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THE INFLUENCE OF HYDROLOGIC FLUCTUATIONS AND PEAT OXIA ON THE PHOSPHORUS AND NITROGEN DYNAMICS OF A CONIFER SWAMP

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ABSTRACT

A mass balance approach was used to determine the factors influencing phosphorus and nitrogen dynamics in wetlands common to headwater catchments of the Precambrian Shield. The relationships of runoff, water level, water temperature, and anoxia to the annual and seasonal total phosphorus (TP) and total nitrogen (TN) retentions of a headwater Sphagnum - conifer swamp, were examined during 1987-88. Annual retentions of TP (4%) and TN (10%) were low in the swamp. On an annual basis, inputs exceeded outputs of total reactive P, NO_3-N, and NH_4-N and outputs exceeded inputs of total unreactive P and total organic N. Seasonal trends in P and N retention were inversely correlated with runoff. The degree of saturated overland flow (SOF) and residence time of water also influenced nutrient export. There was a weak relationship between monthly retention and temperature. No relationship between the mean redox potential of the peat and monthly retention was observed. Decomposition or leaching of organic matter may be an important means of regenerating P and N. Timing of the major processes of nutrient cycling is important in the seasonal and annual retention of P and N. Positive monthly retention coincided with low runoff and increased biotic assimilation during the growing season. Water table drawdown during the summer was associated with peat aeration and increased levels of P and N in surface and pore water. High levels of P and N in the swamp surface water during the fall and winter were coupled with increased runoff, SOF and potentially low biotic assimilation resulting in a net release of TP and TN. Large flow-through of waterborne inputs and flushing of regenerated P and N occurred during peak snowmelt runoff resulting in low annual retention.

KEY WORDS: budgets, conifer swamp, nitrogen, phosphorus, runoff, saturated overland flow, sphagnum, water table drawdown.

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INTRODUCTION

Phosphorus (P) and nitrogen (N) export from headwater catchments is an important source of nutrients to downstream surface waters (Schindler et al. 1976). Sedge fens and conifer swamps are typical of central Ontario wetlands occupying small, headwater basins of the low Boreal region of the Precambrian Shield (Zoltai and Pollett 1983). Such wetlands are often situated at or near the interface between the terrestrial and aquatic ecosystems and may have a large influence on the hydrologic and nutrient dynamics of these catchments (Hill 1990, Pierson and Taylor 1985).

Despite their importance, few data related to P and N dynamics of wetlands on the Precambrian Shield exist. The available information suggests that wetlands in this region exhibit variable nutrient retention efficiencies. Devito (1989) reported low TP and TN retention in a number of headwater wetlands in central Ontario. Devito et al. (1989) measured a net retention of inorganic N and a net release of organic N, but no analysis of the forms of P have been done. Verry and Timmons (1982) and Urban and Eisenreich (1988) measured net retention of N and P in a forested Minnesota bog. Bayley et al. (1987) reported net retention of nitrate in a Sphagnum peatland in northwestern Ontario, but TN was not reported.

Seasonal variations in P and N retention in a number of wetlands on the Precambrian Shield were described by Devito et al. (1989). Annual retention of TP and TN within the wetlands was the difference between positive retention during the "ice free" season and negative retention during the winter and spring. Seasonal dynamics have been reported in other wetlands with export of nutrients occurring only during certain times of the year (Klopatek 1978, Elder 1985), suggesting that nutrient flux and transformation may be controlled by seasonal variations in hydrologic fluctuations and/or temperature related biotic assimilation.

There is evidence that hydrologic and biogeochemical processes influence nutrient export and cycling in wetlands (Hill 1990, Richardson and Marshall 1986). Water acts as a vehicle for export, and the loss of dissolved and particulate substances has been related to the magnitude of runoff, water retention time and water flow pathways in both aquatic and terrestrial ecosystems (Hill 1991, Howard-Williams 1985, Pierson and Taylor 1985). The hydrologic mobility of P and N may be controlled by homeostatic processes in the peat or surface water which may either limit or enhance the transformation and mobility of nutrients in solution (Richardson and Marshall 1986, Hemond 1983, Hill 1988). Anoxic environments in saturated sediments are important sites for the transformation and retention of P and N in wetlands (Gorham et al. 1984, Ponnamperuma 1972). Knowledge of the interaction of hydrology, peat redox and homeostatic processes and how these vary seasonally is necessary to develop reliable generalizations about the role of small wetlands in the nutrient dynamics in headwater catchments.

We examine the influences of runoff magnitude and water table fluctuation and peat redox processes on phosphorus and nitrogen dynamics in a Sphagnum - conifer swamp. This quantitative information is needed to generalize about the role of wetlands in nutrient transport and retention in small headwater Precambrian catchments. The magnitude of runoff, water residence time and water level fluctuations of the swamp were examined in relation to annual and seasonal patterns of TP and TN export and retention. Physical and chemical parameters and nutrient concentrations of water in the swamp were measured through the 1987/88 year to determine the relationship between redox potential, the form and availability of P and N and its influence on annual and seasonal retention of these nutrients.

STUDY AREA

The conifer swamp (Pc1-sw) is in Plastic Lake subcatchment #1 (45° 11′ N, 78°0 50′ W), central Ontario. The mean annual January and July air temperatures are -11.0 and 17.7 °C, respectively. The area receives 900-1100 mm yr^{-1} of precipitation with 240 -300 mm falling as snow. Each month during the period of snow cover some precipitation falls as rain. The long-term annual runoff is 400 - 600 mm yr^{-1}. A more detailed description of the climate, physiography, geology, and geochemistry of the area have been reported by LaZerte and Dillon (1984), Devito et al. (1989), Scheider et al. (1983), Girard et al. (1985),and Wels et al. (1990).

The peat deposits, 0.5 to 5.0 m in depth, overlaying shallow layers of clay and sand, occupy a bedrock depression in the centre of the subcatchment (Fig. 1). Well decomposed peat extends to within 20 to 30 cm of surface. The bulk density of the top 20 cm of peat in the depressions ranges from 0.02 to 0.11 g/cm^3, and the top 30 cm of the mounds 0.00 to 0.09 g/cm^3. The swamp is forested primarily with white cedar (Thuja occidentalis) and black spruce (Picea mariana) with lesser amounts of balsam fir (Abies balsamifer), white pine (Pinus strobus), Larix laricina, and birch (Betula spp.) and maple (Acer spp.). An understorey of Alnus spp. and black alder (Ilex verticillata) exists, with shrubs dominating in the open areas. There is a well defined ground layer of Sphagnum. A mound-depression microtopography exists, with pools of standing water present well into the growing season.

Four intermittent channelized inflows enter the swamp (Fig. 1). Pc1-08 and Pc1-C drain small, primarily conifer forest upland microcatchments. Pc1-04 and Pc1-A originate from a small bog and flow through moderately-sloped, conifer forested uplands. A large portion of the watershed (9.9 ha) consisting of moderately sloping, conifer-forested uplands contributes unchannelized inputs. The outlet, Pc1-03, is an ephemeral stream originating at the southeast corner of the swamp. The depth of overburden surrounding the swamp ranges from zero to about 1 m.

METHODS

Precipitation depths and air temperature data were obtained from meteorological stations located within 1 km of the wetland (Locke and deGrosbois 1986). Stream discharge at the mouth of Pc1 catchment and at Pc1-08 subcatchment has been continuously monitored at

90° v-notch wiers (Scheider et al. 1983, Locke and Scott 1986). Instantaneous discharges of the other inflow streams were measured at least once a week, but more frequently (often daily) during peak flow. Mean daily discharge was calculated by linear integration of instantaneous discharge measurements (Scheider et al. 1979). Discharge at the swamp outflow and ungauged runoff from adjacent uplands were estimated by prorating unit area runoff at the mouth of Pc1 and Pc1-08, respectively. Water levels in Pc1 conifer swamp were monitored daily to weekly in six locations, the frequency determined according to discharge (Fig. 1).

Precipitation, stream and swamp water sampling were carried out as described by Locke and Scott (1986). Prior to 1987/88 water year, water samples were collected one to three times per week depending on the time of year. During the 1987/88 water year, water samples were collected 3 times a week to every day depending on runoff. Subsurface water was sampled from wells at sites #1-6. Initially, tubing was inserted vertically 20-30 cm into the Sphagnum and peat. Pore water was drawn up by suction with a syringe. This method greatly reduced the amount of water that could be sampled. By July 1987, the sampler was inserted into PVC wells, which were inserted 0.5 m into the peat, and water was removed from the bottom of the well. The stand pipes had holes cut in the sides extending from 0.20-0.50 m below the surface of the Sphagnum peat mat. To determine spatial variability, sites #2-5 were sampled approximately monthly.

Analytical methods are reported in Table 1. The platinum/calomel electrode used for ORP measurements was standardized with Zobell solution (Zobell 1946). The calomel electrode potential (EM) was converted to the standard hydrogen potential (EH) and corrected for temperature (T) using the equation of Skoog and West (1976), where: EH = EM + 223 + 0.76 T (^{0}C). Total organic nitrogen (TON) was calculated as TKN - NH_4, total unreactive P (TUP) as TP-TRP, and total nitrogen (TN) as TKN+NO_3.

Water and Nutrient Budgets

A general water budget equation for the swamp is:

$$P + U_i + \Sigma^n S_i - ET - S_o \pm \Delta W = O \pm e \qquad (1)$$

All runoff from the base of each microcatchment was assumed to be stream flow. Inputs include stream inflows (S_i), precipitation depth (P) and ungauged runoff (U_i). Both subsurface and diffuse surface flow from ungauged areas adjacent to the pond were combined into ungauged runoff. Outputs include outflow (S_o), evapotranspiration (ET) and change in water storage (W). The inputs should balance the outputs ± measurement error (e). For water storage, change in volume was assumed constant with depth. The specific yield of the peat was not determined. The top 20 cm of peat have a bulk density of <0.10 g/cm^3. Peat with bulk densities <0.09 g/cm^3 has been reported to have specific yields >0.45 (Boelter and Verry 1977). The specific yield of Pc1 conifer swamp was assumed to be 0.5. Potential ET was estimated from Thornthwaite's (1948) equation. Deep ground water inputs and outputs are negligible (Devito, unpubl. data).

Waterborne nutrient retention (RT) was calculated from inputs which include bulk atmospheric deposition (P_i), stream inflow (S_i), unchannelized or ungauged inflows (U_i). Outputs are via stream outflow (S_o)

$$P_i + \Sigma^n S_i + U_i - S_o = RT \pm e \qquad (2)$$

Wet precipitation and dry depostion are incorporated into P_i.

Atmospheric deposition (mass/m^2) was calculated as described by Locke and de Grosbois (1986). Reactive phosphorus measurements in bulk deposition were previously determined to be 34% of the TP deposition (Dillon and Reid 1981).

Stream load was determined by integrating the estimated daily average discharge (L/s) over time and multiplying the total volume of water by the nutrient concentration at the midpoint of the time interval (Scheider et al. 1979). Nutrient loads from adjacent ungauged areas were determined from the mean monthly volume-weighted concentration of nearby upland streams multiplied by the prorated monthly runoff volume. Annual budgets were determined by addition of the monthly budgets for the hydrologic year June 1 to May 31. Seasonal budgets were determined by addition of the months June to Aug. (summer), Sept to Nov. (fall), Dec. to Feb (winter) and March to May (spring).

Absolute retention (RT) was calculated as:

RT = (total input-total output) / (swamp area),

Percent retention (%RT) as:

%RT = ((total input-total output)/total inputs)*100.

Error Estimates

The variance of water and chemical budgets was calculated from the sum of squares error (Winter 1981):

$$S_T^2 = S_P^2 + S_U^2 + \Sigma^n S_i^2 + S_E^2 + S_{SO}^2 + S_{\Delta W}^2 \qquad (3)$$

where n equals the number of inflow streams (S_i) and S_T is the standard deviation (SD) of the total monthly water budget. To obtain S_T^2, total monthly water volumes were multiplied by their associated fractional error (C.V.) and then squared and summed. The variance of all products in this study was approximated as (Mood et al. 1974):

$$VAR(X,Y) \simeq u_x^2 * VAR(Y) + u_y^2 * VAR(X) + VAR(Y)VAR(X) \quad (4)$$

Calculation of SD estimates and measured or literature estimates of C.V.'s associated with analytical and sampling error to determining budget inputs and outputs are outlined in Devito (1989) and Devito and Dillon (1992).

RESULTS

Water and Waterborne Nutrient Budgets

Annual inputs and outputs of water and chloride for 1987/88 roughly balanced using only runoff and precipitation components (Table 2). Estimated ET by budget difference was 20% greater than PET estimates. On an annual basis, the major input was runoff with precipitation contributing <20%. ET and change in storage were minor outputs representing

≤10 and <1% respectively. The relative contribution of each budget component varied seasonally. Positive retention of water and Cl occurred during the summer and winter with negative retention occurring during the spring (Table 2). Precipitation, ET and change in storage were dominant components of the summer budget. Runoff increased in importance and represented the major input and output during the spring months.

In 1987/88, annual retentions of TP and TN were low with absolute retentions less than the budget uncertainties (Tables 3 & 4). The swamp transformed N and P by retaining TRP (53%), NH_4-N (89%) and NO_3-N (51%) with a concomitant release of organic N (-79%) and unreactive P (-15%).

Seasonal trends in nutrient retention were observed in Pc1-sw (Tables 3 & 4). TUP, TP and TN were retained during the summer and released during the winter and spring. A negative retention of TON was observed throughout much of the year. TON was only retained during the summer when outflows were low or ceased. TRP, NH_4-N and NO_3-N were retained throughout the year, but lower absolute and relative retention occurred during the spring.

The absolute input and output of nutrients varied seasonally (Table 5). The majority of the runoff and flux of P and N occurred during the winter and early spring and was primarily confined to only a few rain and snowmelt events. Ninety-four percent of the runoff and greater than 60% of N and P inputs and 85% of the outputs occurred from December 1

1987 to May 31 1988. During April 1988, 23 - 28% of the annual inputs and 38 - 47% of the annual outputs of TP and TN occurred.

Swamp Hydrology

The outflow hydrograph and water table (WT) elevation from March 1987 to May 1988 are shown in Fig. 2. There was no outflow during the summer and peak discharge occurred during snow melt in March or April. Discharge peaks in late fall and winter were a result of snowmelt associated with rain, where much of the accumulated snow pack was lost.

Water levels varied seasonally in response to rainfall, evapotranspiration and upland runoff, with peaks in water level coinciding with peak outflow (Fig. 2). The WT elevation relative to the surface appeared to follow the elevation of the surface peat and the depth of standing water in depressions was similar at each sample site (unpubl. data; Devito 1989). The surface peat of the entire swamp was saturated with 10 to 15 cm of water from October to June. The water level fell below the surface from late June to late October, reaching a maximum depth of 50 cm in September 1987. The WT responded rapidly to increases in upland runoff with up to 40 cm of standing water during peak snow melt.

Assuming maximum storage of 35 cm, the residence time of water for 1987/88 averaged 30 days over the year (Table 5). The residence time of the water varied seasonally with discharge, being 247 days for summer/fall and 16 days for winter/spring. During peak spring melt, April 7 1988, the residence time was less than one day. An average residence time of 2 days was determined by LiBr tracing in Pc1-sw during the recession of the 1987 snowmelt (Wels and Devito 1989). The outflow discharge at the time of the tracer experiment was about 1/3 (15 to 20 L/s) that of peak discharges (50 to 60 L/s).

The LiBr tracing suggests that movement of water through the swamp is probably an integration of surface flow via various pathways and subsurface flow through shallow peat (Wels and Devito 1989). Although lateral dispersion of waters from the Pc1-08 tributary occurred, it was limited, and water preferentially flowed along the east side (lagg) of the swamp. During peak snowmelt, movement of surface water was visible, primarily at the lagg. Surface flow over ice and through mounds (macropores) was observed. The velocity of surface water passing through the depressions in site 1 was 20 and 24 cm/s on April 5 and 7 1988, respectively. Surface water velocities exceeding 1 cm/s occurred at all sample sites during the 1987 and 1988 spring melt. Wels and Devito (1989) estimated average water velocities of 0.27 cm/s during the recession of 1987 spring melt.

Swamp Chemistry

Temperatures of the surface and interstitial water varied seasonally, with maximum temperature in excess of 20° C in the summer, 1°C in the winter. The temperature of the peat water remained about 1 to 2°C warmer than the surface water through the winter and was similar to the surface water during spring melt.

The chemistry of the surface and subsurface (well) water varied with WT fluctuations and runoff through the year. Stratification is apparent in the DO and ORP profiles (Fig. 3). DO concentrations and ORP remained low in peat interstitial water through much of the year. Sporadic increases in ORP and DO occurred through the summer, in association with rainfall events during periods when the peat was exposed to air, and with increased runoff in the fall and during the spring melt. The surface water generally remained oxygenated when significant outflow discharge occurred. DO concentrations dropped to levels below 2 mg/L as surface water fell and stagnated during summer and in late March.

Temporal variations in P and N concentrations and variation between depths generally followed those observed for temperature, DO and ORP profiles (Figs. 4 & 5). TP and TN concentrations were higher in the interstitial water than the surface. TRP was the dominant form of TP in the well water and TUP (not shown) was the dominant form in the surface water (Fig. 4). TRP and TP concentration of the peat pore water showed large temporal variability, increasing with reductions in DO during the summer and winter. A large increase in TP and TRP occurred in early summer as the WT dropped below the peat surface. TRP and TP concentrations declined to surface values with a rise in WT and increased runoff during the fall and during spring snowmelt. Surface concentrations of TRP remained near detection limit for most of the year, with some increase in late summer. TP concentrations remained relatively constant through most of the year, with a large increase during the summer, as the WT fell to the peat surface.

TON was the primary form of TN in both the surface and well water (Fig. 5). TON in the interstitial and surface water showed similar temporal variations to TP. NH_4-N concentrations increased to about 200-300 μg/L with anoxic conditions during the early summer and winter, with lower concentrations following increased runoff in the fall and spring. Very high NH_4-N concentrations (>1000 μg/L) occurred in the peat pore water as WT elevations dropped during the summer. The NH_4-N concentration of the surface water remained near detection for much of the year, as expected with oxic conditions. A large increase in concentration occurred in early summer and in October as the WT rose to and above the surface. NO_3-N concentrations in the well water were low, with some increase during periods of higher runoff in the fall and spring. NO_3-N concentrations of >500 μg/L occurred during the summer draw down. Surface water concentrations showed marked seasonal variations. Concentrations remained near detection limit through the summer, and increased to >500 μg/L during the fall following the WT draw down. NO_3-N concentrations remained around 150 μg/L through the winter, with peak concentrations associated with the ascending limb of outflow storm hydrographs.

The concentration of the wetland outflow followed that of the surface water at Site 1. The marked seasonal patterns in P and N concentrations observed in the outflow were not observed in the inflows (i.e., Pc1-08). TP, NO_3-N and TON concentrations of the inflows did not exceed 8, 100 and 200 μg/L, respectively during the fall.

Monthly Retention in Relation to ORP and Discharge

Visual analyses of the relationship between monthly retention, runoff, mean water ORP and temperature of Pc1-sw are shown in Figs. 6 & 7. There is a strong inverse relationship between monthly retention of TP and TN and outflow runoff (adj. R^2= 0.80 and 0.89). There is a very weak relationship between mean monthly temperature and TP retention. Highly reducing conditions occurred sporadically and, therefore, there appears to be no relationship between retention and mean ORP. A significant correlation was observed between TP and TN retention and mean monthly DO concentration (r= -0.723 and -0.573). The linear relationship between mean DO and TP and TN retention was primarily due to an observed relationship between mean DO and runoff (r=0.635).

The scatter of data in the relationship between monthly TP and TN retention and runoff was relatively close for the years 1984/85 to 1987/88 (Fig. 8). There is an apparent linear relationship from zero runoff to about 1000 mm mn^{-1}. Beyond 1000 mm mn^{-1} there is an apparent threshold and net export levels off.

DISCUSSION

Annual Budgets

Low annual TP and TN retention in Pc1 swamp appears to be a long-erm phenomenon. No significant retention was observed for 5 years (1983/84 to 1987/88; Devito et al. 1989, Devito 1989). The study swamp primarily functions to transform inorganic forms of N and P into organic forms which are subsequently transported downstream. These results are similar to wetland-dominated watersheds in the northern Precambrian Shield and Sweden which receive a large portion of water and nutrients from mineral soils (Chapman 1987, Lundin and Bergquist 1990). Very low annual retention and net transformation of inorganic to organic TP and TN have been reported in freshwater wetlands from a wide geographical distribution (Elder 1985, Hill 1991, Kemp and Day 1984, Koerselman et al. 1990). This contrasts with the high retention efficiency of P and N in bogs or poor fens which receive little upland runoff and atmospheric deposition dominates the total inputs (Hemond 1983, Urban and Eisenreich 1988, Verry and Timmons 1982).

The water volume and chemistry of unchannelized runoff from hillslopes adjacent to the swamp were not measured directly and uncertainities in ungauged estimates can bias interpretation of budget estimates. Recent analysis of groundwater flow confirms that deep ground water inputs are minimal. The runoff coefficients for Pc1-08 sub-catchment were the same as the entire Pc1 catchment (Devito 1989). Using unit area runoff estimates for the ungauged area resulted in good water and Cl balances. The greatest errors would be associated with estimating the chemistry. Concentrations varied between measured sites and are reflected in the relatively high uncertainty of the ungauged estimates. The N chemistry of deep soil water extracted by lysimeters in Pc1-08 sub-catchment was similar to stream chemistry, particularly during peak hydrographs when most of the water and nutrient transport occurs (B. LaZerte, unpubl. data). Due to the dominance of precipitation inputs of inorganic nitrogen (>90%), large uncertainties in ungauged inputs have little impact. Estimates of inputs from ungauged areas represented 30, 28, 52 and 23% of the TUP, TP, TON and TN inputs to the swamp, respectively. Doubling the estimated ungauged inputs would result in a rough balance of TUP and TON and a positive retention of TP and TN in excess of budget uncertainties. However, TUP and TON concentrations are low in mineral upland soils. Halving the ungauged inputs would result in the observed net release of TUP and TON and balance of TP and TN.

Seasonal Variations in Nutrient Retention

The seasonal, and thus annual, retentions of P and N in the swamp are controlled by 1) hydrologic variables, particularly runoff magnitude, water residence time, the occurrence of saturated overland flow (SOF), and the interaction between hydrologic fluctuations and 2) nutrient assimilation by vegetation, and 3) regeneration rates of P and N via decomposition and leaching of organic sediments.

(i) Hydrologic Fluctuations

Gross export and absolute retention of P and N within Pc1 swamp were controlled by seasonal variations in runoff. Discharge varied over four orders of magnitude while outflow concentration remained relatively constant; thus, P and N export were directly proportional to stream discharge. Increased gross export of elements as discharge increases has been widely reported (Klein 1981, Peverly 1982, Hill 1988).

Episodic events are extremely important in the annual retention and transport of P and N transport in the study swamp. Accumulation of precipitation within a snow pack redistributes several months precipitation into one or a few hydrologic events. Greater than 40% of the annual P and N inputs and outputs to the swamp occurred in 4 events. Very low residence times and potentially high rates of saturation overland flow (SOF) restrict nutrient removal from the water to instantaneous reactions, and result in low retention of nutrients. Greater than 50% of the annual water and nutrient yield from temperate and boreal watersheds has also been reported to occur during episodic storms or snow melt (Pierson and Taylor 1985, Scheider et al. 1983, Schindler et al. 1976).

Saturated overland flow predominates through the year in Pc1 swamp. The reduced porosity and hydraulic conductivity of minerotrophic wetland peat limit the capacity for subsurface flow and are conducive to surface pooling and SOF (Ivanov 1981). Small valley wetlands in the study area act as variable source areas for quickflow generation and major stream discharge peaks are produced by SOF on these wetland surfaces (McDonnell and Taylor 1987, Shibitani 1988, Pierson and Taylor 1985). Because runoff magnitude is related to the degree of SOF, the influence of either can not be separated; however, SOF appears to reduce the monthly and annual P and N retention. Relatively high surface water velocities occur during peak hydrographs in the swamp. Reduction in P and N concentration of the surface and well water suggests that flushing of nutrients from the peat occurred. SOF may be the major export pathway of elements from minerotrophic wetlands as the increased velocity and water depth both limit the interaction of dissolved elements with the peat and increase the potential scouring of nutrients (Pierson and Taylor 1985, Kadlec et al. 1981). In addition, preferential flow along specific channels may result in major flushing of nutrients from these zones but also results in effective short circuiting of flow-through water from other areas of the swamp (Wels and Devito 1989, Roulet 1991). During lower flows, the WT declines to the peat surface and runoff is increasingly confined to large portions of surface peat or acrotelm, increasing the potential sequestering of P and N. The predominance of subsurface flow in the deeper acrotelm in bogs (Ivanov 1981) and lower unit areal runoff than minerotrophic wetlands receiving runoff from adjacent hill slopes may partly explain the greater retention efficiencies of some bog systems (e.g., Verry and Timmons 1982).

(ii) Interaction of Hydrology and Biotic Assimilation

An important consideration is the timing of the major nutrient cycling processes relative to variations in runoff and nutrient transport. Biotic assimilation controls P and N retention in the swamp during periods of low flow when high water retention and long residence times are coupled with warmer temperatures (Hill 1988). Evapotranspiration exceeded rainfall in the swamp during the summer causing outflow cessation and resulting in 100% retention of atmospheric inputs. However, periods of high assimilation occur when nutrient transport is low and contribute little to the annual nutrient flux. About 90 percent of the annual runoff and 60 to 80 percent of the annual input and outputs to the swamp occurred from late fall to spring. Sustained runoff throughout the winter has been reported in other temperate and subarctic fens (Price and FitzGibbon 1987). Saturated soil conditions prior to snowmelt in Pc1-sw also limit retention of early melt water which occurs in unsaturated peats of bogs or northern peatlands which are hydrologically inactive during the winter (Chapman 1987, Bay 1969). Short residence time and SOF coupled with low temperatures further limit the influence of ecosystem production on surface water concentrations. Thus, a large portion of the annual P and N input may bypass biotic and abiotic assimilation and long term sequestering, resulting in a large through-flow of nutrients and low annual retention efficiencies.

Inorganic forms of P and N were efficiently retained within the swamp throughout the year, suggesting rapid assimilation into a component which is independent of runoff magnitude. Microbes rapidly assimilate P and N and may limit the amount of available (non-refractory) P and N in surface waters (Sanville 1986, Richardson and Marshall 1986, Urban and Eisenreich 1988). This may occur under ice and snow (Verry and Timmons 1982) or at times when plants are dormant and hydrological fluxes high (Atchue et al. 1983). Microorganisms are readily transported in surface runoff and are influenced by runoff magnitude, water levels and hydraulic retention times (Richardson and Marshall 1986). Intense competition for inputs and regenerated N and P by the microbial community may partially explain the efficient retention and transformation of inorganic P and N, the predominance of organic P and N in the surface waters and the large throughflow of TP and TN in the swamp.

The low annual retention in the swamp suggests that a large part of the P and N assimilated during the growing season is temporary. The annual accumulation by shrubs and trees may be low relative to the total inputs due to nutrient recycling in living and dying plant material (Urban and Eisenreich 1988). Although herbs and algal epiphytes may be very important in removing P and N directly from the surface water, a large portion of assimilated nutrients is lost to the water column following senescence when runoff increases in the fall and winter (Bernard and Solsky 1977, Davis and van der Valk 1983, Atchue et al. 1983). Translocation of nutrients from sediments by vegetation can also function in recycling nutrients from the sediments to surface waters further limiting nutrient retention by vegetation (Richardson and Marshall 1986).

(iii) Water Table Fluctuations and Nutrient Regeneration

Outflow water P and N concentrations were buffered from dilution of increased runoff through the winter and spring. The probable source of P and N is decomposition and leaching of peat. Increased concentrations of DOC are associated with organic decomposition and were observed during the summer and winter (Devito 1989). Nitrogen and P mineralization and mobilization have been measured in aerobic and anaerobic sediments of many northern peatlands (Verhoeven et al. 1988, Urban and Eisenreich 1988, Richardson and Marshall 1986). Although P and N mineralization rates are low during the winter as a result of low temperatures, they are measurable (Hill and Shackleton 1989). Decomposition of litter has also been reported under the snowpack during the winter (Moore 1983). Leaching of P and N from organic matter during the winter via freeze thaw processes may also be important in releasing P and N to the surface waters (Richardson and Marshall 1986, Timmons et al. 1970).

Summer drawdown of the water table, resulting in aeration of the peat, had a large influence on the regeneration and concentration of P and N in the surface water and outflow. There are few data available on the influence of WT fluctuations on mineralization and nutrient dynamics of unperturbed northern peatlands, but peat decomposition is stimulated by the warmer temperatures and aeration of peat following wetland drainage (Lieffers 1988, Williams 1974). Large export of elements following water table drawdown during the summer or drought conditions has been observed in other wetlands (Bayley et al. 1987, Van dam 1988).

The periodicity and amplitude of water table fluctuations are a function of the source and magnitude of water inputs (i.e., precipitation) and vary between wetlands and between years. At Pc1-sw, the annual variations in water table fluctuations were not measured; however, during summers with little precipitation elevated NO_3-N, TON, TP and DOC concentrations were observed during the fall when outflow runoff commenced (unpubl. data; LaZerte and Dillon 1984). This was not observed following summers with ample precipitation. However, little annual variation in TP and TN retention was observed over the past 5 years (Devito 1989). It is unclear how important water table drawdown is to the long-term dynamics of P and N in this swamp.

Low ORP in the pore water was observed infrequently in Pc1-sw, which was not expected. Reduced conditions and increased availability of P and N in association with increased water levels are characteristic of many wetlands, and anoxic processes have been suggested as important in regenerating nutrients (Bayley et al. 1985, Ponnamperuma 1972). Low oxygen tension of the surface water only occurred in late winter and early summer as runoff and water levels decreased and water stagnated in depressions. Although the concentration of TP, NH_4-N, and TON increased in the surface water, the total flux of P and N during these periods was small relative to the annual fluxes. Maintenance of an anaerobic zone at depth for most of the year may be important in diffusive flux of TRP and NH_4-N from deeper peats. NH_4-N and NO_3-N may be lost from the system as NO_2 or N_2 gas via nitrification and denitrification, but may be partially offset by nitrogen fixation (Dierberg and Brezonik 1983, Urban and Eisenreich 1988). However, Warwick and Hill (1988) report negligible rates of nitrification and denitrification in a riparian cedar-hemlock swamp in southern Ontario.

Aerobic processes (i.e., mineralization) appear to dominate P and N cycling with little TRP and NH_4-N export from the swamp. Oxygenation of the peat surface occurred seasonally and was influenced by seasonal variations in WT fluctuations and runoff. Aeration of surface peat occurred during most of the summer and fall as water levels dropped below the surface. High WT elevation and saturation of the peat were associated with increased surface water velocities and oxygenation of the surface waters. Sparling (1966) reported increases in DO concentration and declines in reduced forms of N in the surface water, to a depth of 20 cm, with increasing flow in a number of wetlands in central Ontario. DO saturation occurred at surface water velocities of 1 cm/s. Surface velocities greater than 1 cm/s were observed in Pc1-sw. Oxygenated surface peats may be common in small valley wetlands which receive large water volume from surrounding hillslopes.

CONCLUSIONS

The results presented help clarify the relative importance of conifer swamps to the water chemistry of small headwater streams of the Precambrian Shield. Waterborne P and N may not be effectively retained in small valley conifer swamps. It appears that the pools of N and P have reached an equilibrium at some time during succession (Koerselman et al. 1990), or the retention rate may be too low to be detected when compared to the large influxes and effluxes. The primary role of conifer swamps may be to transform P and N, the outflow of re-mineralized or leached P and N, balancing the inorganic P and N inputs.

Wetlands are important landscape units representing a hydrologic link between uplands and downstream aquatic systems. The low annual retention in Pc1-sw may be representative of small valley wetlands common to the Precambrian Shield where large throughput of water and nutrients from the surrounding uplands and flushing of available nutrients, especially during storm and snowmelt events, result in low nutrient retention. Due to the hydraulic characteristics, greater export of nutrients via runoff to downstream ecosystems may occur in headwater catchments with wetlands than catchments without wetlands (Wels et al. 1990).

The magnitude of runoff, occurrence of saturated overland flow and water residence time within the swamp influenced the seasonal and annual retention of TP and TN. Anoxic processes, often associated with wetlands (Gorham et al. 1984), occurred infrequently in Pc1-sw due to the hydrologic characteristics of the wetland. Water table drawdown during drought periods may be important in the export of P and N from the swamp. Variations in nutrient retention efficiencies between wetlands reflect differences in the hydrology which determine both the magnitude and rate of nutrient transport as well as influence the biogeochemistry of a system. Low order streams in the Precambrian Shield are consistently interrupted by complex channel and riparian structures with differing hydrology, redox environments and autotrophic and heterotrophic production, limiting the applicability of black box budget approach in developing generalizations of wetland nutrient efficiencies. This work shows that characterizing how biotic and geochemical cycling vary temporally with the magnitude of hydrologic fluctuations in conjunction with a budget approach are needed to develop reliable generalizations of the influence of wetlands on the Precambrian Shield landscape.

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TABLE 1 Analytical Procedures

	Parameter	Abbreviation	Units	Procedure[+]
	Water Parameters			
1	Total phosphorus	TP	μg/L as P	Acid digestion, acid molybdate colorimetry
3	Total reactive phosphorus	TRP	μg/L as P	Acid molybdate colorimetry*
1	Ammonium	NH_4-N	μg/L as N	Phenate - Hypochlorite colorimetry
1	Nitrite/nitrate	NO_3-N	μg/L as N	Hydrozine reduction - Azo dye colorimetry
2	Total Kjehdahl nitrogen	TKN	μg/L as N	Acid digestion - neutralization nitrogen and colorimetry
2	Chloride	Cl	mg/L	Thyocyanate colorimetry
3	Dissolved Oxygen	DO	mg/L	Winkler method
3	Redox potential	ORP	mV	Platinum/colamel electrode[@]
3	pH	pH		Ag/Cl electrode

1 OME laboratory, Dorset
2 OME laboratory, Rexdale
3 By the author, Dorset
\+ Reference OME (1981)
* Modified from Stainton et al. (1977)
@ Skoog and West (1976)

TABLE 2 Seasonal and annual water (mm) and chloride (mg/m^2) balance for Plastic 1 conifer swamp for the 1987/88 hydrologic year, ±1 SD. A negative balance represents inputs < outputs, and a positive value represents inputs > outputs.

	Input			Output		Evapotranspiration	
	Stream Flow	Ungauged Runoff	Precipitation	Stream Flow	Change in Storage	Balance (In-Out)	Thornthwaite
Plastic 1 conifer swamp							
Water (mm)							
summer	9 ± 1	38 ± 11	182 ± 22	40 ± 7	-220 ± 110	409 ± 113	275
fall	82 ± 6	202 ± 53	235 ± 30	217 ± 33	+213 ± 107	89 ± 127	100
winter	280 ± 13	719 ± 143	301 ± 37	1082 ± 127	-15 ± 7	233 ± 195	0
spring	924 ± 49	1651 ± 370	205 ± 25	2973 ± 420	-11 ± 6	-182 ± 562	86
annual	1295 ± 51	2610 ± 400	923 ± 58	4312 ± 440	-33 ± 17	549 ± 600	461
Chloride (mg/m^2)							
summer	<0.01 ± <0.01	0.01 ± 0.01	0.03 ± <0.01	0.03 ± 0.01	-	0.01 ± 0.01	
fall	0.08 ± 0.01	0.26 ± 0.09	0.05 ± 0.01	0.28 ± 0.07	-	0.11 ± 0.11	
winter	0.19 ± 0.01	0.65 ± 0.24	0.08 ± 0.01	0.95 ± 0.19	-	-0.03 ± 0.31	
spring	0.42 ± 0.03	0.83 ± 0.30	0.04 ± 0.01	1.36 ± 0.31	-	-0.07 ± 0.43	
annual	0.69 ± 0.03	1.75 ± 0.39	0.20 ± 0.02	2.62 ± 0.37	-	0.2 ± 0.54	

TABLE 3 Plastic 1 conifer swamp phosphorus input, output and retention (mg P/m^2) for the 1987/88 hydrologic year. Shown are estimates ± 1 SD.

	Input				Output	Retention	
Phosphorus Form	Stream Flow	Ungauged Runoff	Precipitation	Total	Stream Flow	Absolute (In-Out)	Relative %
<u>TRP</u>							
summer	<0.1 ±<0.1	<0.1 ± <0.1	1.8 ± 0.7	1.8 ± 0.7	0.1 ± <0.1	1.7 ± 0.7	94
fall	0.1 ± <0.1	0.2 ± 0.1	1.2 ± 0.4	1.5 ± 0.5	0.2 ± 0.1	1.3 ± 0.5	87
winter	0.3 ± <0.1	0.7 ± 0.4	0.9 ± 0.3	1.9 ± 0.5	1.1 ± 0.2	0.8 ± 0.5	42
spring	0.7 ± 0.1	1.2 ± 0.8	1.5 ± 0.5	3.4 ± 0.9	2.6 ± 0.5	0.8 ± 1.0	24
annual	1.1 ± 0.1	2.1 ± 0.8	5.4 ± 1.0	8.6 ± 1.3	4.0 ± 0.6	4.6 ± 1.4	53
<u>TUP</u>							
summer	<0.1 ± <0.1	0.1 ± <0.1	3.9 ± 1.0	4.0 ± 1.0	0.6 ± 0.1	3.4 ± 1.0	85
fall	0.3 ± <0.1	0.9 ± 0.5	2.6 ± 0.7	3.8 ± 0.8	1.5 ± 0.3	2.3 ± 0.9	61
winter	0.6 ± 0.1	1.6 ± 1.3	1.9 ± 0.5	4.1 ± 1.4	5.6 ± 0.9	-1.5 ± 1.7	37
spring	2.5 ± 0.3	3.4 ± 3.1	3.1 ± 0.8	9.0 ± 3.2	16.4 ± 2.8	-7.4 ± 4.2	-82
annual	3.4 ± 0.3	6.0 ± 3.4	11.5 ± 1.6	20.9 ± 3.8	24.1 ± 2.9	-3.2 ± 4.85	-15

Table 3 (continued)

	Input				Output	Retention	
Phosphorus Form	Stream Flow	Ungauged Runoff	Precipitation	Total	Stream Flow	Absolute (In-Out)	Relative %
TP							
summer	<0.1 ± <0.1	0.1 ± <0.1	5.7 ± 0.8	5.8 ± 0.8	0.6 ± 0.1	5.2 ± 0.8	90
fall	0.4 ± <0.1	1.0 ± 0.5	3.8 ± 0.5	5.2 ± 0.7	1.8 ± 0.3	3.4 ± 0.8	65
winter	0.8 ± 0.1	2.3 ± 1.3	2.7 ± 0.4	5.8 ± 1.3	6.7 ± 0.8	-0.9 ± 1.6	-16
spring	3.1 ± 0.3	4.8 ± 3.0	4.5 ± 0.6	12.4 ± 3.1	19.0 ± 2.7	-6.6 ± 4.1	-53
annual	4.3 ± 0.3	8.2 ± 3.3	16.7 ± 1.2	29.2 ± 3.5	28.1 ± 2.9	1.1 ± 4.5	4

TABLE 4 Plastic 1 conifer swamp waterborne nitrogen input, output and retention (gN/m^2) for the 1987/88 hydrologic year. Shown are estimates ± 1 SD.

Nitrogen Form	Input				Output	Retention	
	Stream Flow	Ungauged Runoff	Precipitation	Total	Stream Flow	Absolute (In-Out)	Relative %
NH_4-N							
summer	<0.00 ± 0.01	<0.00 ± 0.01	0.07 ± 0.01	0.07 ± 0.01	0.00	0.07 ± 0.01	100
fall	<0.01 ± <0.01	<0.01 ± <0.01	0.09 ± 0.01	0.09 ± 0.01	<0.01 ± <0.01	0.09 ± 0.01	99
winter	<0.01 ± <0.01	<0.01 ± <0.01	0.09 ± 0.01	0.09 ± 0.01	0.01 ± <0.01	0.08 ± 0.01	89
spring	0.01 ± <0.01	0.01 ± <0.01	0.10 ± 0.01	0.02 ± 0.01	0.03 ± 0.02	0.09 ± 0.02	75
annual	0.01 ± <0.01	0.01 ± <0.01	0.35 ± 0.02	0.37 ± 0.02	0.04 ± 0.02	0.33 ± 0.03	89
NO_3-N							
summer	<0.00 ± <0.01	<0.01 ± <0.01	0.09 ± 0.01	0.09 ± 0.01	<0.01 ± <0.01	0.09 ± 0.01	100
fall	<0.01 ± <0.01	0.01 ± 0.01	0.15 ± 0.02	0.16 ± 0.02	0.08 ± 0.01	0.08 ± 0.02	50
winter	<0.01 ± <0.01	0.01 ± <0.01	0.20 ± 0.02	0.21 ± 0.02	0.10 ± 0.01	0.11 ± 0.03	52
spring	0.01 ± <0.01	0.03 ± 0.02	0.14 ± 0.02	0.18 ± 0.03	0.13 ± 0.06	0.05 ± 0.07	28
annual	0.01 ± <0.01	0.05 ± 0.02	0.58 ± 0.04	0.64 ± 0.04	0.31 ± 0.07	0.33 ± 0.08	51

Table 4 (continued)

Nitrogen Form	Input				Output	Retention	
	Stream Flow	Ungauged Runoff	Precipitation	Total	Stream Flow	Absolute (In-Out)	Relative %
TON							
summer	<0.01 ± <0.01	<0.01 ± <0.01	0.06 ± 0.02	0.06 ± 0.02	0.02 ± <0.01	0.04 ± 0.02	67
fall	0.01 ± <0.01	0.03 ± 0.01	0.02 ± 0.02	0.06 ± 0.02	0.10 ± 0.02	-0.04 ± 0.03	-67
winter	0.04 ± <0.01	0.10 ± 0.04	0.03 ± 0.02	0.17 ± 0.05	0.31 ± 0.04	-0.14 ± 0.06	-82
spring	0.10 ± 0.01	0.20 ± 0.10	0.04 ± 0.02	0.34 ± 0.11	0.68 ± 0.09	-0.34 ± 0.14	-100
annual	0.15 ± 0.01	0.33 ± 0.11	0.15 ± 0.04	0.63 ± 0.12	1.11 ± 0.10	-0.48 ± 0.16	-76
TN							
summer	<0.01 ± <0.01	<0.01 ± <0.01	0.22 ± 0.02	0.22 ± 0.02	0.02 ± <0.01	0.20 ± 0.02	91
fall	0.01 ± <0.01	0.03 ± 0.01	0.26 ± 0.02	0.30 ± 0.03	0.18 ± 0.02	0.12 ± 0.03	40
winter	0.04 ± <0.01	0.12 ± 0.04	0.33 ± 0.03	0.49 ± 0.05	0.42 ± 0.04	0.07 ± 0.07	14
spring	0.12 ± 0.01	0.23 ± 0.11	0.28 ± 0.03	0.63 ± 0.11	0.85 ± 0.11	-0.22 ± 0.16	-35
annual	0.17 ± 0.01	0.38 ± 0.11	1.09 ± 0.05	1.64 ± 0.13	1.47 ± 0.12	0.17 ± 0.18	10

TABLE 5 Runoff, water retention and phosphorus and nitrogen export and import from Plastic 1 conifer swamp for the 1987/88 hydrologic year.

	Period						
	Annual 1987/88	Summer & Fall	Winter & Spring	April 1988	April 1-10, 1988	Dec. 10-16, 1987	Jan 31 - Feb 6, 1988
No. Days	365	182	183	30	10	7	7
Runoff (1×10^6 L) (% annual)	95	6 (6%)	89 (94%)	50 (53%)	30 (32%)	6 (6%)	6 (6%)
Residence Time (days)	30	247	16	5	3	10	9
<u>Total Phosphorus (g)</u>							
Export	617	53 (9%)	564 (91%)	291 (47%)	186 (30%)	33 (5%)	55 (9%)
Import	645	243 (38%)	402 (62%)	181 (28%)	-	-	-
<u>Total Nitrogen (Kg)</u>							
Export	32	4 (13%)	28 (88%)	12 (38%)	9 (28%)	2 (6%)	3 (9%)
Import	36	12 (33%)	24 (67%)	8 (23%)	-	-	-

Figure 1

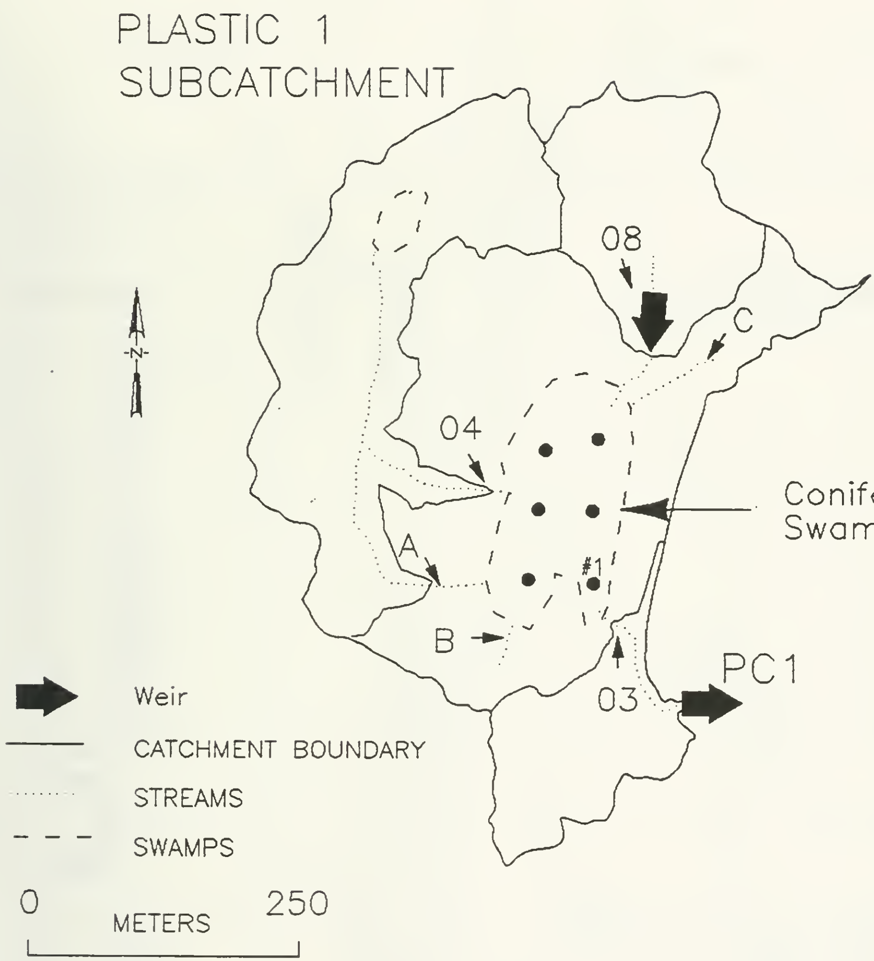
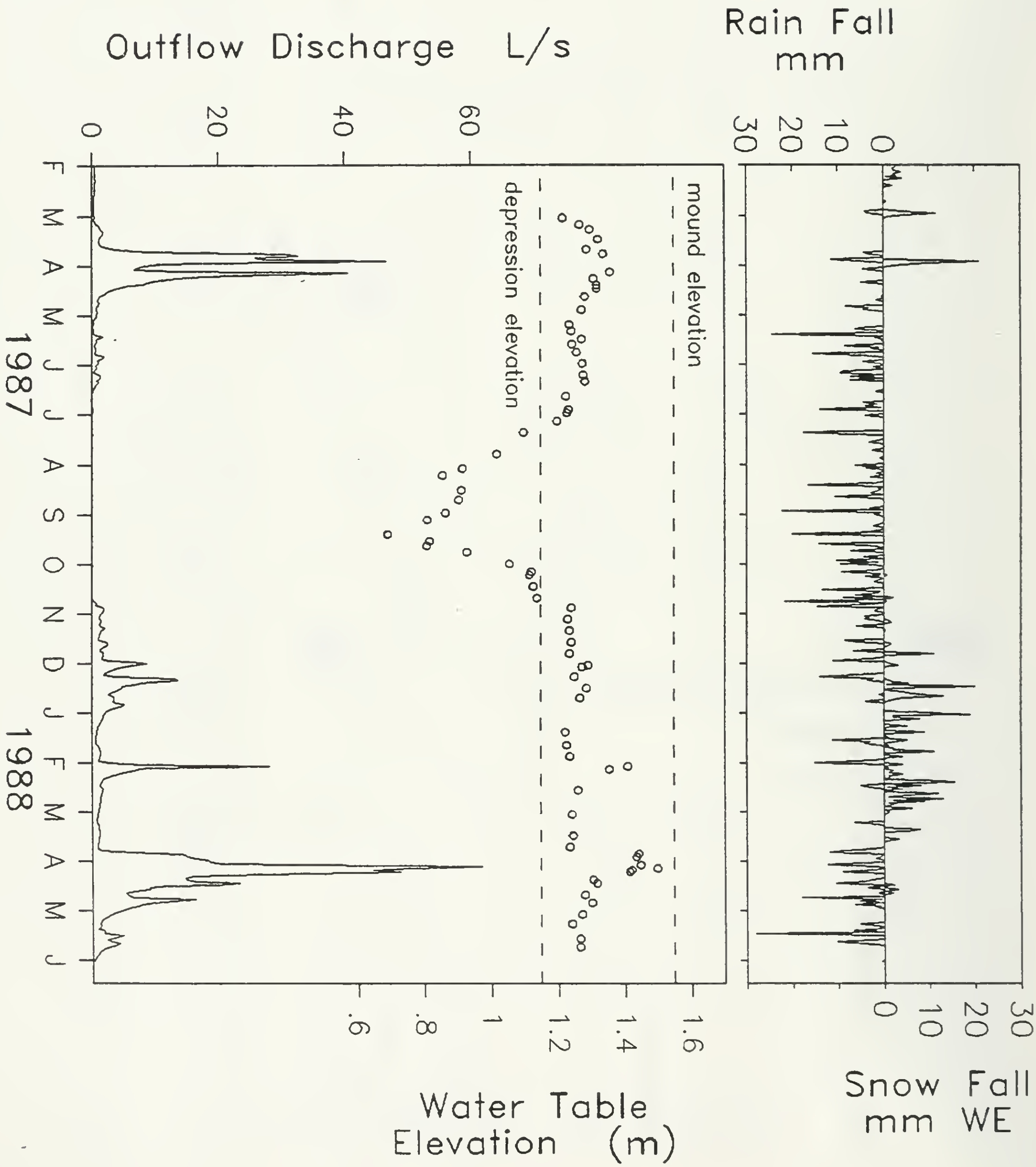
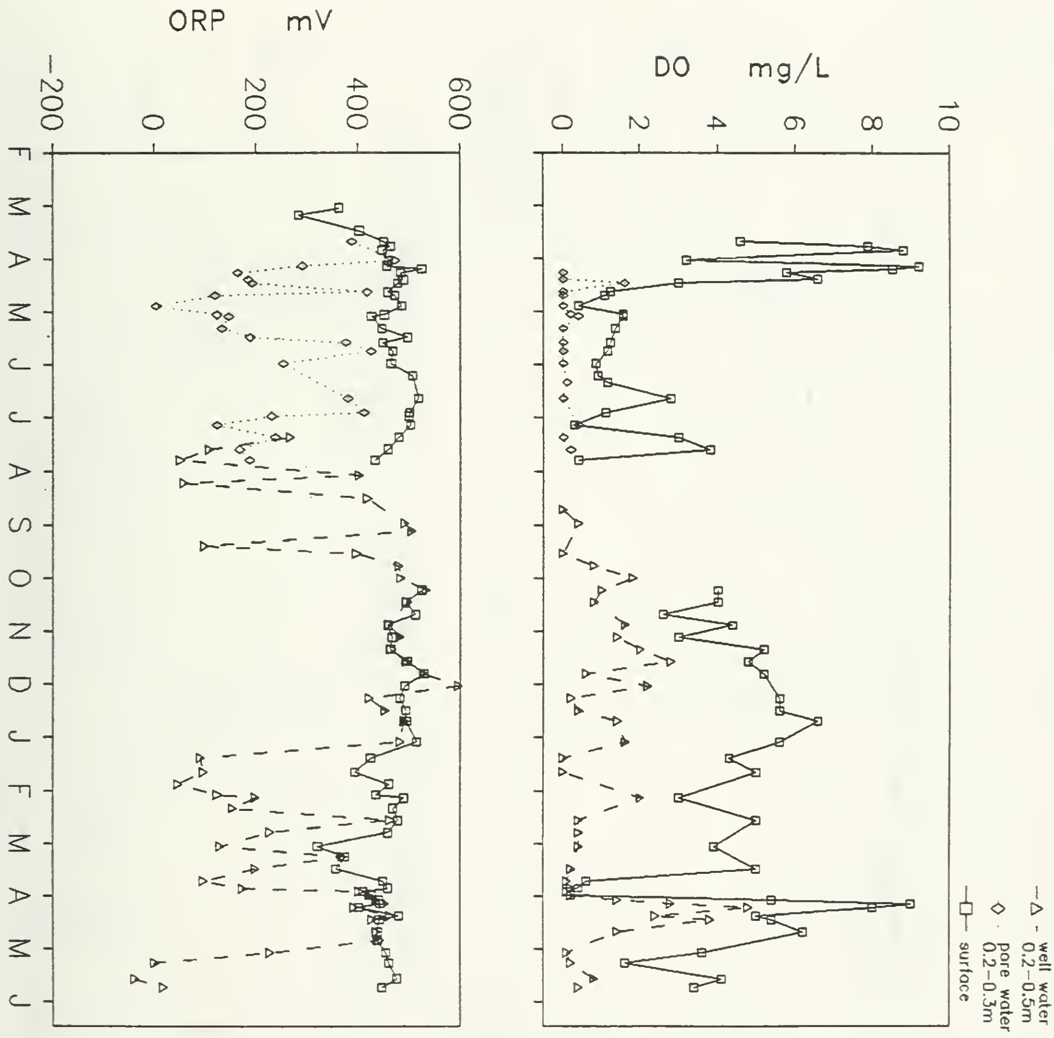

PLASTIC 1
SUBCATCHMENT
-N-
08
C
04
Conifer
Swamp
A
#1
B
03
PC1
Weir
CATCHMENT BOUNDARY
STREAMS
SWAMPS
0
METERS
250

Figure 2



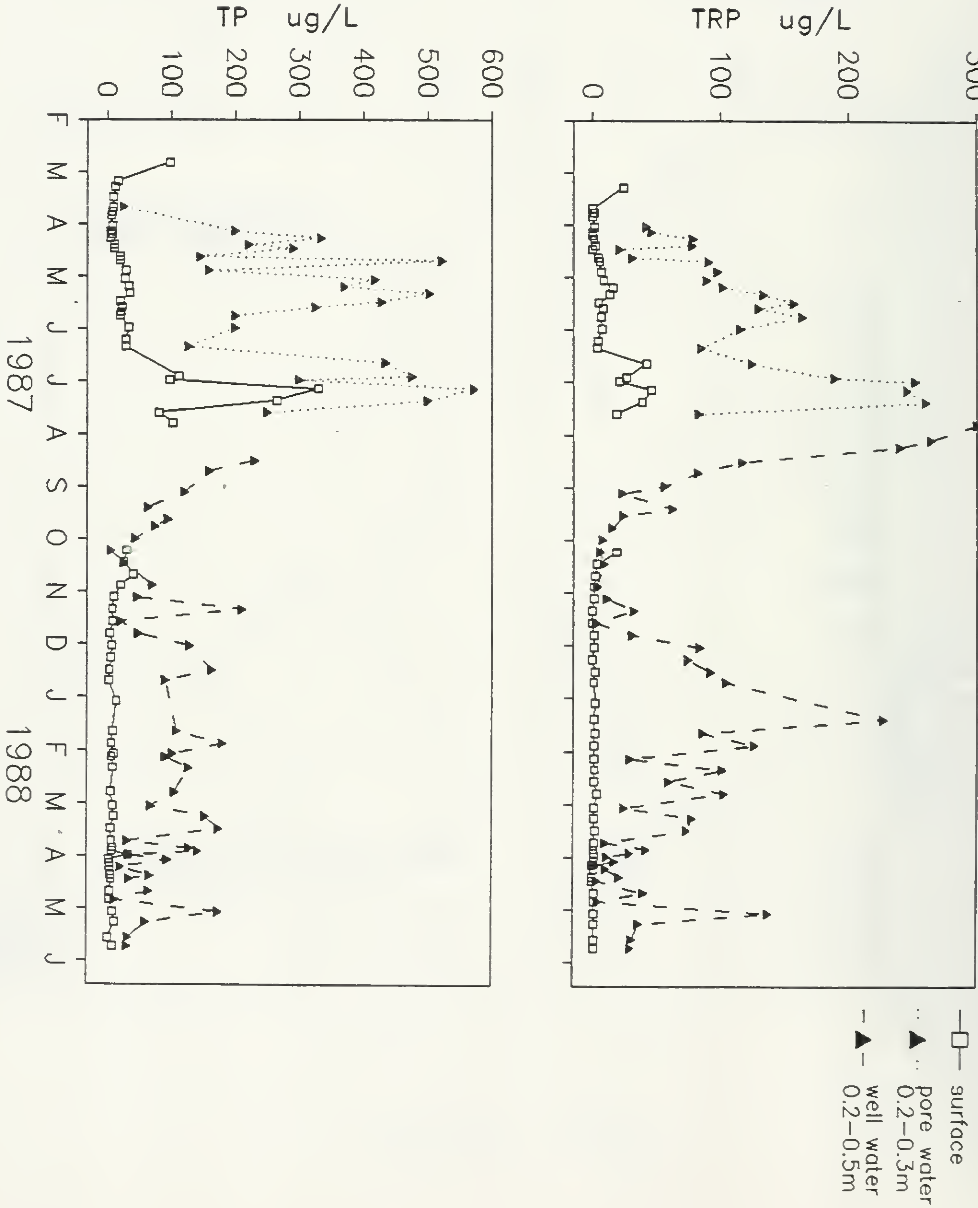
Outflow Discharge L/s
Rain Fall mm
Snow Fall mm WE
Water Table Elevation (m)
mound elevation
depression elevation
1987
1988
F M A M J J A S O N D J F M A M J
0 20 40 60
.6 .8 1 1.2 1.4 1.6
0 10 20 30

Figure 3



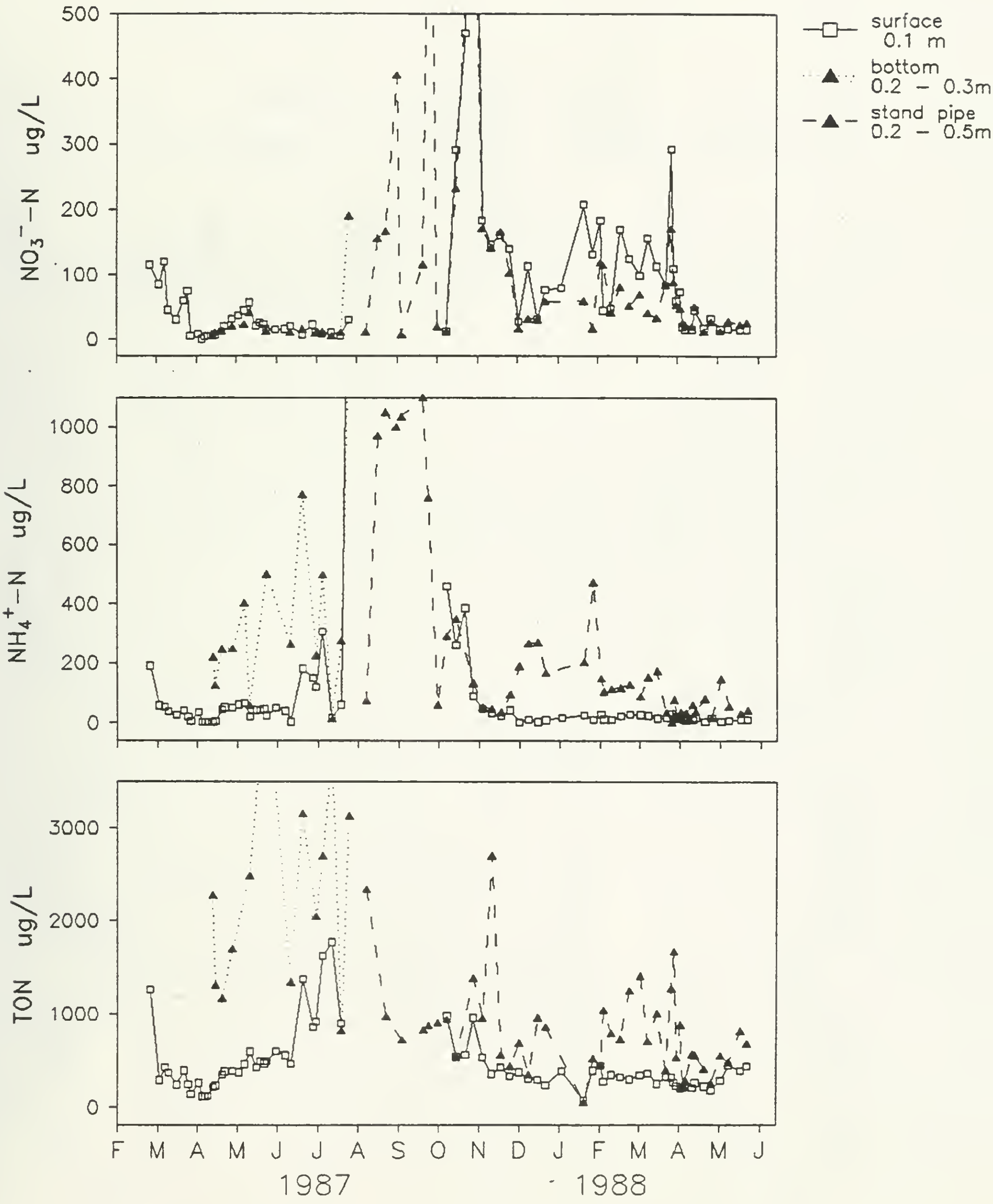
DO mg/L
ORP mV
well water 0.2–0.5m
pore water 0.2–0.3m
surface
1987
1988
F M A M J J A S O N D J F M A M J

Figure 4



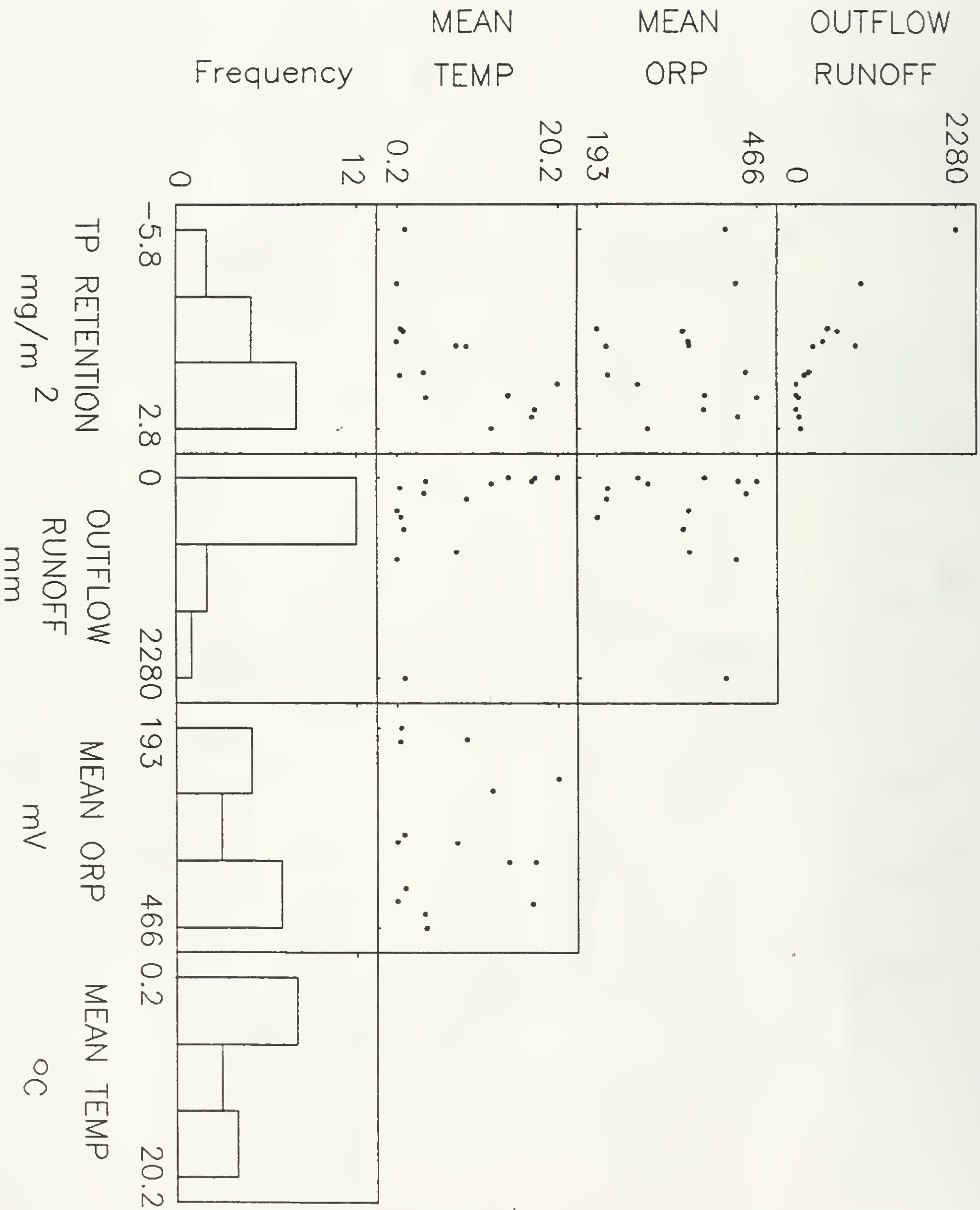
TRP ug/L
0
100
200
300
TP ug/L
0
100
200
300
400
500
600
F M A M J J A S O N D J F M A M J
1987
1988
surface
pore water 0.2–0.3m
well water 0.2–0.5m

Figure 5



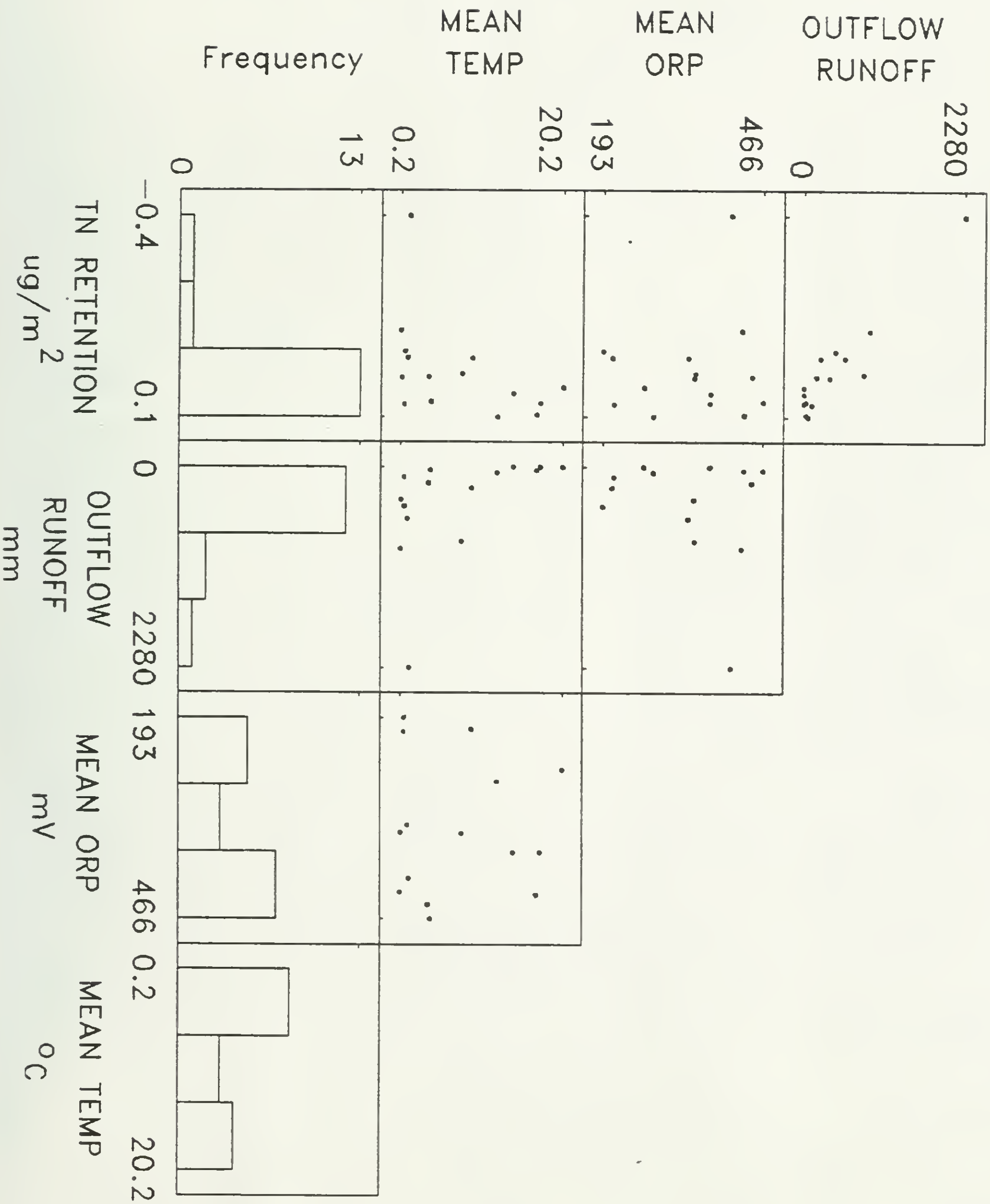
surface 0.1 m
bottom 0.2 - 0.3m
stand pipe 0.2 - 0.5m
NO_3^--N ug/L
NH_4^+-N ug/L
TON ug/L
F M A M J J A S O N D J F M A M J
1987
1988

Figure 6



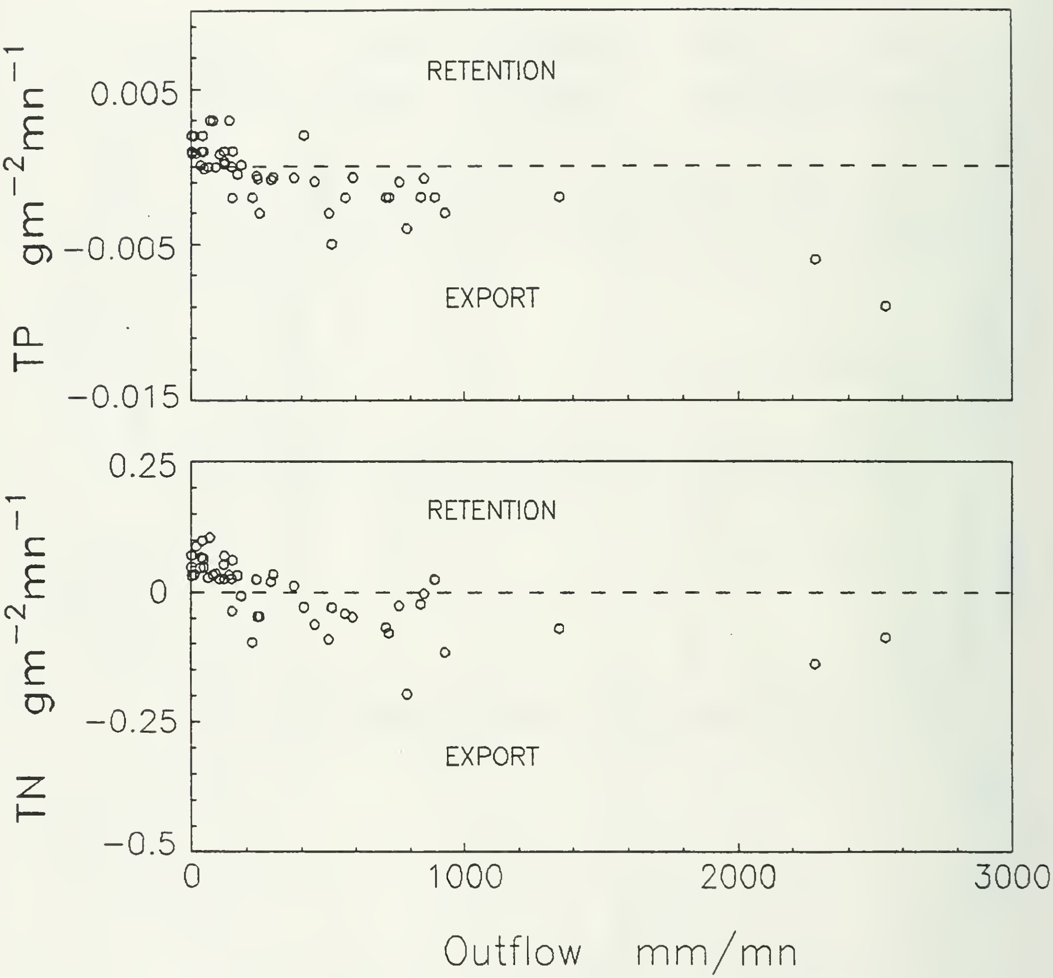
OUTFLOW RUNOFF
MEAN ORP
MEAN TEMP
Frequency
2280
0
466
193
20.2
0.2
12
0
-5.8
2.8
TP RETENTION
mg/m 2
0
2280
OUTFLOW RUNOFF
mm
193
466
MEAN ORP
mV
0.2
20.2
MEAN TEMP
°C

Figure 7



OUTFLOW RUNOFF
MEAN ORP
MEAN TEMP
Frequency
2280
0
466
193
20.2
0.2
13
0
-0.4
0.1
TN RETENTION ug/m2
0
2280
OUTFLOW RUNOFF mm
193
466
MEAN ORP mV
0.2
20.2
MEAN TEMP °C

Figure 8



RETENTION
EXPORT
TP gm^{-2}mn^{-1}
0.005
−0.005
−0.015
RETENTION
EXPORT
TN gm^{-2}mn^{-1}
0.25
0
−0.25
−0.5
0
1000
2000
3000
Outflow mm/mn