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A ground water nitrogen budget for a headwater swamp in an area of permanent ground water discharge

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Abstract. Ground water inputs and outputs of N were studied for a small ground water discharge swamp situated in a headwater drainage basin in southern Ontario, Canada. Darcy's equation with data for piezometers was used to measure inputs of shallow local ground water at the swamp margin and deep regional ground water beneath the swamp. Ground water flux was also quantified by measuring ground water discharge to the outlet stream draining the swamp in combination with a chemical mixing model to separate shallow and deep ground water components based on chloride differences. Estimates of shallow ground water flux determined by these two approaches agreed closely however, the piezometer data seriously underestimated the deep ground water input to the swamp. An average ground water input-output budget of total N (TN) total organic nitrogen (TON) ammonium (NH_4^+-N) and nitrate (NO_3^--N) was estimated for stream base flow periods which occurred on an average of 328 days each year during 1986—1990. Approximately 90% of the annual NO_3^--N input was contributed by shallow ground water at the swamp margin. Deep ground water represented about 65% of the total ground water input and a similar proportion of TON and NH_4^+-N inputs. Annual ground water NO_3^--N inputs and outputs were similar whereas NH_4^+-N retention was 4 kg ha^{-1} representing about 68% of annual ground water input. Annual TON inputs in ground water exceeded outputs by 7.7 kg ha (27%). The capacity of the swamp to regulate ground water N fluxes was influenced by the N chemistry of ground water inputs and the hydrologic pathways of transport within the swamp.

Introduction

Small valley bottom wetlands are a common element of headwater drainage basins in humid landscapes. The location of these wetlands within the drainage basin makes them potentially important in modifying the chemistry of water fluxes between upland areas and streams. Hydrologic linkages between wetlands and the surrounding watershed, as well as pathways of water movement through the wetland influence the ability of these systems to regulate nutrient fluxes (Cooper 1990; Hill 1990b).

Riparian wetland zones in agricultural watersheds in the southeastern

US and New Zealand retained 90—100% of the NO_3^--N inputs in transient ground water associated with perched shallow aquifers (Lowrance et al. 1983; Lowrance et al. 1984; Cooper 1990). Peterjohn & Correll (1984) found that a riparian forest in a Maryland agricultural watershed retained 80% of the total phosphorus that entered it in surface runoff from cropland. In contrast, annual mass balances for headwater wetlands occupying bedrock depressions on the Precambrian Shield in eastern Ontario showed low retention of total phosphorus and NO_3^--N retention of < 50% of inputs in some wetlands (Devito et al. 1989). Stream and unchannelized flow from hillslopes constituted the major hydrologic inputs to these wetlands and patterns of nutrient retention were strongly influenced by significant export during periods of high runoff. Urban & Eisenreich (1988) found that a forested Minnesota bog in an upland watershed retained approximately 65% of annual total nitrogen inputs. However, the bog was isolated from upland runoff by a surrounding lagg and atmospheric deposition was the major input pathway. Inclusion of the lagg in the budget analysis reduced total nitrogen retention to 46%.

Nutrient budgets have not been evaluated for headwater wetlands which occur in permanent ground water discharge zones. These wetlands occur frequently in regions of glacial deposition in Eastern Canada and the northeastern US (Roulet 1990). The persistent and large input of ground water to the wetlands may produce patterns of nutrient regulation that differ from those occurring in wetlands which are either isolated from or are seasonally connected to ground water.

The objective of this paper is to examine the effect of a small ground water discharge wetland on nitrogen transport to a headwater stream. A mass balance approach was used to measure the magnitude of nitrogen inputs and outputs associated with ground water flux. Most previous studies of wetland chemical balances have not included comprehensive measurements of ground water inputs and outputs (La Baugh 1986). However, ground water is the dominant component of the water balance in ground discharge wetlands and this paper therefore focuses on evaluating the ground water contribution to the wetland nitrogen budget.

Study area

The study watershed is located on the southern slope of the Oak Ridges moraine in the headwater region of the Duffin Creek drainage basin near Toronto, Ontario (Fig. 1). The Oak ridges moraine consists of kame and glacial outwash deposits which contain an aquifer approximately 218 km^2 in area and 15 m thick (Sibul et al. 1977; Howard & Beck 1986). The

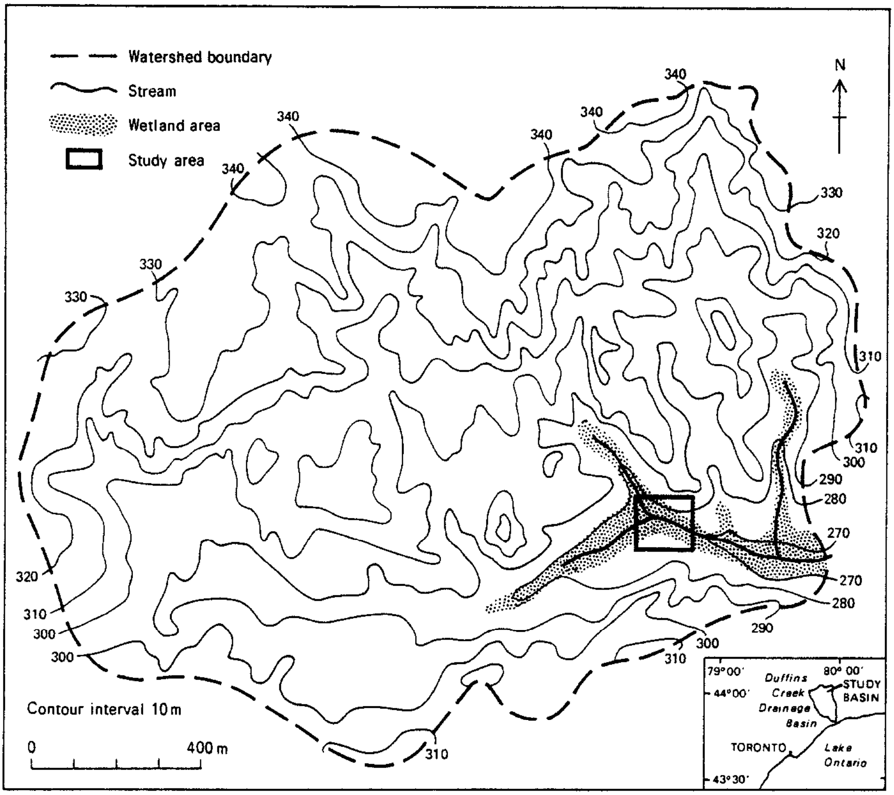

Fig. 1. Location of the study basin and topographic map of the watershed showing the study site.

regional water table slopes towards the south and lies near the ground surface in the study watershed.

The study watershed is 2 km^2 in area and is characterized by hummocky topography which ranges in elevation from 260 to 346 m. The watershed is drained by several perennial tributaries which flow into the second order outlet stream. A groundwater discharge zone produces a riparian wetland zone 20—100m wide along the perennial streams (Fig. 1). The swamp is forested with an 80—100 year old stand of hemlock (*Tsuga canadensis*) and white cedar (*Thuja occidentalis*), whereas the uplands are covered by mature sugar maple-beech (*Acer saccharum-Fagus grandifolia*) interspersed with younger stands of white pine-birch (*Pinus strobus-Betula papyrifera*) and old-field areas of grasses and forbs. Soils on the moraine slopes and riparian zone are well-drained luvisols and peaty histosols, respectively.

The swamp receives a constant large ground water input (Roulet 1990).

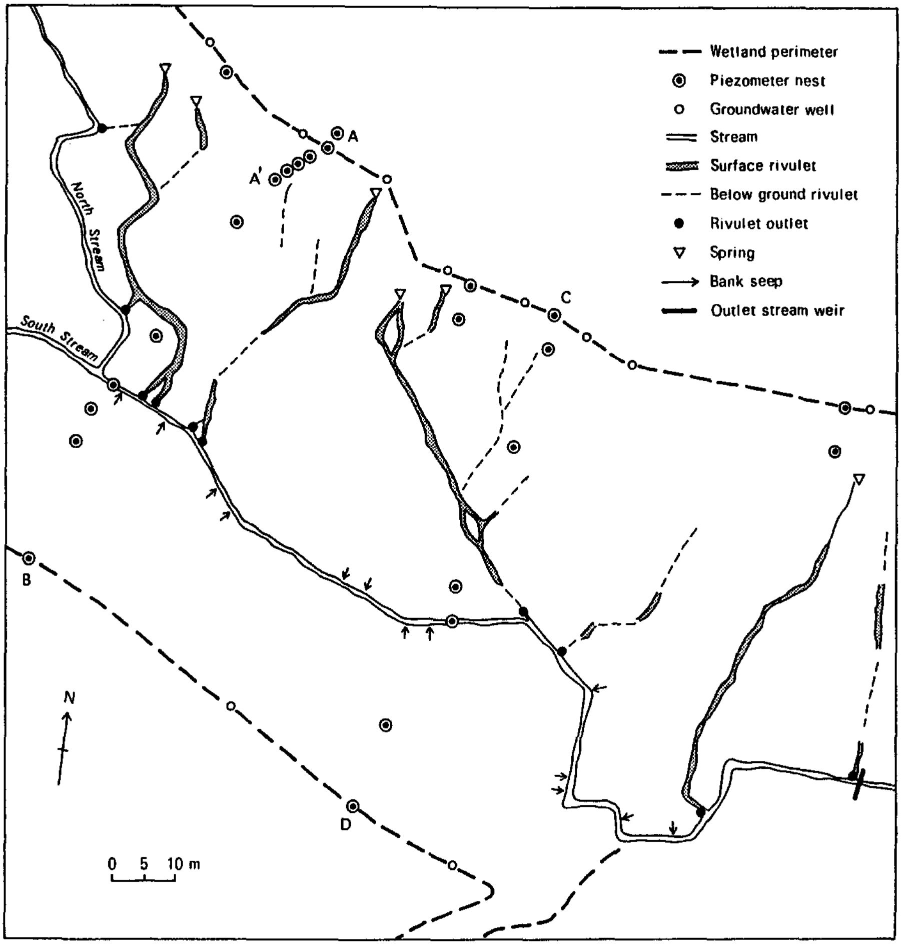

Fig. 2. Instrumentation and sampling locations within the wetland study site.

Ground water flow is lateral at the upland perimeter of the swamp and near vertical around the second order stream. An annual water balance for a 3.1 ha area of the swamp comprising the north first order stream valley and the second order stream valley upstream of the outlet weir (Fig. 2) indicates that ground water accounts for 94% of the water input, whereas measured annual precipitation and actual evapotranspiration was 886 mm and 554 mm, respectively (Roulet 1990). Significant variations in a natural isotope (oxygen-18) and a conservative chemical tracer (chloride) indicate that ground water inputs to the swamp comprise two distinct flow systems which differ in chemistry (Hill 1990b). Shallow local ground water had NO_3^--N concentrations of 100—180 μg L^{-1} and a high dissolved O_2 concentration (4.6—9.1 mg L^{-1}), whereas deep ground water from a larger scale flow system had trace levels of NO_3^--N ($<10\ \mu g\ L^{-1}$) and low O_2 level (0.4—2.2 mg L^{-1}).

Stream storm flow response and recession are rapid, producing small storm flow volumes which contribute <10% of the annual runoff from the study watershed (Roulet 1991). Storm runoff is generated from direct precipitation onto areas of permanent saturation and surface rivulets within the swamp (Roulet 1991). The surrounding moraine slopes do not provide storm runoff inputs to the swamp and high flow events are confined within the perennial stream channels so that flooding of the swamp surface is absent.

The study site (1.0 ha) was located between the junction of the north and south tributary streams and outlet weir on the second order stream (Fig. 2). A cross-section of the study site shows the vertical stratification of the soil (Fig. 3). Histosols which vary in thickness from a few cm at the swamp perimeter to >1.5 m near the stream are underlain by glacial sands containing layers of gravel and fine sand and silt.

Ground water travels through the study site to the second order stream by three pathways (Hill 1990a, b). Shallow ground water emerges as springs near the northern boundary producing diffuse surface rivulets which cross the swamp to the stream (Fig. 2). A second pathway involves deep ground water which flows upward through the organic soils and enters the rivulets within the wetland. The third pathway consists of deep ground water which reaches the stream as bed and bank seepage.

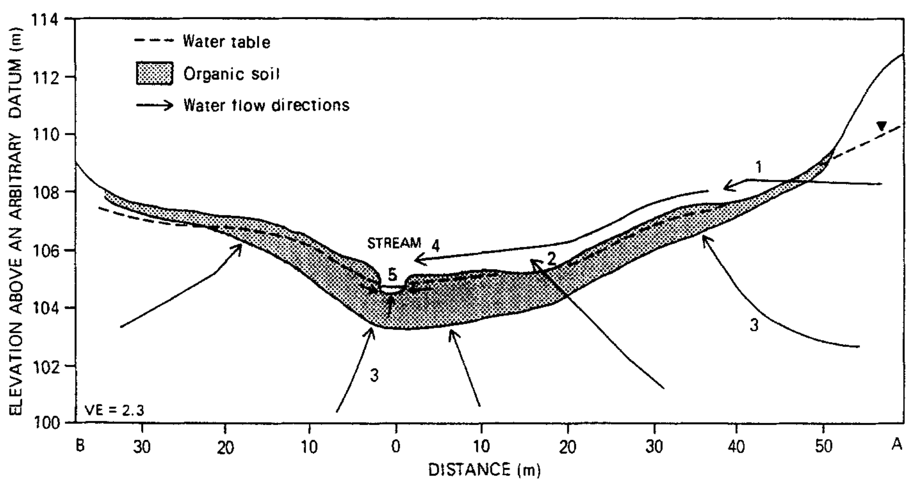

Fig. 3. Swamp cross-section showing soil stratification and major ground water input and output pathways. 1. Shallow ground water input to rivulets; 2. Deep ground water input to swamp which enters rivulets; 3. Deep ground water input to swamp; 4. Rivulet output to stream; 5. Subsurface output to stream.

Methods

Hydrology and chemistry

A network of piezometers and ground water wells was used to investigate the direction, volume and chemistry of ground water flow at the study site from September 1986 to July 1990. Piezometer nests were installed at intervals along two transects across the wetland (Fig. 2). Additional piezometer nests were located within the shallow ground water zone along the northern perimeter of the swamp. Piezometer nests consisted of 2 to 5 piezometers located at depths of 0.5 to 3.4 m and a water-table well. The piezometers were 1.27 cm ID schedule 80 PVC pipe with a 20 cm slotted screen and the water table wells were 3.8 cm ID ABS pipe drilled with 0.5 cm holes along the entire length. Ground water wells made of the ABS pipe were installed at 1—1.5 m depths along the wetland perimeter. These wells were perforated along the lower 20 cm and covered with nylon mesh to prevent siltation. Water levels were monitored at monthly intervals and hydraulic conductivity (K) was measured in the piezometers using the Hvoslev water level recovery method (Freeze & Cherry 1979).

A thin plate 53° V-notch weir was installed on the second order stream at the downstream boundary of the study site (Fig. 2). Continuous water level measurements behind the weir have been made from 1987 with a Stevens Type F recorder. Small weirs were installed in June 1986 on all 8 rivulet outlets that discharged into the second order stream between the north and south tributary stream junction and the outlet weir. Instantaneous discharge below the north and south tributary junction was measured manually using an Ott current meter in conjection with rivulet discharge measurements. Rivulet discharge was measured by timing the filling of a graduated cylinder at each weir site biweekly in June—August 1986, every two weeks from September 1986—September 1987 and at two to four week intervals from September 1987 to July 1990.

Water samples for nitrogen analysis were collected every two weeks in April—November and at 2—4 week intervals in December—March from ground water, rivulets and bank seeps. Ground water wells and piezometers were pumped out prior to sampling and allowed to refill. Samples of fresh ground water were collected using a hand operated vacuum pump. Water samples were taken from 6 springs that form the source of rivulets near the northern boundary of the swamp (Fig. 2). The 8 rivulet outlets to the second order stream and 13 bank seeps were also sampled. Ammonium-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N) and chloride (Cl^-) were determined by standard techniques for a continuous flow autoanalyzer (Technicon 1977, 1978; Environment Canada 1979). Total nitrogen (TN) was analyzed by continuous flow analysis on unfiltered samples following persulfate digestion in an autoclave (Solorzano & Sharp 1980). Total organic nitrogen (TON) was calculated by subtracting NH_4^+-N and NO_3^--N from total persulfate nitrogen.

Ground water nitrogen budget

Analysis of the N budget for the swamp was restricted to periods of baseflow discharge when hydrologic fluxes were not influenced by either snowmelt or rainfall. An analysis of the continuous discharge record for the second order stream between 1987—1990 indicated that baseflow occurred on an average of 328 days (ranges 323—331 days) each year.

The construction of a N budget for the study site during base flow periods requires the measurement of the volume of flow and nitrogen chemistry associated with several ground water input and output pathways (Fig. 3). Ground water inputs to the swamp consist of shallow ground water emerging at the northern footslope as spring-fed rivulets and a deep ground water input from glacial sands into the organic soil underlying the swamp. A portion of this deep ground water enters the surface rivulets within the swamp and the remainder flows by subsurface pathways to the second order stream. The ground water outputs from the swamp consist of the rivulet discharge to the second order stream and the ground water seepage through the stream bed and banks (Fig. 3).

Two approaches were used to estimate ground water flow. Ground water flow was estimated with Darcy's equation:

$$Q = KIA \tag{1}$$

where Q (m s^{-1}) is ground water discharge, K (m s^{-1}) is hydraulic conductivity, I is hydraulic gradient and A is the cross-sectional area of ground water flow. Values of K and I from 30 piezometers located within 10 m of the northern edge of the wetland were used to calculate shallow ground water flux. Previous research indicated that the upward sloping boundary between the shallow and deep ground water flow systems occurs at a distance of approximately 10 m from the footslope (Hill 1990b). Values of K and I from 23 piezometers located in sands beneath the organic soil in the central area of the wetland were used to estimate the flux of deep ground water.

The increase in discharge in the second order stream between the junction of the north and south tributaries and the outlet weir provides a second method of estimating the total flux of ground water through the swamp. The combined discharge of the 8 rivulets measures the output of shallow and deep ground water from the swamp by the surface rivulet pathway. Deep ground water output from the swamp via stream bank and bed seepage, was estimated by the difference between combined rivulet discharge and the second order stream flow increase between the junction of the two tributaries and the outlet weir.

Shallow and deep ground water differ significantly in chloride concentrations (Hill 1990b). Consequently, chloride can be used as a tracer in a simple chemical mixing model to evaluate the contribution of shallow and deep ground water flow systems to rivulet output:

$$\frac{Q_1}{Q_T} = \frac{C_T - C_2}{C_1 - C_2} \qquad (2)$$

where C is chloride concentration, Q is discharge, 1, 2 and T are the shallow ground water, deep ground water and rivulets, respectively.

Average monthly nitrogen input and output fluxes were calculated by multiplying average daily water fluxes and nitrogen concentrations for sampling dates in each month by the number of days of stream base flow discharge. The average annual budget for the study period was determined by addition of the monthly budgets.

Measurement errors can have an important effect on the calculation of water and nutrient budgets. A detailed error analysis indicated that the magnitude of total error in monthly nutrient budgets for headwater wetlands on the Precambrian Shield was ±20 to ±40% (Devito et al. 1989). Few studies have assessed uncertainties associated with ground water discharge, however errors in estimating hydraulic conductivity are probably 50—100% (Winter 1981). Errors in the measurement of stream flow using volumetric measurements, weirs and current meters are considered to range from 5—10% (Winter 1981). Extrapolation of measurements of water flux and chemistry on sampling dates to estimate monthly and annual budgets can also produce considerable errors. These temporal errors are probably small in the present study because of the focus on base flow discharge periods. Rivulet and stream discharges were relatively constant throughout the year. Element concentrations varied over a relatively small range with the exception of NO_3^--N concentrations in shallow ground water and rivulets which varied seasonally. Nevertheless, this seasonal pattern of NO_3^--N variation was consistent from year to year.

Results

Hydrologic budget

Hydraulic conductivity (K) in sands in the shallow ground water emergence zone along the northern edge of the swamp ranged from 4.5 × 10^{-5}m s^{-1} to 2.1 × 10^{-6}m s^{-1} with a mean value of 1.8 × 10^{-5} m s^{-1}. Average daily shallow ground water flux computed from flow net analysis along the four transects in the 10 m wide perimeter zone of the wetland was 0.216 m^3 m^{-2}. Calculated for the entire surface saturated area along the footslope zone, shallow ground water input to the swamp was 185.5 m^3 d^{-1}. Hydraulic conductivity in the zone of deep ground water input beneath the swamp showed very large variations ranging over three orders of magnitude (2.1 × 10^{-5} to 2.3 × 10^{-8} m s^{-1}). Mean daily ground water discharge along the A–B and C–D transects excluding the initial 10 m zone at the northern edge of the wetland was 0.013 m^3 d^{-2} and the flux of deep ground water calculated for the surface area of the swamp was 117.3 m^3 d^{-1}. The shallow and deep ground water inputs expressed as annual depth of runoff per unit area of the study site were 6.59 m and 4.1 m respectively (Table 1).

The combined mean daily discharge (±SD) of the 8 rivulets was 377.6 ± 25.9 m^3. Flow showed little seasonal variation; mean daily flows in July–September and December–February periods were 370.6 and

Table 1. Annual ground water budget calculated with two methods of measuring ground water inputs.

	Method	
	Piezometers	Ground water output + chemical mixing model
Input		
Shallow ground water	6.59	6.49[1]
Deep ground water to rivulets		6.70[1]
	4.10	
Deep ground water to stream		5.13
Total input	10.69	18.32
Output		
Rivulets		13.19
Stream seeps		5.13[2]
Total output		18.32[3]

All data in meters.

[1] Total rivulet flux separated into a shallow and deep ground water component using Cl in a chemical mixing model.

[2] Increase in outlet stream discharge within the study site minus combined rivulet discharge.

[3] Increase in outlet stream discharge within the study site.

385.3 m^3, respectively. Annual rivulet discharge was equivalent to a runoff depth of 13.19 m (Table 1). Separation of the rivulet flux into a shallow and deep ground water component using chloride as a tracer indicated that the average shallow ground water contribution was 49% (range 40—57%). Annual inputs of shallow and deep ground water which discharge from the swamp in the rivulet pathway estimated from the chemical mixing model were 6.49 and 6.70 m, respectively (Table 1). The shallow ground water flux of 6.49 m yr^{-1} estimated from the chemical mixing model was approximately 98% of the 6.59 m yr^{-1} value derived from the shallow ground water piezometer data (Table 1).

The combined rivulet discharge subtracted from the increase in stream flow between the junction of the north and south tributaries and the outlet weir indicated that the mean daily deep ground water flux from the wetland as bank and bed seepage into the second order stream was 146.9 $\pm$ 50 m^3. The annual unit area runoff via this pathway was estimated as 5.13 m yr^{-1} (Table 1).

A comparison of the annual input of ground water to the swamp determined by the two methods revealed that the piezometer data provided a much lower estimate. Although increased discharge in the second order stream within the study area indicated an annual ground water output of 18.32 m yr^{-1} from the swamp the annual input estimated from the piezometer data was only 10.69 m yr^{-1} (Table 1). The large discrepancy of 7.63 m yr^{-1} suggests that the piezometer data seriously underestimated the deep ground water input to the swamp. Therefore, the analysis of the ground water nitrogen budget was based on estimates of the ground water fluxes determined by measurement of ground water discharge from the swamp to the outlet stream combined with separation of shallow and deep ground water components in rivulet discharge using the chemical mixing model.

Water chemistry

Chloride concentrations in the shallow ground water flow system were generally in the range of 1.2 to 1.4 mg L^{-1} in comparison to levels of 0.85 to 0.95 mg L^{-1} in the deep ground water beneath the swamp (Table 2). Shallow ground water had NO_3^--N concentrations of >100 μg L^{-1}, whereas concentrations in the deep ground water system were always <10 μg L^{-1}. Nitrate -N showed consistent seasonal variations in concentration in the shallow ground water system increasing rapidly during late fall to levels of 50 to 160 μg L^{-1} in January—March before declining to minimum concentrations of 100—120 μg L^{-1} in August—October. No seasonality was apparent in NH_4^+-N concentrations which were similar in

Table 2. Element concentrations for major ground water input and output pathways.

	NO_3^--N	NH_4^+-N	Organic N	Cl^-
	$\mu g\ L^{-1}$			$mg\ L^{-1}$
Shallow ground water	131 ± 20 (742)	28 ± 8 (650)	151 ± 51 (650)	1.28 ± 0.08 (742)
Deep ground water	7 ± 2 (530)	35 ± 8 (375)	160 ± 50 (375)	0.89 ± 0.03 (450)
Springs	121 ± 24 (190)	5 ± 3 (155)	–	1.31 ± 0.13 (155)
Rivulets	74 ± 38 (424)	6 ± 4 (360)	114 ± 59 (360)	1.08 ± 0.05 (424)
Stream bank seeps	8 ± 2 (387)	30 ± 7 (300)	128 ± 47 (300)	0.85 ± 0.04 (350)

Values are means ±1SD for the 1986–1990 period. Number of analyses shown in brackets.

the two ground water flow systems. A considerable proportion of the nitrogen in ground water input was in organic rather than inorganic forms (Table 2).

Shallow ground water emerging as springs along the northern edge of the swamp had average NO_3^--N and Cl^- concentrations that were similar to levels in piezometers at depths of 1–3 m. However, NH_4^+-N concentrations in springs were significantly lower than in the shallow ground water beneath the surface (Table 2). Rivulet outlets had NO_3^--N and Cl^- concentrations that were intermediate in value between the concentrations of the deep and shallow ground water systems. The chemistry of the bank seeps was similar to deep ground water beneath the swamp.

Ground water nitrogen budget

Approximately 90% of the annual ground water NO_3^--N input to the swamp was contributed by shallow ground water emerging along the northern footslope (Table 3). Although the deep ground water system contributed about 65% of the ground water flux, NO_3^--N input was minor because of very low NO_3^--N concentrations. Inputs of NH_4^+-N and TON by shallow and deep ground water were similar to the proportion of water contributed by the two flow systems. Surface rivulets transported 72% of the annual ground water discharge and 97% of the NO_3^--N from the

Table 3. Annual ground water nitrogen budget for the headwater swamp during periods of stream base flow discharge.

	NO_3-N	NH_4-N	Organic N	Total N
	kg ha $^{-1}$ year^{-1}			
Input				
Shallow ground water	8.63	1.90	9.68	20.21
Deep ground water to rivulets	0.44	2.29	11.24	13.97
Deep ground water to stream	0.26	1.70	7.49	9.45
Total input	9.33	5.89	28.41	43.63
Output				
Rivulets	9.41	0.58	14.50	24.49
Stream seeps	0.27	1.29	6.22	7.78
Total output	9.68	1.87	20.72	32.27
Net exchange	+0.35	−4.02	−7.69	−11.36
% of input	4	68	27	26

swamp (Table 3). In contrast subsurface output from the swamp as stream bed and bank seepage represented 68% of the annual NH_4^+-N output.

Annual ground water NO_3^--N inputs were similar to outputs, whereas the NH_4^+-N balance showed a retention of approximately 4 kg ha^{-1} representing about 68% of input. Both TN and TON inputs exceeded outputs by approximately 25%. Organic N represented 65% of the total N input and a similar proportion of the annual output, however NH_4^+-N accounted for 14% of the input and only 6% of the output (Table 3).

Discussion

The importance of accurate measurements of hydrology in the determination of nutrient budgets has been widely recognized (Hemond 1980; Winter 1981; La Baugh 1986). Ground water fluxes were therefore estimated by two independent methods in the present study. Shallow ground water input at the northern edge of the swamp determined by piezometer data agreed closely with values estimated using Cl^- as a tracer. Despite inherent errors, the agreement between the methods suggests that the approximate volume of shallow ground water input was estimated correctly. In contrast, the value of deep ground water flux determined by the two methods gave widely different estimates. Large spatial variation in hydraulic conductivity (K) at the organic-mineral soil boundary beneath the swamp may explain the unrealistically low value of deep ground water flux estimated with the piezometers. Conversely the absence of large variations in K along the swamp edge may have facilitated a reliable estimate of shallow ground water flux. Roulet (1990) found that flow from the deep ground water system emerged in isolated areas of higher conductivity within the swamp. The vertical flux of deep ground water through such localized 'channels' of higher conductivity would not be reliably estimated from a small number of piezometers along two transects across the swamp. Koerselman (1989) has also suggested that the heterogeneity of vertical ground water flow in a small fen in The Netherlands accounted for errors in flux estimates based on point estimates of hydraulic conductivity.

The annual ground water nitrogen budget indicates that the swamp was efficient at retaining NH_4^+-N but was not a major sink for other forms of N. Very low NH_4^+-N concentrations in rivulet springs in comparison to higher concentrations in shallow ground water at 1—2 m depths shows that NH_4^+-N retention occurs as this ground water emerges through a thin layer of organic soil at the swamp margin. Deep ground water at 0.5—1 m in the peat layer had NH_4^+-N concentrations similar to concentrations in the sands beneath the swamp (Hill 1990b). These findings suggest that NH_4^+-N retention occurs mainly as the deep ground water enters the rivulets rather than within the peat layer. This conclusion is supported by field enrichments of rivulets with NH_4^+-N and lab experiments with rivulet substrates which revealed rapid NH_4^+-N uptake mainly by microbial immobilization (Hill & Warwick 1987).

The annual nitrogen budget suggests that the swamp had a relatively small effect on the TN content of ground waterflow. Annual retention of TON which forms the major portion of TN input was only 27%. With respect to individual ground water pathway fluxes, the rivulets retained 31% of the ground water TON input, whereas approximately 17% was retained along the deep ground water flowpath which reached the stream as bed and bank seepage. It is possible that microbial uptake of organic -N occurred particularly in the rivulets as water flowed over organic litter debris on the wetland surface. However, the significance of the TON retention remains uncertain. In contrast to NH_4^+, field and lab experiments have not been conducted to confirm the occurrence of organic-N uptake within the swamp. Moreover, Winters (1981) and Devito et al. (1989) concluded that estimated errors in annual water and nutrient budgets are often ± 10 to 20%, an error range which is not much less than the TON retention rates in the swamp.

The absence of nitrate retention in the headwater swamp, contrasts with the high levels of nitrate removal found in riparian zones of agricultural watersheds of the southeast US and New Zealand. Transient ground water entering these riparian zones from cropland had high NO_3^--N concentrations and followed a shallow horizontal path above an impermeable layer. High NO_3^--N concentrations in combination with anaerobic soils and considerable water residence times in this subsurface zone favour rapid denitrification. However, the shallow ground water flow system in the headwater swamp has low NO_3^--N concentrations and high O_2 levels. The short residence time (<1 hr) of the emergent shallow ground water in the aerobic surface rivulets within the swamp also probably limits denitrification. Previous research has revealed an absence of nitrate retention in rivulets during short term nitrate enrichments and generally low denitrification rates in swamp soils (Warwick & Hill 1988). The large volume of deep ground water flowing upward through the organic soil within the wetland had low O_2 concentrations and a longer residence time than the shallow ground water. Nevertheless, denitrification is inhibited by the low NO_3^--N concentrations in the deep ground water flow system.

This study demonstrates the difficulty of constructing reliable nutrient mass balances which are dependent on accurate measurements of ground water flux. The use of two different methods of estimating ground water flux was useful in revealing inconsistencies in the water budget. Flow net analysis based on a few transects may give erroneous estimates of flux because of the substrantial heterogeneity of hydraulic conductivity in wetland soils. The use of a large number of piezometers in a sampling design which adequately identifies localized zones of high conductivity in wetlands would be required to provide a reasonable flux estimate. The measurement of ground water fluxes can also be complicated by the occurrence of local and larger scale flow systems that differ in chemistry, thus requiring estimates of ground water discharge for each flow system in order to construct a nutrient budget.

The persistent flow of ground water through wetlands located in permanent ground water discharge zones creates a high potential for nutrient regulation. However, the result of the present study indicate that this particular swamp was an efficient sink for NH_4^+-N but probably did not regulate the flux of NO_3^--N to the stream during periods of base flow. The low NO_3^--N concentrations of ground water inputs and the hydrologic flow paths of transport within the swamp had an important influence on the swamp's capacity to regulate nitrogen fluxes.

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References

Cooper AB (1990) Nitrate depletion in the riparian zone and stream channel of a small headwater catchment. Hydrobiol. 202: 13–26

Devito KJ, Dillon PJ & Lazerte BD (1989) Phosphorus and nitrogen retention in five Precambrian Shield wetlands. Biogeochemistry 8: 185–204

Environment Canada (1979) Analytical methods manual. Inland Waters Directorate, Water Quality Branch, Ottawa, Canada

Freeze RA & Cherry JA (1979) Groundwater. Prentice-Hall, New Jersey, 604 pp

Hemond HF (1980) Biogeochemistry of Thoreau's bog, Concord, Massachusetts, Ecol. Monog. 50: 507–526

Hill AR (1990a) Groundwater cation concentrations in the riparian zone of a forested headwater stream. Hydrol. Processes 4: 121–130

Hill AR (1990b) Ground water flow paths in relation to nitrogen chemistry in the near-stream zone. Hydrobiol. 206: 39–52

Hill AR & Warwick J (1987) Ammonium transformations in springwater within the riparian zone of a small woodland stream. Can. Fish. Aquat. Sci. 44: 1948–1956

Howard KWF & Beck P (986) Hydrochemical interpretation of groundwater flow system in Quaternary sediments of southern Ontario. Can. J. Earth Sci. 23: 938–947

Koerselman W (1989) Groundwater and surface water hydrology of a small groundwater fed fen. Wetlands Ecology and Management 1: 31–43

La Baugh JW (1986) Wetland ecosystem studies from a hydrologic perspective. Water Res. Bull. 22: 1–10

Lowrance RR, Todd RL & Asmussen LE (1983) Waterborne nutrient budgets for the riparian zone of an agricultural watershed. Agric. Ecosyst. Environ. 10: 371–384

Lowrance R, Todd R, Fail J, Hendrickson O, Leonard R & Asmussen L (1984) Riparian forests as nutrient filters in agricultural watersheds. Biosci. 34: 374–377

Peterjohn WT & Correll DL (1984) Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65: 1466–1475

Roulet NT (1990) Hydrology of a headwater basin wetland: Groundwater discharge and wetland maintenance. Hydrol. Processes 4: 387–400

Roulet NT (1991) Storm runoff production in a headwater basin wetland. Nordic Hydrol. (in press)

Sibul V, Wang KT & Vallery D (1977) Ground water resources of the Duffins Creek Rouge river drainage basins. Water Resources Report 8, Ontario Ministry of the Environment, Toronto, Canada

Solorzano L & Sharp JH (1980) Determination of total dissolved nitrogen in natural waters. Limnol. Oceanogr. 25: 751–754

Technicon (1977) Nitrate and nitrite in water and seawater. Industrial Method 158–71W1A. Technicon Industrial System, Tarrytown, NY

Technicon (1978) Ammonia in water and seawater. Industrial Method 154–71W/B. Technicon Industrial systems, Tarrytown, NY

Urban NR & Eisenreich SJ (1988) Nitrogen cycling in a forested Minnesota bog. Can. J. Bot. 66: 435–449

Warwick J & Hill AR (1988) Nitrate depletion in the riparian zone of a small woodland stream. Hydrobiol. 157: 231–240

Winter TC (1981) Uncertainties in estimating the water balance of lakes. Water Res. Bull. 17: 82–115