable sediments to the confining layer was determined during well installation, or where deeper than a few meters, was estimated using surficial geology maps (Vidon and Hill, 2004c). The horizontal distance between each well and the difference in elevation between them were measured using a total station (SOKKIA-Set 4B–II) and recorded immediately after installation. Installation of the three wells and the confining layer determination can generally be performed in one day by one or two persons.

On the second day of field work, the water level was measured in wells 1 and 2, water samples were collected for analysis of nitrate-nitrogen concentration from wells 1, 2, and 3, and saturated soil hydraulic conductivity was measured in well 1 using the Hvorslev water recovery method (Freeze and Cherry, 1979). The Hvorslev water recovery method consists in pumping water out of the well using a peristaltic pump and measuring the time it takes for the water level to recover. The main advantage of this approach over the traditional slug test where a hydraulic head is applied is that there is no need to take into account water infiltration in the unsaturated zone. This method generally allows for the estimation of the saturated soil hydraulic conductivity within a few minutes to a few hours depending on soil texture.

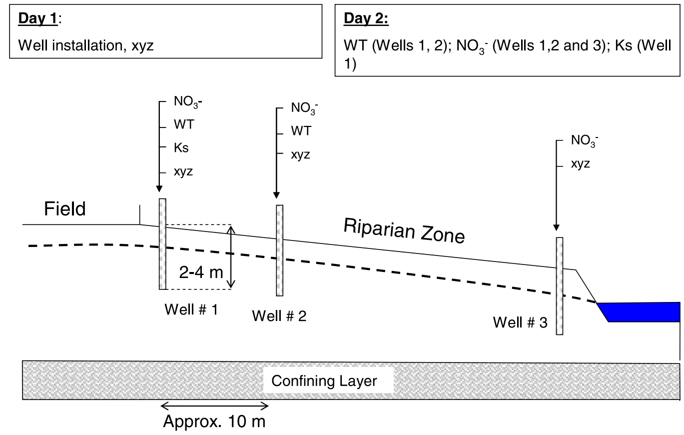


FIGURE 1. Schematic Diagram of the Field Layout and Summary of Measurements for the Simplified Method (NO_3^-, nitrate concentration measurement; WT, water table elevation measurement; Ks, saturated soil hydraulic conductivity measurement; xyz, measurement of relative distances and elevations between wells). The dashed line indicates the water table.

The nitrate concentration measured in well 1 was used to indicate the nitrate concentration of all ground water entering the riparian zone. The difference between the nitrate concentrations in well 1 and well 3 (expressed as a percentage of concentration in well 1) estimated the nitrate removal efficiency (%) across the entire riparian zone. The ground water flux entering the riparian zone was calculated using the one dimensional form of Darcy's Law with the assumption that water flows parallel to the water table surface with:

$$Q = -(K_s i A) \times 1000, \qquad (1)$$

where Q is the water flux (l/day per meter of stream length); K_s is the saturated soil hydraulic conductivity (m/day) measured in well 1 and i is the water table gradient (m/m) between wells 1 and 2. The flow path area A (m^2) for which fluxes were calculated is estimated as the product of the vertical depth from the water table to the confining layer times a width of 1 m. Nitrate flux (mg/day per meter stream length) entering the riparian zone was calculated by multiplying the water input (l/day per meter stream length) by the nitrate concentration (mg N/l) measured in well 1. The mass of nitrate removed daily across each riparian zone was determined using the nitrate input flux (mg/day per meter of stream length) times the nitrate removal efficiency (%) across the riparian zone. Nitrate concentrations measured in wells 1, 2, and 3 were used to estimate the distance necessary to achieve 90% nitrate removal by assuming a linear decline in nitrate concentration between each well (Lowrance, 1998; Vidon and Hill, 2004a). At its simplest, the method could be conducted with only two wells (wells 1 and 3), but an intermediate well (well 2) enables a better description of nitrate concentration across the riparian zone of sites having complex topography or sediment texture, and therefore likely to exhibit a nonlinear nitrate removal behavior (Hill, 2000).

Assessments were made during periods of high water tables. At these times, water and nitrate fluxes into riparian zones are highest, nitrate removal function is most likely to be challenged, and riparian zones probably play their most critical role for nitrate removal at the watershed scale. In southern Ontario, high water tables are typically experienced between March and July.

Comparing Reference and Simplified Methods

Results obtained at each site by the simplified method were compared directly to those obtained using the reference method on three separate dates when high water tables occurred. On each date, corresponding values were obtained for nitrate concentration at the field edge, nitrate concentration depletion across the riparian zone (i.e., nitrate removal efficiency), distance across the riparian zone for 90% nitrate concentration depletion to occur, water and nitrate fluxes entering the riparian zone, and the amount of nitrate removed daily per meter of stream length. Accuracy of the simplified method was determined on each date for each of these parameters by the difference between the simplified and reference values expressed as a percentage of the reference value.

The reference method results obtained over the entire three-year period were used to determine the spatial and temporal patterns of ground water and nitrate flow at the test sites. Detailed accounts of these patterns, including estimates of denitrification and dilution can be found in Vidon and Hill (2004a,b). The importance of dilution was assessed using the nitrate/chloride ratio method (Pinay *et al.*, 1998; Vidon and Hill, 2004a) and denitrification using the natural abundance of ^{15}N-nitrate in ground water or the acetylene block technique (Vidon and Hill, 2004b).

RESULTS AND DISCUSSION

Spatial Patterns of N Removal at Each Site

A wide range of water flux and nitrate behavior is represented among the eight test sites. Several sampling dates between March 2000 and September 2002 were selected from the dataset compiled by Vidon and Hill (2004a) to illustrate the general character of the test sites (Table 2). Nitrate concentrations at the field edge differ greatly among the test sites with a maximum of 42.6 mg N/l for the Road 10 site and a minimum of 0.04 mg N/l for the Vivian site. Nitrate removal efficiency is high (83–100%) at all sites during high water table conditions. As indicated by Vidon and Hill (2004a,b), the nitrate removal at the sites is not due to dilution and is associated with evidence of denitrification at all sites. Nevertheless, although nitrate removal is high at all sites, the average distance to achieve a 90% nitrate removal varied greatly from 7 m at Maskinonge to 187 m at Boyne. Distances reported for Ganatsekiagon and Speed sites only correspond to those individual dates for which a 90% nitrate removal was found and, consequently, are biased low for these two sites. For the Vivian site, the distance necessary to achieve a 90% nitrate

TABLE 2. Average Reference Values for Nitrate Concentration at the Field Edge, Nitrate Removal Efficiency, Distance for a 90% Nitrate Removal, Water and Nitrate Fluxes at the Field Edge Per Meter of Stream Length, and Amount of Nitrate Removed per Meter of Stream Length for the Eight Test Sites.

Site Name	Field Edge Nitrate-N Conc. (mg/l)	Nitrate Removal Efficiency (%)	Distance for 90% Nitrate-N Removal (m)	Water Input Flux (L/d)	Nitrate-N Input Flux (g N/d)	Amount of Nitrate-N Removed (g N/d)
Eramosa (2, 26, 7)*	11.4	95	55	390	4.4	4.2
Boyne (3, 65, 10)	28.9	95	187	228	6.4	6.0
Road 10 (2, 20, 6)	42.6	100	15	38	1.7	1.7
Speed (2, 29, 6)	5.7	89	38	42	0.2	0.2
Maskinonge (2, 37, 11)	18.0	100	7	56	1.0	1.0
Ganatsekiagon (2, 22, 6)	10.6	83	16	228	2.4	1.8
Highway 27 (2, 28, 6)	9.9	99	15	18	0.2	0.2
Vivian (3, 25, 9)	0.04	n/a	n/a	0.14	<0.001	n/a

Notes: Values are mean values for three dates at each site that are representative of high-medium water table conditions between March 2000 and September 2002.
*The first number indicates the number of piezometer and well transects at the site, the second number the number of piezometers, and the third number the number of wells.

removal is not reported because the nitrate concentration at the field edge is too low (< 1 mg N/l) to enable an accurate gage of concentration reduction across the riparian zone. Indeed, nitrate concentration at this site generally varied between the detection limit (0.01 mg N/l) and 1 mg N/l for most dates. Such variations are within the natural variability of nitrate concentrations in agricultural soil and therefore did not allow us to estimate the distance to achieve a 90% nitrate removal at this site. Water and nitrate input fluxes vary by almost four orders of magnitude among the test sites with larger fluxes occurring at sites with a steeper riparian topography and thicker aquifers (e.g., Boyne and Eramosa) and smaller fluxes occurring at sites with flatter riparian topography and thinner aquifers (e.g., Vivian and Highway 27). Because all sites have high overall nitrate removal efficiencies, the amount of nitrate removed across each riparian zone is similar to nitrate fluxes entering each of them. However, the total amount of nitrate removed typically differs by more than three orders of magnitude among the sites, from less than 0.001 g N/day per meter stream length at the Vivian site to 6.0 g N/day per meter stream length at the Boyne site, with an average nitrate removal rate of about 2.0 g N/day per meter stream length for all sites.

Accuracy of the Simplified Method

The nitrate concentration in ground water at the field edge and the nitrate removal efficiency at each site were estimated using the simplified methodology on three different dates when relatively high water tables occurred and were compared to values for those same dates obtained using the reference method (Table 3). For several sites (Boyne, Eramosa, Speed, Highway 27, and Vivian), high water tables in 2001 occurred outside of the typical March-June high water table period (August 14 and November 1), but were included in this analysis in order to provide a wide temporal range of sampling dates. Nitrate concentrations at the field edge varied between 0.02 and 51.3 mg N/l depending on date and site (Table 3). On average, differences to reference values are <20% for the Eramosa, Road 10, Speed, Maskinonge, Ganatsekiagon and Vivian sites. At the Boyne site, nitrate concentrations measured in the upper four meters of the sediment profile typically underestimated that of the whole aquifer by 30–40%. At the Highway 27 site, the average error for field-edge nitrate concentration was only 26% compared to reference values but it varied greatly between the three sample times from (−41.2) to 9.1%. This indicates that the simplified method worked best where wells 1, 2, and 3 sampled most of the ground water column. Deeper aquifers where nitrate concentration sampled near the water table is much different from that at depth can lead to large errors in the estimation of nitrate properties in the aquifer as a whole. This situation occurred at the Boyne site (Table 3) where concentration in the upper four meters (15-21 mg/l) for high water table conditions was always much lower than the reference values for the entire water column (29 mg/l).

The estimated nitrate removal efficiency was very high for all sites, within 8% of the reference values, except at the Ganatsekiagon site where one observation on April 9, 2002 overestimated nitrate removal efficiency by 43%. The nitrate removal efficiency at the Vivian site was not calculated because nitrate concentrations at the field and stream edge were too low to properly evaluate differences across this buffer

TABLE 3. Simplified Method Estimates of Nitrate Concentration at the Field Edge and Nitrate Removal Efficiency for the Eight Sites on Three Dates During High Water Table Conditions.

Site Name	Date	Field Edge Nitrate-N Conc. (mg/l)	Difference to Reference Value (%)	Nitrate-N Removal Efficiency (%)	Difference to Reference Value (%)
Eramosa	23 April 2001	9.1	−20.6	96	4.3
	21 June 2001	11.2	−9.7	99	0
	6 November 2001	9.3	−8.8	92	−3.2
Boyne	26 February 2001	21.1	−42.8	86	−7.5
	19 June 2001	15.9	−37.2	91	−5.2
	14 August 2001	15.7	−35.9	91	−4.2
Road 10	24 May 2001	45.2	0.9	98	−1.0
	27 June 2001	51.3	0.0	100	0
	18 July 2001	31.7	0.0	100	0
Speed	4 April 2001	5.2	8.3	98	−1.0
	17 May 2001	7.3	9.0	75	−5.1
	6 November 2001	6.3	12.5	86	−2.3
Maskinonge	20 April 2001	17.7	−2.7	99	0
	15 May 2001	17.5	−3.3	100	0
	20 June 2001	17.3	−1.7	100	0
Ganatsekiagon	3 April 2001	12.0	−10.4	98	0
	30 May 2001	3.9	29.2	98	3.2
	9 April 2002	17.5	14.4	80	42.9
Highway 27	16 April 2001	9.3	9.1	99	−1.0
	24 May 2001	8.3	−28.7	99	0
	5 November 2001	5.6	−41.2	99	0
Vivian	3 April 2001	0.06	0	n/a	n/a
	20 June 2001	0.02	0	n/a	n/a
	1 November 2001	0.05	0	n/a	n/a

Note: Differences to reference method values (in percent of the reference value) for each date are indicated.

site. Large errors (>20%) were observed in this study when concentrations at the field edge were small enough to be within the range of natural sampling variation (i.e., Vivian site – data not shown), and when well samples were collected during flooded conditions that allowed stream water to enter well 3 and dilute the ground water (i.e., Ganatsekiagon on 2 April 2002; Table 3). Measuring chloride concentration along with nitrate concentration can be a quick way to determine if dilution of riparian water with another water source (e.g., stream water) affects nitrate concentrations (Pinay *et al.*, 1998; Vidon and Hill, 2004a).

The estimated distance necessary for 90% nitrate removal (d_{90}) differed greatly among the test sites. Distances estimated using the simplified method ranged from 7 to 179 m among the sites and dates (Table 4). Average differences to reference values ranged from about 4% for the Boyne site to about 70% for the Road 10 site. Large overestimations at the Road 10 and Highway 27 sites were due to nitrate depletion occurring abruptly before reaching well 3 at these sites. For most of the sites, error was <20% and overestimation was typical. It is important to note here that in 14 out of 18 cases, the three-well method overestimates or correctly estimates d_{90}, which signifies that the method tends to underestimate the N removal capability of the riparian zones tested. For assessments where an accurate estimation of d_{90} is critical, a more extensive experimental set-up involving the installation of more wells or piezometers and the monitoring of nitrate concentration over multiple days is essential.

Estimated fluxes of water and nitrate into the riparian buffer zone were less-accurately estimated by the simplified method than were concentrations of ground water nitrate. For most sites, water fluxes are of the same order of magnitude (<10-fold variation) as the reference values (Table 5). Large relative error tended to correlate with sites having lower fluxes, particularly for Vivian and Highway 27 sites, except for Eramosa where high water fluxes of about 390 l/day per meter stream length were determined using the reference method. Sites for which estimated values are closest to references values are the Speed and Ganatsekiagon sites with average differences of only 29 and 40%, respectively. Water flux estimates for the Boyne site are excluded from this comparison to reference values because the same water table gradient approach was used for both methods, therefore making the reference and simplified values identical. These results indicate that for estimating water flux, the simplified method (Equation 1) works best for shallow aquifers where water flow is parallel to the water table surface and the aquifer permeability is homogeneous throughout the riparian zone.

TABLE 4. Simplified Method Estimates of Distance for 90% Nitrate Removal Across Each Riparian Site on Three Dates During High Water Conditions.

Site Name	Date	Distance for 90% Nitrate-N Removal (m)	Difference to Reference Value (%)
Eramosa	23 April 2001	55	–11.3
	21 June 2001	54	0.0
	6 November 2001	58	16.0
Boyne	26 February 2001	178	–5.3
	19 June 2001	179	–4.3
	14 August 2001	179	–3.2
Road 10	24 May 2001	26	74.5
	27 June 2001	25	64.5
	18 July 2001	25	71.2
Speed	4 April 2001	52	36.8
	17 May 2001	n/a	n/a
	6 November 2001	n/a	n/a
Maskinonge	20 April 2001	7.8	2.6
	15 May 2001	7.6	18.8
	20 June 2001	7.5	–3.8
Ganatsekiagon	3 April 2001	17.3	1.8
	30 May 2001	17.3	23.6
	9 April 2002	n/a	n/a
Highway 27	16 April 2001	16.7	31.5
	24 May 2001	23.8	61.9
	5 November 2001	27.1	64.2
Vivian	3 April 2001	n/a	n/a
	20 June 2001	n/a	n/a
	1 November 2001	n/a	n/a

Differences to reference method values (in percent of the reference value) for each date are indicated.

Particularly large errors occurred on sites where ground water upwelling occurred within the riparian zone (i.e., Eramosa and Maskinonge; Vidon and Hill, 2004c) and where sediment texture changed substantially across the riparian zone (i.e., Highway 27; Vidon and Hill, 2004c). Large relative error for the Vivian site may be attributable to difficulty in precisely measuring very small water table gradients.

Since water flux estimates are used to calculate nitrate input and amount of nitrate removed daily, the large error in water flux estimation is also reflected in these other two parameters. Errors in estimating nitrate fluxes were therefore very similar to those for water fluxes (Table 5). Similarly, the percent difference relative to reference values for the amount of nitrate removed daily for every meter of stream length is similar to the errors found for water fluxes, indicating the dominance of water flux error in the estimation of error for nitrate removal amount using the simplified method (Table 6).

Data therefore indicate that nitrate removal variables depending on ground water flux estimates cannot be determined with precision with the three-well method, namely the nitrate fluxes entering the riparian zone and the amount of nitrate removed daily in the riparian zone. Nevertheless, the simplified method allows for crude estimation of these variables within one order of magnitude of reference values. As indicated in Table 2, ground water fluxes entering the riparian test sites vary from 0.14 l/day per meter of stream length to 390 l/day per meter of stream length and nitrate fluxes from <0.001 to 6.4 g N/day per meter stream length. In both cases, this is four orders of magnitude. Consequently, considering the range of variation of fluxes in riparian zones, results indicate that the simplified method is accurate enough to group most riparian sites into four categories based on the magnitude of fluxes, except for sites where ground water does not flow parallel to the water table (e.g., Eramosa). Results confirmed that the three-well method works relatively well for sites with ground-water flow parallel to the ground surface and with relatively homogenous soil, but perform poorly at sites where the parallel flow assumption is violated.

Temporal Limitations of the Simplified Method

It is assumed that the simplified method would be conducted during high water table conditions to assess nitrate removal performance when nitrate flows are greatest and removal functions are needed the most. In southern Ontario, March through June is typically when water tables are the highest and fluxes are therefore maximum (Figure 2). However, selecting specific dates when high water table conditions actually occur can be difficult at some sites. Water table levels fluctuated very differently between the eight test sites (Figure 2). Sites like Boyne and Eramosa have large, thick aquifers that support very steady water tables (Figures 2 and 3) and measurements can be taken on almost any date. However, other sites that are connected to small, shallow aquifers may experience wide and rapid fluctuations even during the March-June period, such as Ganatsekiagon and Highway 27 (Figures 2 and 3). Nitrate concentrations at the field edge can also fluctuate substantially during the March-June period (Figure 4) and influence the nitrate flux to riparian zones. Monitoring wells may be needed at some sites to ensure sampling during high nitrate flux conditions.

Sites that exhibit wide fluctuations present an additional difficulty. To the extent that they generally exhibit low nitrate flow between short periods of very high fluxes, estimations made during the high flow periods will overestimate their importance to year-round fluxes compared to sites with lower, but steadier flows. Greater familiarity with hydrologic and nitrate runoff patterns in riparian zones will improve selection of appropriate sampling dates and interpretation of results.

TABLE 5. Simplified Method Estimates for Water and Nitrate Input Flux per Meter of Stream Length to the Field Edge of the Riparian Buffer Zone at the Eight Test Sites on Three Dates During High Water Table Conditions.

Site Name	Date	Water Input Flux (L/d)	Difference to Reference Value (%)	Nitrate-N Input Flux (g N/d)	Difference to Reference Value (%)
Eramosa	23 April 2001	32	−92.0	0.3	−93.6
	21 June 2001	31	−92.1	0.3	−92.8
	6 November 2001	32	−91.6	0.3	−92.3
Boyne	26 February 2001	186	n/a*	3.9	−42.8
	19 June 2001	154	n/a	2.4	−37.2
	14 August 2001	343	n/a	5.4	−35.9
Road 10	24 May 2001	18	−30.8	0.8	−30.2
	27 June 2001	27	−50.9	1.4	−50.9
	18 July 2001	41	20.6	1.3	20.6
Speed	4 April 2001	58	−12.1	0.3	−4.8
	17 May 2001	36	33.3	0.3	45.3
	6 November 2001	47	42.4	0.3	60.2
Maskinonge	20 April 2001	19	−73.6	0.3	−74.3
	15 May 2001	23	−58.9	0.4	−60.3
	20 June 2001	21	−47.5	0.4	−48.4
Ganatsekiagon	3 April 2001	283	38.0	3.4	23.6
	30 May 2001	322	37.0	1.3	77.0
	9 April 2002	353	44.7	6.2	65.5
Highway 27	16 April 2001	3.8	−76.3	0.04	−74.1
	24 May 2001	1.3	−85.2	0.01	−89.5
	5 November 2001	0.3	−93.9	0.002	−96.4
Vivian	3 April 2001	0.62	−7.5	<0.001	n/a
	20 June 2001	−0.22	340.0	<0.001	n/a
	1 November 2001	−0.6	200.0	<0.001	n/a

Note: Differences to reference method values (in percent of the reference value) for each date are indicated.
*For the Boyne site, error was not calculated for water fluxes since water fluxes were calculated using the same water table gradient procedure for both the reference and the simplified methods.

Application to Management

In general, using the simplified field approach for quantifying nitrate removal invites potentially large errors that limit the utility of this method for supporting management decisions. Among our test sites, accuracy of the simplified method was relatively good for assessing nitrate concentration depletion across riparian zones, but poor for assessing water and nitrate fluxes. The simplified method provides relatively better estimates of water and nitrate fluxes on sites where ground water flow is parallel to the water table through homogeneous aquifer material, such as the Speed and Ganatsekiagon sites in this study. These conditions have been generally confirmed at some research sites located on the U.S. Southeastern Coastal Plain (e.g., Bosch *et al.*, 1996) but departures have also been noted for other sites in this region (Böhlke and Denver, 1995; Correll *et al.*, 1997). These conditions do not appear to be common in other regions (Pionke *et al.*, 1988; Haycock and Burt, 1993; Schnabel *et al.*, 1993; Altman and Parizek, 1995; Lowrance *et al.*, 1997), thereby greatly limiting the geographic applicability of the simplified method. Results therefore clearly indicate a need for prior information on site-scale hydrogeomorphic patterns in order to determine if the simplified method is suitable for a given area.

Regardless of its inaccuracies, the simplified method could find practical use in some situations. The simplified method is suitably accurate for assessing nitrate concentrations at the field edge, at the stream edge, and concentration depletion across a riparian buffer zone in a wide range of geomorphic settings. The simplified three-well method therefore appears suitable for site planning when the purpose is to assess and compare nitrate concentration depletion among many riparian sites. In this way, the adequacy of existing buffer widths can be assessed, and the need for protection or augmentation to achieve nitrate concentration goals (e.g., Maximum Concentration Level or MCL) can be determined. However, the minimum width of riparian buffer necessary to achieve a specific water quality goal cannot be determined with precision with the simplified method as the simplified method failed to estimate accurately the minimum width necessary to achieve a 90% nitrate removal at most sites.

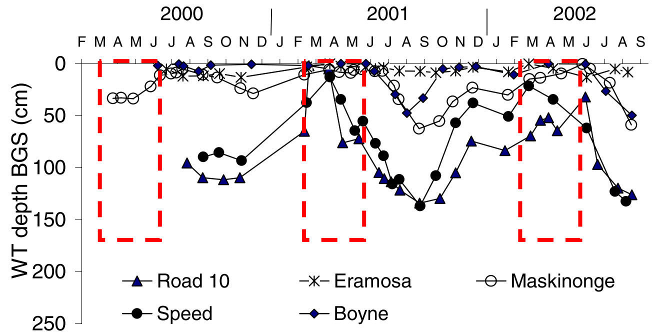
For watershed-scale planning, such as to achieve total maximum daily load (TMDL) requirements,

TABLE 6. Simplified Method Estimates of the Amount of Nitrate Removed Daily per Meter of Stream Length for the Eight Test Sites on Three Days During High Water Table Conditions.

Site Name	Date	Amount of Nitrate-N Removed (g/d)	Difference to Reference Value (%)
Eramosa	23 April 2001	0.3	–93.4
	21 June 2001	0.3	–92.8
	6 November 2001	0.3	–92.6
Boyne	26 February 2001	3.4	–47.1
	19 June 2001	2.2	–40.4
	14 August 2001	4.9	–38.6
Road 10	24 May 2001	0.7	–42.4
	27 June 2001	0.3	–90.9
	18 July 2001	1.3	20.6
Speed	4 April 2001	0.3	–5.8
	17 May 2001	0.2	37.9
	6 November 2001	0.3	56.6
Maskinonge	20 April 2001	0.3	–74.3
	15 May 2001	0.4	–60.3
	20 June 2001	0.4	–48.4
Ganatsekiagon	3 April 2001	3.3	23.6
	30 May 2001	1.2	82.6
	9 April 2002	4.9	136.4
Highway 27	16 April 2001	0.04	–74.3
	24 May 2001	0.01	–89.5
	5 November 2001	0.002	–96.4
Vivian	3 April 2001	n/a	n/a
	20 June 2001	n/a	n/a
	1 November 2001	n/a	n/a

Note: Differences to reference method values (in percent of the reference value) for each date are indicated.

nitrate flux information is critical to identify locations where nitrate runoff load is higher and where nitrate removal is greater. The simplified method only allows the determination of nitrate runoff and removal fluxes within one order of magnitude of reference values. Considering that fluxes varied over four orders of magnitude across a wide range of hydrogeomorphic settings in this study, the simplified method appears adequate to group sites into at least three tiers: small, medium and large nitrate sources and sinks in the landscape, except for sites where the ground water flow pattern is far from parallel to the water table (e.g., Eramosa). Categorization of many sites in this way may be adequate in some planning efforts to establish priority locations for riparian buffer management. For regulatory/management purposes, a limited number of categories can be useful. For instance, Correll (1997) identified three riparian zone cross-section types based on depth to a confining layer and depth of channel incision, and linked these landscape characteristics to hydrological functioning and N removal. In a similar manner, the simplified method tested in this study may be useful to watershed managers where the purpose is to identify riparian sites likely to have relatively greater impact on water quality at the watershed scale.



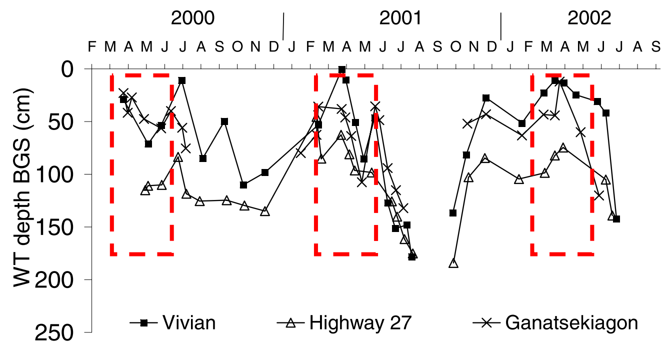


FIGURE 2. Mean Water Table Depth Below Ground Surface (BGS) for the Eight Sites Studied. Dashed lines indicate the March-June period for each year.

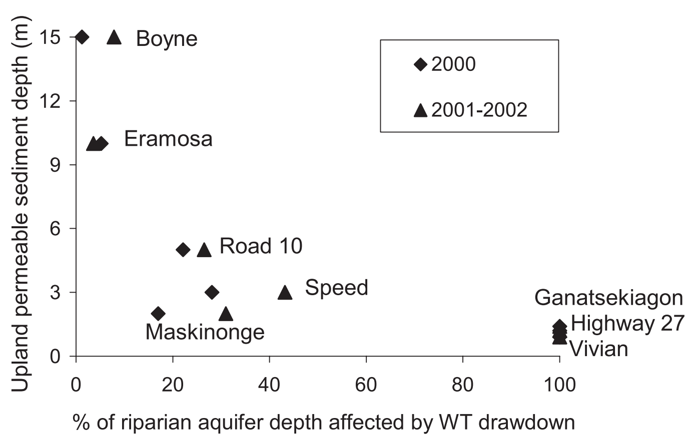


FIGURE 3. Percentage of the Riparian Aquifer Depth Affected by the Annual Water Table Drawdown vs. Upland Permeable Sediment Depth (m) for the Eight Sites from 2000 to 2002 (differences between 2002 and 2001 data for each site are too small to be shown).

CONCLUSIONS

Among eight test sites covering a wide range of hydrogeomorphic settings, the accuracy of a 3-well, 1 day measurement method was relatively good for

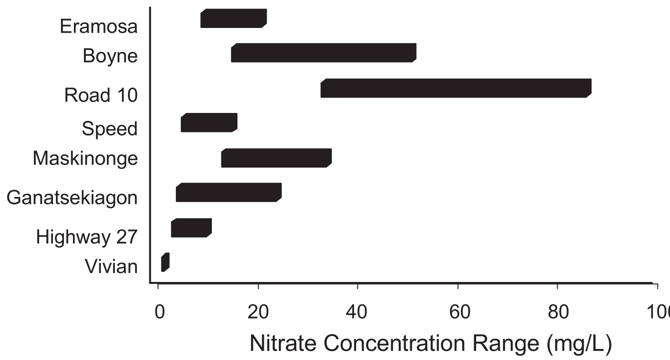


FIGURE 4. Nitrate Concentration Range (mg N/l) at the Field Edge During the March-June Period Over a Two to Three-Year Period for the Eight Test Sites in Southern Ontario, Canada.

assessing nitrate-N concentration depletion across riparian zones, but poor for assessing the distance necessary to achieve a 90% nitrate removal and for estimating water and nitrate fluxes compared to a reference flow net approach. The simplified three-well method provides relatively better estimates of water and nitrate fluxes on sites where ground water flow is parallel to the water table through homogeneous aquifer material, but such conditions may not be geographically widespread. Despite limited overall accuracy, some parameters that are estimated using the simplified method may be useful to water resource managers. Nitrate depletion information may be used to assess the adequacy of existing buffers to achieve nitrate concentration goals for runoff. Estimates of field nitrate runoff and buffer removal fluxes may be adequate for prioritizing management toward sites where riparian buffers are likely to have greater impact on stream water quality.

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