Factors Limiting Processes in Freshwater Wetlands: An Agricultural Primary Stream Riparian Forest

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Abstract: We advocate a broader perspective for wetland studies and present a case study to illustrate our approach. The case study focuses on the hydrology and belowground processing of nitrate and sulfate in a riparian forest wetland that receives hydrologic inputs from a cropland watershed and from direct precipitation. A conceptual model is presented that relates the nitrate and sulfate uptake in the wetland to wetland processes, such as evapotranspiration, plant uptake, oxidation-reduction reactions, and gaseous diffusion, and to external controlling factors, such as temperature, groundwater input, and precipitation. The forest wetland transpired an average of 67% of the sum of precipitation and groundwater inputs and took up averages of 86% of the nitrate and 25% of the sulfate that entered in precipitation and groundwater. Approximately 25% of this nitrogen was assimilated by trees and stored as woody biomass accretion. The efficiency of nitrate uptake was relatively constant from year to year, but was highest in the autumn (97%) and lowest in the winter (81%). The case study illustrates some general features of the proposed broader perspective. A wetland process cannot be studied in isolation but must be related to factors that may limit this process. A classification of important wetland processes and potential limiting or controlling factors is presented. Limits on a process can originate from geomorphic and climatic considerations or from human management. In each of these categories, the controls can act directly within the wetland or act on a wetland process externally by controlling the inputs to the wetland from its watershed or airshed. The important internal and external controls that should be considered in studies of belowground oxidation and reduction processes in wetlands are listed; examples of how those controls yield negative feedback that limits the progress of a belowground process are given.

INTRODUCTION

Studies of freshwater wetlands are often narrowly focused on a very limited set of internal wetland processes that are not closely related to other

internal processes or to controlling external factors and processes. Important internal wetland processes include primary production, storm surge suppression, aquifer recharge, sediment trapping, toxin processing, organic matter processing, nutrient binding, and nutrient assimilation and dissimilation. External processes are those which affect the internal processes of the wetland but occur in the wetland's airshed or watershed. We use the term "watershed" in its most general sense: the land surface from which surficial waters flow into the wetland or the wetland's aquifer and recharge areas. Examples of important external inputs include storm runoff from uplands with high sediment and phosphate contents, groundwater inputs with high nitrate content, or atmospheric deposition of sulfate and nitrate.

One cannot fully understand a given wetland process unless one studies all of the other internal and external processes important in controlling that process. Wetlands are only a part of the landscape and could not function or exist without dynamic interactions with their surrounding ecosystems. Thus, to understand a wetland we must not only gain a reasonable understanding of its internal hydrology, biogeochemistry, and biology but also its watershed's hydrology, biogeochemistry, meteorology, and interactions with the atmosphere.

Few if any freshwater wetlands have been studied in such detail. Most studies are limited to a few aspects of this overall menu of needs. Perhaps for this reason it is fairly common for wetland scientists to infer a rather unreasonable lack of limitation on the capacity of wetlands to carry out specific processes. Wetlands, like all other systems, obey physical and chemical laws. They respond to a given set of internal conditions and to given rates and compositions of external inputs by maximizing their use of the available free energy, chemical substrates, and physical conditions. Because physical and chemical conditions within a wetland are constantly changing, the relative importances of various internal processes also constantly shift in response to alterations in the limiting factors. Various physical, chemical, and biological feedback mechanisms can also exert a stabilizing effect on internal processes. These feedback mechanisms are more effective when the rate of change in input factors is low; this allows more time for their development.

Some of these freshwater wetland mechanisms and principles are illustrated by describing a case study of belowground processes in an agricultural field–riparian forest primary stream system in the inner coastal plain of Maryland. The focus is on the riparian forest, a freshwater wetland. It is an end member of a continuum of wetlands that extends from second- and third-order stream floodplains to freshwater forested swamps to brackish tidal marshes in the tidal Rhode River landscape system. The relationship of this riparian forest with its cropland watershed and the atmosphere are described with an emphasis on hydrology and nitrate and sulfate processing.

MATERIAL AND METHODS

Site Description

The study site (Rhode River subwatershed 109, 38°53′ N; 76°38′ W; Correll, 1977) is a 16.3 ha drainage basin of which 10.4 ha of uplands are

managed for corn production under conventional tillage. A primary stream and 5.9 ha of riparian deciduous hardwood forest account for the rest of the basin. The soils are fine sandy loams from the Eocene Nanjemoy formation. Low-elevation soils are primarily of the Collington soil classification series, whereas high-elevation soils are mostly from the Westphalia series. Soils contain high levels of montmorillonite; intermediate levels of illite and kaolinite; and lower levels of gibbsite, chlorite, plagioclase, and potassium feldspar. The soils are noncalcareous and are composed roughly of 50% fine sand, 40% silt, and 10% clay (Correll and Dixon, 1980; Correll, 1983). An effective aquiclude, the Marlboro clay layer underlies these soils at an elevation just above sea level and thus prevents hydrologic interactions with deeper aquifers (Chirlin and Schaffner, 1977). Average basin and channel slopes for the watershed are 5.4 and 2.6%. The riparian forest is dominated by *Liquidambar styraciflua* (sweet gum) and *Acer rubrum* (red maple) (Peterjohn and Correll, 1984).

Hydrology

Stream discharge was monitored and water samples taken at a 120° sharp-crested vee-notch weir, the foundation of which rested upon the Marlboro Clay layer. A stilling well and Stevens model 7000 depth monitor were used to record discharge every 5 min. Surface (quick) flow rates and groundwater (slow) flow rates were calculated graphically from the hydrograph (Barnes, 1940). A chloride mass balance among precipitation, cropland groundwater discharge, and riparian forest groundwater discharge at the weir was used to calculate the evapotranspiration term of the hydrologic balance (Peterjohn and Correll, 1986). A Stevens model 61R flow meter was modified to close a sampling switch every 38,000 l of discharge. Switch closure activated a sampling cycle in which a fixed volume of stream water was taken from the base of the vee-notch and composited with previous sample aliquots. These volume-integrated composite samples were analyzed weekly along with weekly spot samples. Parallel weekly composite samples were taken with and without sulfuric acid preservative.

Four transects of wells were used to sample groundwater. These transects consisted of clusters of three to five replicate wells at the boundary between cropland and forest and at different distances into the forest along the expected direction of water flow. The wells were perforated PVC pipes with their lower ends at the surface of the Marlboro Clay layer (Peterjohn and Correll, 1984; Peterjohn and Correll, 1986). Before sampling, wells were pumped dry and allowed to refill overnight.

Surface water collectors were also placed at well cluster sites along the transects. These were plastic bottles modified to trap overland flow during storm events (Peterjohn and Correll, 1984). Bottles were cleaned before storm events and sampled soon after the events. Bulk precipitation was sampled for chemical analysis on an event basis (Correll and Ford, 1982).

The dissolved oxygen content and temperature of well waters were measured in the field with a YSI model 54 meter and a Clark-type polarographic electrode sensor and thermistor by lowering the sensor into the well as groundwater was flowing back after the well was pumped dry. The acidities of well and stream water samples were measured in the laboratory after air equilibration with an expanded range pH meter and a Ross electrode.

Forest Production and Nutrient Storage

Three riparian forest study sites were surveyed. Each extended for 70 m along the stream and was approximately 40 m wide. Two relatively mature forest sites were permanently marked with a 10 m × 10 m grid, whereas the youngest site was marked with a 5 m × 5 m grid. At the 10-m gridded sites, three quadrats from each of the four rows of quadrats were selected randomly for vegetation censuses, whereas six quadrats were randomly selected from each of the eight rows of quadrats at the 5-m gridded site. Thus a total area of 1200 m^2 was censused at each of the three study sites. At the two more mature sites, all trees of diameter at breast height (DBH)$\geq$ 3 cm were identified to species and tagged. At the young forest site, all trees of DBH $\geq$ 1 cm were tagged, identified, and measured.

Annual increments in DBH were used to estimate increments in woody biomass (branches, boles, and large roots) by the allometric relations developed by Harris et al. (1973). Estimates of component biomass production were multiplied by the total density of trees and by the tissue nutrient content measured on incremental core samples. For trees of less than 5-cm DBH, we estimated the allometric relationships by harvesting 5 *Acer rubrum* and 10 *Liquidambar styraciflua* from each DBH size class (1 to 2 cm, 2 to 3 cm, and 3 to 4 cm). Aboveground biomass (dry weight) was determined for boles and branches. Tree age was also determined from annual rings. Subsamples of boles and branches were taken for total N and P analyses. Incremental cores were taken from 55 individual trees in the older stands for total N and P analyses.

Analytical Chemistry

Unfiltered bulk precipitation and filtered (0.45 μm pore size) water from surface runoff collector samples and groundwater samples were analyzed for total Kjeldahl nitrogen (TKN), total phosphorus, nitrate, chloride, sulfate, and organic matter content. Unfiltered water from surface runoff collectors and water samples from the weir were analyzed for TKN, total P, total suspended sediments, and organic matter content. Filtered weir water samples were analyzed for nitrate, sulfate, and chloride. Plant biomass samples were analyzed for TKN and total P.

Nitrate, chloride, and sulfate were determined with a Dionex model 16 ion chromatograph. The TKN was determined by digestion with sulfuric acid and hydrogen peroxide (Martin, 1972), by distillation, and by Nesslerization (APHA, 1976). Total P was determined by perchloric acid digestion (King, 1932), development of a phosphomolybdic acid–blue complex, and colorimetry (APHA, 1976). In samples that contained sediment, the complex was extracted with isobutyl alcohol before colorimetry (Correll and Miklas, 1976). Organic matter was determined as chemical oxygen demand (Maciolek, 1962). An empirical conversion factor of 0.417 was used to convert from milligrams of oxygen consumed per liter to milligrams of organic carbon per liter. Total suspended sediment concentration was calculated from the gain in mass of a prewashed, dried, and weighed Millipore filter (with 0.45 μm pores) after filtration of a measured volume of sample.

RESULTS

Conceptual Model

We have constructed a simple conceptual model of the belowground processes that dominate the nitrogen dynamics of this riparian forest wetland (Fig. 1). It represents a lateral cross section of wetland soil extending from the cropland–forest boundary on the left to the primary stream on the right. Within that cross section, a series of processes occur in a defined order. The first zone on the left side is dominated by respiration due to the presence of dissolved molecular oxygen, which enters in ground-water from the cropland, in infiltrating rainwater, and by diffusion from the atmosphere. The second zone is dominated by denitrification and transpiration. Conditions for denitrification are excellent with high concentrations of hydronium ion, electron donor (organic matter), and electron acceptor (nitrate). High transpiration by the forest trees may also imply high trans-location of nitrate from roots to leaf stoma as the result of entrainment in the xylem sap. Finally, in the third zone, feedback mechanisms, such as pH rise and low nitrate concentration, slow the rate of denitrification. However, the low E_h and high sulfate are suitable conditions for sulfate reduction.
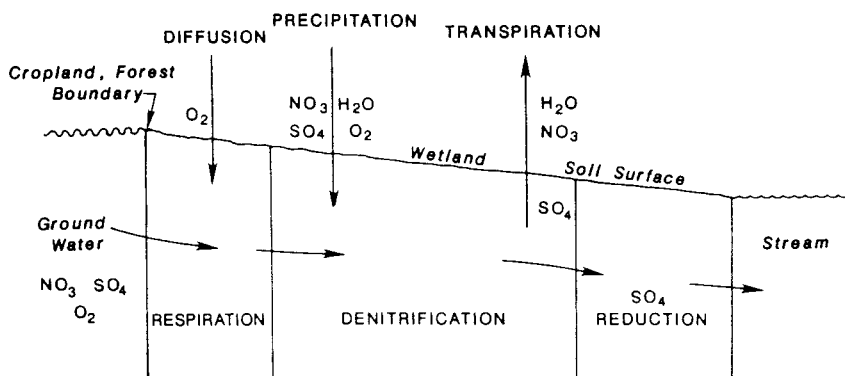

Fig. 1 Conceptual model of belowground processes affecting groundwater composition in a riparian forest.

The widths of the zones vary seasonally with hydrologic factors. The third zone may not exist much of the time, and nitrate may escape into the stream at higher than normal concentrations. Not only is the actual pattern temporally variable, but also it is highly spatially variable within the wet-land. One would expect to see an overall direct relationship between ground-water flow rates and nitrate concentrations in the stream, however, because soil contact time is inversely related to groundwater flow rates. This is indeed the case. Monthly baseflow (groundwater) discharge rates for a series of years were compared to average baseflow nitrate concentrations (Fig. 2). Generally, high nitrate concentrations were associated with high baseflow rates. All cases in which samples were taken while surface runoff was occur-ring were removed before this analysis. These same data were used to create the scatter plot in Fig. 3, and an R^2 of 0.40 was obtained. Thus, although
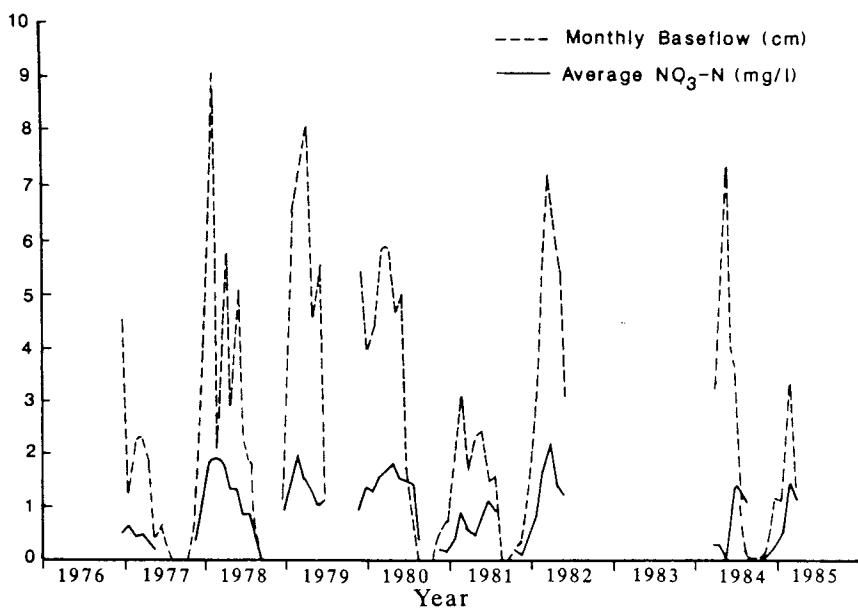
Fig. 2 Temporal patterns for volume and nitrate content of baseflow (groundwater flow) of stream draining the study site. Gaps in data are periods of no flow, except for the gaps in mid 1979 and early 1983.
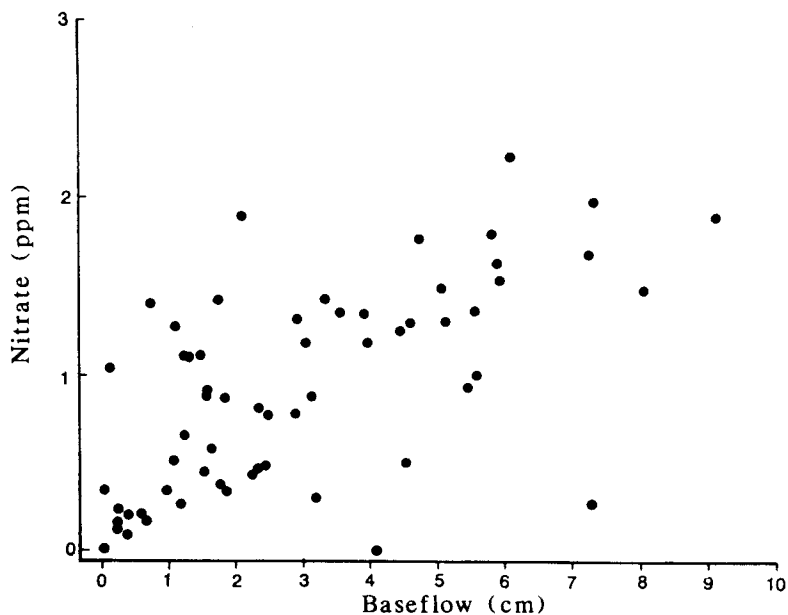

Fig. 3 Scatter plot of data from Fig. 2. Coefficient of determination ($R^2 = 0.40$) an probability ($P < .001$) relate to a linear least squares regression of the data.

rate of baseflow is not the only factor affecting baseflow nitrate concentration in the stream, it accounts for 40% of the variance in the data set.

Hydrology

Watershed and riparian forest wetland hydrologic balances were determined for three complete years (March 1, 1980–March 1, 1981; September 1, 1983–September 1, 1985). The first of these years had less than normal precipitation, the third had almost the long-term norm of 108 cm for this area (Higman and Correll, 1982), and the second had much more than normal (Table 1). Evapotranspiration in the riparian forest was roughly double that of the upland croplands and exceeded precipitation each year. Stream baseflow volumes fluctuated much more than precipitation from year to year. Wetland groundwater outputs ranged from 18% of inputs (precipitation plus cropland drainage) in year three to 39% in year two, averaging 33% of inputs. Wetland groundwater outputs averaged 8% of inputs in the fall, 28% in the summer, 39% in the spring, and 44% in the winter.

Wetland Process Rates

Primary production of forest trees resulted in the net storage of 4 to 8 tonnes of organic carbon per hectare year in woody biomass. The lowest rates were in a stand of 8- to 9-year-old saplings, whereas the highest rates were found in a 30-year-old stand more representative of the overall forest. For the year from March 1, 1980, to March 1, 1981, organic input–output budget calculations for surface waters gave inputs from cropland of 48 kg C ha^{-1} yr^{-1} and outputs of 31 kg C ha^{-1} yr^{-1} for a net removal of 17 kg C ha^{-1} yr^{-1} (Peterjohn and Correll, 1984). For subsurface flows, inputs from cropland were 13 kg C ha^{-1} yr^{-1} and outputs were 19 kg C ha^{-1} yr^{-1} for a net release of 6 kg C ha^{-1} yr^{-1} (Peterjohn and Correll, 1984). Nutrient mass balances among cropland discharges, precipitation content, and wetland discharges indicated a net retention by the wetland of 75 kg total N ha^{-1} yr^{-1} and 3 kg total P ha^{-1} yr^{-1}. Of these net retentions, nutrient assimilation and long-term storage in woody biomass ranged from 12 to 20 kg N ha^{-1} yr^{-1} and from 3 to 5 kg P ha^{-1} yr^{-1}. Nitrogen dissimilation as a result of denitrification in the wetland was estimated to be 45 kg N ha^{-1} yr^{-1} (Peterjohn and Correll, 1984). Sediment deposition within the riparian forest was estimated to be 4 tonnes ha^{-1} yr^{-1}. These retained sediments contained 12 kg total N ha^{-1} yr^{-1}.

The picture that emerges from the study of this agricultural watershed is that of a very strong interaction between the cornfield uplands and the riparian forest wetland. Continuous disturbance of the uplands by cultivation and fertilization fosters year-round high rates of nitrification, which also release high concentrations of hydronium ions. Shallow groundwaters moving from the cropland into the forest have mean nitrate-N concentrations of 6 ppm and a mean pH of 4.5 (Peterjohn and Correll, 1986), but pH sometimes drops to 3.8. Within the normally wet soils of the forest, high denitrification and assimilation of nitrate by trees reduce average groundwater nitrate-N concentrations to less than 1 ppm and brings the average pH up to 5.5.

TABLE 1

Fluxes of Water, Nitrate, and Sulfate Entering the Riparian Forest Wetland via Precipitation and Cropland Groundwater Drainage and Leaving via Stream Base Flow and Evapotranspiration (ET)

| Time period | Season | Water volume, cm | | | | Nitrate, keq/season or year | | | Sulfate, keq/season or year | | |
		Precip-itation	Crop drainage*	ET	Stream baseflow	Input	Output	Input–output	Input	Output	Input–output
Mar. 81–May 81	2	25.4	18.9	26.9	17.3	4.60	0.57	4.04	3.55	2.45	1.09
Jun. 81–Aug. 81	3	29.7	10.4	31.3	8.8	3.28	0.39	2.90	2.03	1.28	0.75
Sept. 81–Nov. 81	4	18.8	1.1	18.2	1.7	0.77	0.04	0.73	0.85	0.40	0.45
Dec. 81–Feb. 82	1	26.5	38.3	33.1	31.7	14.97	2.02	12.94	8.81	6.12	2.70
Year one		100.4	68.7	109.6	59.5	23.62	3.01	20.61	15.24	10.26	4.98
Sept. 83–Nov. 83	4	28.4	4.3	28.9	3.8	1.50	0.05	1.44	1.37	0.75	0.62
Dec. 83–Feb. 84	1	34.0	40.4	38.6	35.8	6.91	2.11	4.81	6.28	4.76	1.52
Mar. 84–May 84	2	50.8	47.2	55.6	42.4	13.64	1.04	12.60	7.57	5.80	1.77
Jun. 84–Aug. 84	3	22.2	18.1	25.8	14.6	4.04	0.91	3.13	2.89	4.43	-1.53
Year two		135.5	110.0	148.9	96.6	26.09	4.10	21.98	18.11	15.74	2.37
Sept. 84–Nov. 84	4	31.0	1.0	30.5	1.5	0.96	0.01	0.95	0.80	0.22	0.58
Dec. 84–Feb. 85	1	34.4	13.6	33.5	14.4	3.31	0.59	2.71	2.21	1.66	0.54
Mar. 85–May 85	2	18.8	9.1	20.8	7.1	1.89	0.36	1.53	1.49	1.02	0.47
Jun. 85–Aug. 85	3	20.2	0.9	20.4	0.7	0.48	0.04	0.44	0.70	0.07	0.63
Year three		104.3	24.6	105.2	23.7	6.64	1.00	5.64	5.19	2.97	2.22
Mean fluxes averaged over three years											
Winter	1	31.6	30.8	35.1	27.3	8.39	1.57	6.82	5.77	4.18	1.59
Spring	2	31.7	25.0	34.4	22.3	6.71	0.65	6.06	4.20	3.09	1.11
Summer	3	24.0	9.8	25.8	8.0	2.60	0.44	2.16	1.88	1.93	-0.05
Fall	4	26.1	2.1	25.9	2.3	1.08	0.03	1.04	1.01	0.45	0.55
Complete year		113.4	67.8	121.2	59.9	18.78	2.71	16.08	12.85	9.66	3.19

*Groundwater discharge from watershed times 1.8 (the ratio of watershed area to wetland area).

Direct measurements in groundwater monitoring wells arrayed at differing distances from the cropland–forest interface support this picture of dominant processes within the wetland. Mean nitrate and dissolved oxygen concentrations in groundwater decline within the first 20 m from the forest edge (Figs. 4A and 4B). These dissolved oxygen measurements are probably overestimates because the wells are exposed to air in their headspaces. However, values still decline to approximately 1 ppm in hot weather. Nitrate concentrations decline slowly with distance into the wetland except during the planting and fertilizing season (May) when the decline is very rapid. Groundwater temperatures (Fig. 5) had a monthly mean minimum of about 7°C in February and a maximum of about 16°C in September. These temperatures are delayed and less extreme than air temperatures, as might be expected.
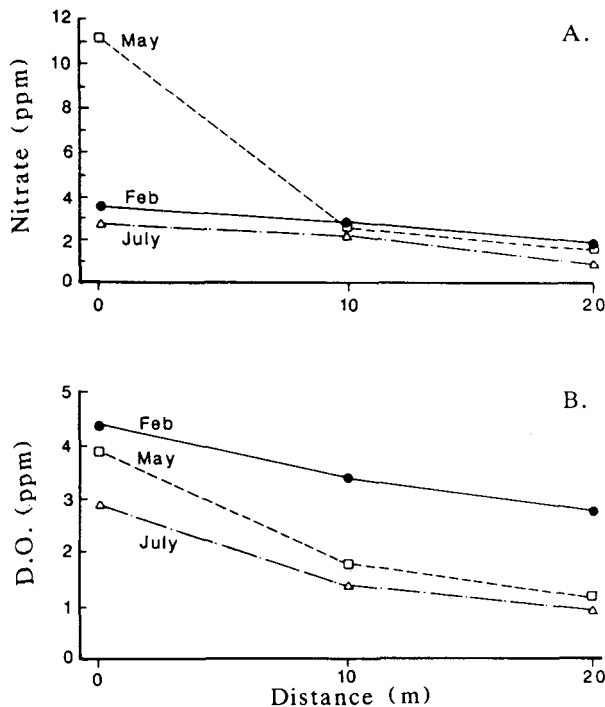
Fig. 4 Changes in terminal electron acceptor concentrations in groundwater at various distances from cropland into riparian forest. (A) nitrate concentration in ppm N; (B) dissolved oxygen concentration in ppm.

Belowground Mass Balances

Sufficient data were collected for three years to construct monthly mass balances of the fluxes of nitrate and sulfate into and out of the soils of the riparian forest wetland. Nitrate and sulfate entered the wetland in cropland groundwater drainage and bulk precipitation that fell directly on the forest and left the forest in stream baseflow (Fig. 6). These mass balances give a more detailed view of the temporal variation in the efficiencies of nitrate and sulfate removal below ground. It is apparent that nitrate inputs far
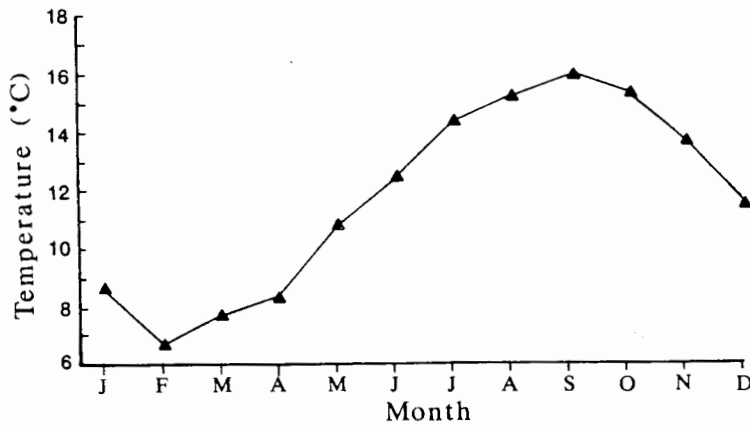
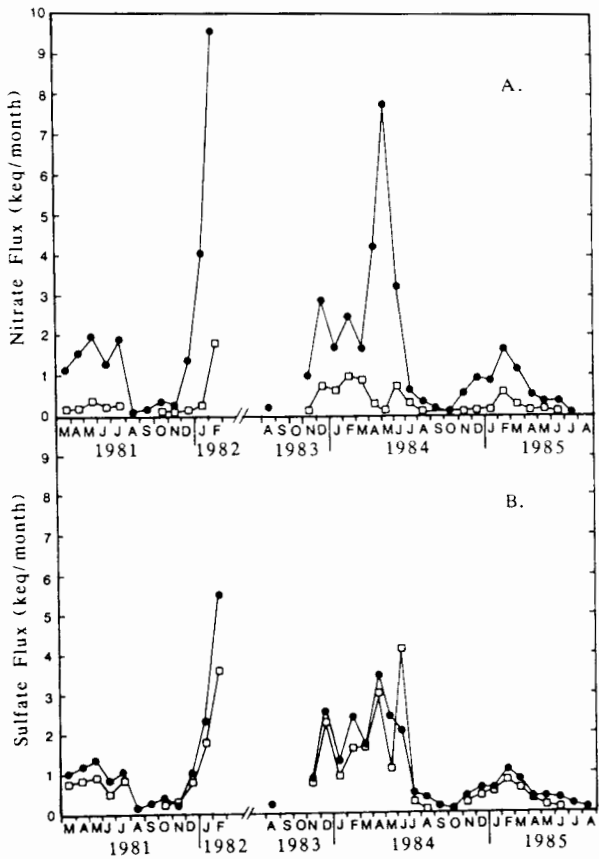Fig. 5   Changes in mean monthly groundwater temperatures entering riparian forest.

Fig. 6   Monthly input–output mass balances for the riparian forest wetland during three study years. Inputs from cropland groundwater plus precipitation are denoted by circular symbols, whereas outputs via the stream channel are denoted by square symbols. (A) nitrate; (B) sulfate. Gaps in data are periods of no stream flow as the result of dry weather.

exceed outputs, whereas sulfate inputs were usually not very much greater than outputs. For 1 month, June 1984, sulfate outputs greatly exceeded inputs. These data are summarized seasonally and annually in Table 1. For this purpose, seasons are three-month periods with winter being December, January, and February.

Averages of 86% of nitrate inputs and 25% of sulfate inputs were removed in the wetland. Annual removal of nitrate was surprisingly constant, varying from 84% in the second year to 87% in the first year. Annual efficiency of sulfate removal varied from 13% in year two to 43% in year three. Inputs of nitrate and sulfate were highest in the winter on average, although they were highest in the spring of the second study year. Nitrate outputs were always highest in the winter. Efficiencies of nitrate removal were always highest in the fall (average of 96%) when input fluxes were lowest, and removal efficiencies were lowest in winter (average of 81%) when input fluxes were usually highest. To a large extent, this reflects the fact that the volumes of groundwater moving through the wetland are usually high in the winter and low in the fall, but nitrate concentration in the stream is positively correlated with groundwater flow (Fig. 3). For the summer of the second study year, sulfate output was greater than the total input. This anomaly, a release of 2.1 keq of sulfate, occurred in June 1984 (Fig. 6). This release may have been due to a net oxidation of pyrite or of sulfides (Table 2Bb) that had been stored in the soil as a result of sulfate

TABLE 2

Wetland Belowground Oxidation–Reduction Processes*

A. Reduction process

    a. $E_{h7} \sim +400$ mV: Manganate reduction
    $2MnO_2 + \,'CH_2O' + 4H_3O^+ \rightarrow CO_2 + 2Mn^{2+} + 7H_2O$

    b. $E_{h7} \sim +300$ mV: Denitrification
    $NO_3^- + \,'CH_2O' + H_3O^+ \rightarrow CO_2 + \frac{1}{2}N_2O + 2\frac{1}{2}H_2O$

    c. $E_{h7} \sim -200$ mV: Iron reduction
    $4Fe(OH)_3 + \,'CH_2O' \rightarrow 4Fe(OH)_2 + CO_2 + 3H_2O$

    d. $E_{h7} \sim -220$ mV: Sulfate reduction
    $SO_4^{2-} + 2'CH_2O' + 2H_3O^+ \rightarrow H_2S + 2CO_2 + 4H_2O$

    e. $E_{h7} \sim < -260$ mV: Methanogenesis
    $2'CH_2O' \rightarrow CO_2 + CH_4$

B. Oxidation process ($E_{h7} > +400$ mV)

    a. Respiration
    $'CH_2O' + O_2 \rightarrow CO_2 + H_2O$

    b. Sulfide oxidation
    $H_2S + 2O_2 + 2H_2O \rightarrow SO_4^{2-} + 2H_3O^+$

    c. Nitrification
    $NH_4^+ + H_2O + O_2 \rightarrow NO_3^- + 2H_3O^+$

*E_{h7} is the oxidation–reduction potential at pH 7.

reduction in prior months. It should be noted that this event followed an extremely wet spring (Table 1).

DISCUSSION

Control Factors

The perspective on limits and controlling factors illustrated by our case study can be extended to wetlands in general. Wetland processes are governed by a series of control factors, which can be categorized as geomorphic, climatic, or human management factors. Each of these categories can also be divided into internal and external factors.

Internal geomorphic control factors include channel morphology, soil nutrient content, soil geochemistry, and hydraulic conductivity. Channel morphology is important because it controls the contact time of waters transiting a wetland. The more diffuse or less channelized the flow, the more contact occurs between the water and the wetland. Soil nutrient content may be important in determining the potential primary productivity of the wetland. Soil geochemistry determines such important factors as chemical binding or exchange capacity and the potential for geochemical reactions. The hydraulic conductivity of the soils determines the proportion of transiting water that can move as soil water. In very sandy systems, almost all movement is via soil water, but in fine silt and clays, almost all movement is via surface water flows.

External geomorphic control factors include watershed area and gradient, soil mineralogy and texture, bedrock type and depth, and the volume and composition of groundwater inputs. Watershed size and gradient are major determinants of the volume and kinetics of external inputs to wetland systems. Soil mineralogy is a very important determinant of the chemical composition of external inputs, whereas soil texture, to a large extent, determines the relative proportions of surface water and groundwater inputs.

The major climatic control factors are the components of the hydrologic cycle: precipitation, runoff, and evapotranspiration (ET). Evapotranspiration is, in turn, governed primarily by such factors as vegetation, humidity, temperature, wind, and sunlight. The output of the external watershed (the wetland input) equals precipitation minus ET minus infiltration to noncommunicating deep aquifers. The output of the wetland equals precipitation plus surface inputs plus groundwater inputs minus ET minus infiltration. An adequate knowledge of the hydrology of a freshwater wetland is fundamental to understanding most of the wetland's processes. Unfortunately, few freshwater wetland studies have established hydrologic budgets, so the rates of internal processes such as nutrient transformations, assimilation, or dissimilation cannot be measured.

Human management of wetland control factors includes watershed land use, airshed alterations, and direct wetland management. Alterations in watershed land use affect the inputs of sediments, nutrients, and toxins; inputs of such terminal electron acceptors as nitrate and sulfate; inputs of hydronium ion; and temporal patterns of hydrology. Airshed alterations regulate inputs of nitrate, sulfate, heavy metals, and hydronium ion via atmospheric deposition as well as exposure to such toxins as ozone. Control fac-

tors that result from direct wetland management include burning, grazing, logging, inputting waste, draining, and damming.

Belowground Processes

Our approach to nitrate and sulfate processing in a riparian forest can also be generalized to other belowground processes and other wetlands. Environmental scientists are increasingly aware of the importance of belowground processes in the control of wetland ecosystems. In salt marsh wetlands, these processes have been the focus of major research projects (Howarth and Hobbie, 1982; Howes et al., 1984; Howarth, 1984). These belowground processes are composed of a series of biogeochemical reactions that occur in a defined order. The availability of terminal electron acceptors determines which level in the series will dominate belowground processes at any one time and place in the wetland. Some of the more commonly important reactions are given in Table 2. They are arranged in order of thermodynamic possibilities as determined by the highest oxidation-reduction potential that will allow a given reaction to proceed. The oxidation-reduction potential (E_h) can be estimated by

$$E_h = \frac{G^\circ}{nF} + \frac{RT}{nF} \ln \frac{a(Ox)}{a(Red)} - \frac{RT}{nF} pH$$

where F = farad of electrons
    n = number of moles that react
    T = absolute temperature
    R = constant in the perfect gas law
    a = activity

As can be seen, E_h is related to a number of factors, including the free energy of reaction, temperature, the ratio of the activities of oxidant and reductant in a given reaction, and pH. This equation is called the Nernst relationship (Billen, 1976).

None of the reduction reactions in Table 2A can proceed in the presence of molecular oxygen. Thus, when significant concentrations of oxygen are present, only respiration and such oxygen consuming processes as sulfide and ammonium ion oxidation (Table 2B) may proceed. Many of these processes generate or consume hydronium ions (e.g., Tables 2Aa, b, and d; 2Bb and c) as well as oxygen. The reversibility of many of the reactions is limited by the production of volatile end products (e.g., Tables 2Ab; 2Ba). The result of these relationships is a series of negative feedback mechanisms which tend to limit the further progress of a belowground process.

Feedback

Let us examine several examples of feedback controls over belowground processes. The first example is sulfate reduction (Table 2Ad). Among the feedback mechanisms are the ratio of electron acceptor to product (e.g., SO_4^{2-}/S^{2-}). As this ratio declines, the equilibrium E_h required for the reaction to proceed declines. As the absolute concentration of sulfate declines, E_h

must also decline for the reaction to proceed. As the pH rises, the E_h must decline for the reaction to proceed. At the same time, rates of entry of oxygen and other more easily reduced electron acceptors, such as nitrate, continue at previous rates, which will raise the E_h if sulfate reduction rates begin to slow down.

A second example is denitrification. As the reaction proceeds (Table 2Ab): (1) pH rises, which affects the composition and metabolic rate of the microbial flora; (2) hydronium ion is consumed in the reaction, the equilibrium shifts and rates decline; (3) nitrate is converted to dinitrogen and nitrous oxide gases which evolve from the system; and (4) the rate slows (and E_h rises), and rates of other processes, such as nitrification, may increase.

SUMMARY

Our case study of the nutrient dynamics of a primary stream riparian forest wetland illustrates the broader perspective which we advocated in the introduction. It includes measures of primary production and nutrient storage in woody biomass, sediment trapping, organic matter flux, and nutrient dissimilation. It considers the internal and external hydrology of the system, including estimates of ET. It includes meteorological inputs. It places the wetland into a landscape perspective by considering the effects of agricultural management of the surrounding uplands. Finally, we have investigated important belowground processes from the perspective of a sequence of interacting oxidation–reduction reactions (Table 1). This has allowed us to model conceptually the wetland belowground processes and to reach a better understanding of their spatial and temporal patterns.

This wetland has a high potential for nitrate removal, and this removal has important environmental effects upon downstream habitats. In the Rhode River landscape, cropland is by far the largest source of total N, most of which is trapped in riparian forests before it reaches a primary stream (Jordan et al., 1986). Although nitrate removal efficiency is always high (51.2% to 99.9% for monthly data in Fig. 6), inefficiency is a relevant concern with respect to downstream environmental impact. Inefficiency, the amount of nitrate not removed, varied from 0.06% to 49%. A better understanding of the factors that control nitrate removal is important from a landscape perspective.

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