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WATERBORNE NUTRIENT FLOW THROUGH AN UPLAND–PEATLAND WATERSHED IN MINNESOTA[1]

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Abstract. Water and nutrient flow were measured on a complex upland–peatland watershed in north central Minnesota. Annual water budgets for upland and peatland components and for the total watershed were developed. Nutrient input and output budgets were developed for each component on a seasonal basis, using net precipitation inputs, and an annual nutrient budget was developed for the entire watershed, using gross precipitation and total outputs. Both components evapotranspire water near potential rates. The upland converts 34% of the water input to water yield, while the peatland (a bog in a lower topographic position) converts 55% of its water input to water yield. The upland annually retains some N, P, K, and Ca from net precipitation, but passes through Mg and supplies Na in excess of inputs. The peatland is a nutrient trap retaining 36–60% of all nutrient inputs annually. There are striking differences in the seasonal retention of nutrient forms between the upland and bog. The total watershed accumulates P and (apparently) N but loses more K, Ca, Mg, and Na than it receives in gross precipitation. Nutrient flow is interpreted for the design of nutrient-added technologies (fertilization and sewage treatment) and as a bench mark for nutrient-depleted technology (whole-tree harvesting).

Key words: evapotranspiration; hydrology; nutrient cycling; nutrient yield; organic soils; water yield.

INTRODUCTION

Water and nutrient flow through watersheds are two vectors investigated to understand ecosystem function. Considerable information on the movement of waterborne nutrients through and from forest ecosystems has been recorded (Bormann et al. 1968, Bormann and Likens 1970, Schindler and Nighswander 1970, Douglas and Swank 1975, Likens et al. 1977), but data from the western Great Lakes area are rare (Schindler et al. 1976) or estimated (Richardson and Lund 1975). No data are available in North America which report flow of waterborne nutrients through a mineral soil upland, then through an organic soil peatland (a bog) to a stream. Yet, in the western Great Lakes area, upland and peatland occur together commonly in basin units that feed first-order streams (Fig. 1).

Our 3-yr study contributes to the understanding of landscape interaction by addressing annual and seasonal cycling rates for water and major plant nutrients. Our study does not define standing states within the watershed ecosystem, although it does infer some of the unknown cycling processes within the landscape components (upland and peatland) from calculations of net nutrient retention and leaching.

Annual water budgets for upland, peatland, and the total watershed are presented to test the integrity of watershed tightness and to define the relation of upland and peatland to groundwater recharge, evapotranspiration, runoff, and streamflow.

A total watershed nutrient budget (inputs and outputs) is calculated using precipitation above the trees (gross precipitation) so that this complex ecosystem can be compared with other terrestrial ecosystems. And, streamflow nutrient outputs (used in lake eutrophication models) are compared with similar values published earlier for the same watershed (Verry 1975).

The nutrient linkage between upland and peatland is illustrated with annual and seasonal nutrient budgets for each landscape unit. These budgets test the hypothesis that either component is a nutrient trap. The soil and its vegetation are considered as an unknown cycling box (trap). Precipitation at the soil surface (net precipitation) is used as the input because the soil surface is where nutrients in fertilizers and sewage would be added in modified ecosystems. In the case of the bog ecosystem, this is also where upland flow enters (Fig. 2).

METHODS

The quantity and quality of water passing through Control Watershed Number 2 (Fig. 1), Marcell Experimental Forest, Itasca County, Minnesota (≈47°32′N, 93°28′W) were measured during 1971, 1972, and 1973. Watershed Number 2 is 9.72 ha in area, with 6.48 ha of mineral soil upland and 3.24 ha of organic soil bog. A cross section of the watershed

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FIG. 1. Watershed Number 2, with an aspen upland and black spruce peatland in center. Arrow near bottom center indicates a small stream draining the area.

(Fig. 2) shows that the bog and upland developed in weakly calcareous ground moraine till (3–10 m deep), which overlies 15–40 m of generally carbonate-free sand and gravel. Between these deep sands and gravels and the Precambrian Ely Greenstone bedrock is ≈24 m of compacted till composed of sand and gravel in a clay matrix with carbonate rock fragments.

The Warba mineral upland soil (Glossic Eutroboralf) is deep, moderately well- to well-drained soil developed under forest vegetation in gray, slightly calcareous, clay loam till (Verry 1969). Surface runoff, mainly snowmelt, flows through the surface organic (O) horizon, and lateral subsurface flow occurs in the A and B horizons, above the slowly permeable B2t horizon.

The organic soil bog (Loxley Series, Dysic Typic Borosaprists) was derived from *Sphagnum* moss and herbaceous plants over limnic materials over glacial sediments. A central profile is: 0–20 cm, fibric; 20–30 cm, hemic; 30–40 cm, sapric; 40–44 cm, hemic; 44–325 cm, sapric; 325–360 cm, hemic; 360–410 cm, coprogenous earth; 410–420 cm, fibric (*Hypnum* moss); 420–440 cm, marl; and 440–450 cm, silty clay loam, slightly sticky (permeability nil).

Upland vegetation is dominated by a mature 54-yr-old stand of quaking aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.) with the following characteristics: height, 23 m; diameter (at 1.4 m), 25 cm; basal area, 25 m^2/ha; total volume, 225 m^3/ha; crown cover, 65%; and site index (50-yr *P. tremuloides*), 23 m. Brush cover under the aspen is dense and composed largely of beaked and American hazel (*Corylus cornuta* Marsh. and *Corylus americana* Walt.).

Bog vegetation is dominated by a mature 103-yr-old stand of black spruce (*Picea mariana* [Mill.] B.S.P.) with the following characteristics: height, 13 m; diameter (at 1.4 m), 14 cm; basal area, 26 m^2/ha; total volume, 133 m^3/ha; crown cover, 59%; and site index (50-yr *P. mariana*), 9 m. Brush cover of speckled alder (*Alnus rugosa* [Du Roi] Spreng.) is restricted to 5 m along the bog periphery. Ericaceous shrubs, fine-leaved sedges, and *Sphagnum* moss cover the peat surface.

Itasca County has a continental climate characterized by wide and rapid variations in temperature, low winter precipitation, and normally ample summer rain. The Marcell Experimental Forest receives an annual average precipitation of 762 mm, with 75% (572 mm) as rain from mid-April to early November and 25% (210 mm) as snow. The average annual temperature is 4°C; the extremes are −46° and 40°. Average January and July temperatures are −14° and 19°, respectively (Aakre 1966).

Precipitation and nutrient concentrations were measured on the Marcell Experimental Forest during 1971–1973 (Verry and Timmons 1977). Techniques for measuring precipitation nutrient input and results for

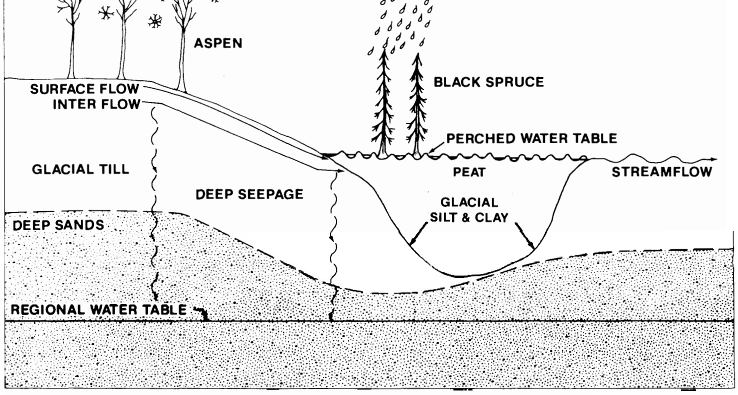

FIG. 2. Cross section of Watershed Number 2 showing water flow routes

TABLE 1. Water balance for Watershed Number 2, Marcell Experimental Forest, Minnesota, USA

Mineral soil upland (6.48 ha)							
	Input (cm/yr)	Output (cm/yr)				Evapotranspiration (cm/yr)	
Year	Precipitation	Surface flow	Inter-flow	Deep seepage	Change in soil moisture storage	Balance	(Thorn-thwaite)
1971	85.0	12.6	8.9	13.7	+2.3	47.4	52.7
1972	80.3	7.0	8.7	11.9	−10.3	63.1	51.1
1973	74.8	5.0	8.6	4.6	+8.6	47.9	53.6
Average	80.0	8.2	8.8	10.1	+0.2	52.8	52.5
Organic soil bog (3.24 ha)								
	Input (cm/yr)			Output (cm/yr)			Evapotranspiration (cm/yr)	
Year	Precipitation	Surface flow	Inter-flow	Deep seepage	Change in water table storage	Stream flow	Balance	Potential (Thorn-thwaite)
1971	85.0	25.2	17.9	13.7	+1.0	53.1	60.2	52.7
1972	80.3	13.9	17.3	11.9	+3.8	57.4	38.4	51.1
1973	74.8	10.1	17.3	4.6	−1.7	46.5	52.8	53.6
Average	80.0	16.4	17.5	10.1	+1.0	52.4	50.5	52.5
Total watershed (9.72 ha)								
	Input (cm/yr)	Output (cm/yr)					Evapotranspiration (cm/yr)	
				Deep Seepage				
Year	Precipitation	Change in soil moisture storage	Change in water table storage	Upland	Bog	Stream flow	Balance	Potential (Thorn-thwaite)
1971	85.0	+1.5	+0.3	9.2	4.5	17.7	51.7	52.7
1972	80.3	−6.9	+1.3	8.0	3.9	19.2	54.9	51.1
1973	74.8	+5.8	−0.6	3.1	1.5	15.5	49.5	53.6
Average	80.0	+0.1	+0.3	6.7	3.3	17.4	52.0	52.5

Division into upland and bag components based on relative areas

a representative precipitation year were reported at that time. In this paper, actual precipitation and nutrient amounts are used. Concentrations for gross precipitation, throughfall, and stemflow for both the aspen and black spruce forests are listed in the earlier report. For this paper, only the nutrient amounts in net precipitation (throughfall + stemflow) are treated as input to either the mineral or organic soil forest when considering the upland and peatland components. Gross precipitation is used for a total watershed nutrient budget.

Techniques for measuring mineral soil surface and interflow nutrient concentrations and amounts were also reported earlier (Timmons et al. 1977). All original data were recalculated to correspond with the years or seasons selected for this study. In summary, two bordered runoff plots on north and south aspects were used to measure the amount and quality of surface flow. Two buried horizontal, stainless-steel well screens (on opposite aspects) were used to collect a quality sample of interflow over the B2t horizon. Amounts of interflow were estimated from total watershed stream hydrographs, using a hydrograph separation technique.

Deep seepage to the regional water table was calculated from deep-well hydrographs (monthly readings) by extending the overwinter recession leg through summer and fall, subtracting the elevation of this value from the recorded water table elevation, and multiplying the difference by a specific yield of 0.3 for medium sands. Deep seepage from the upland and bog was estimated, using their respective areas. Nutrient concentrations for deep seepage were taken to be the same as interflow on the upland and bog water in the bog.

Soil water storage in the mineral soil was measured at three access tubes to 2.3 m with a neutron meter. Water level changes in the bog were measured continuously with a recording well and converted to water storage changes, using a measured specific yield of 0.52.

Streamflow leaving the watershed (near the bog outlet) was measured with a 120° V-notch weir. Annual

TABLE 2. Watershed streamflow nutrient yield, Marcell Experimental Forest, Minnesota, USA

	Nutrient ($kg \cdot ha^{-1} \cdot yr^{-1}$)											
Year or statistic	NO_3	NH_4	Organic N	Total N	Orthophosphorus	Organic P	Total P	K	Ca	Mg	Na	COD†
1968–1972*	0.29	0.64	0.99	1.91	...	...	0.08	1.26	3.46	1.46	1.06	...
1969	0.13	0.16	2.08	2.37	0.06	0.09	0.15	2.19	3.72	1.26	0.60	...
1970	0.15	0.18	1.73	2.06	0.08	0.07	0.15	2.31	3.42	1.08	0.65	...
1971	0.20	0.23	1.83	2.25	0.04	0.09	0.13	2.45	3.07	1.29	0.76	194
1972	0.05	0.10	2.21	2.37	0.06	0.12	0.18	2.33	3.15	1.34	0.94	224
1973	0.03	0.37	1.34	1.75	0.05	0.11	0.16	1.34	3.05	1.20	0.69	191
Mean (1969–1973)	0.11	0.21	1.83	2.16	0.06	0.10	0.15	2.12	3.28	1.23	0.73	203
Coef. Var. (%)	63	49	18	12	26	20	12	21	9	8	18	9
Std. Er. Mn.	0.03	0.05	0.15	0.12	0.01	0.01	0.01	0.20	0.12	0.04	0.06	11

* Completely different data set based on low-intensity samples; not included in the statistics for 1969–1973 data set.
† COD = that portion of the organic matter oxidized by a strong oxidant.

evapotranspiration (ET) was estimated by the water balance method (water input less water output). There is no absolute check we can make on the various water budget values. Three replications are presented by looking at each of 3 yr. A relative check on water budget values is given by comparing potential evapotranspiration (PET) calculated by the Thornthwaite method (Thornthwaite and Mather 1957) with water budget evapotranspiration.

Water samples were analyzed for nutrients, using the following methods. Unfiltered portions of each sample were analyzed for Kjeldahl N, total P, and chemical oxygen demand (COD). Filtered portions (0.45 μm) were analyzed for ammonium nitrogen (NH_4-N), nitrite + nitrate nitrogen (NO_2+NO_3), orthophosphorus (molybdate reactive), K, Na, Ca, and Mg. Kjeldahl N was determined with a macro-Kjeldahl method (United States Environmental Protection Agency 1974) in which the sample was digested with concentrated H_2SO_4 and one Kel Pak (No. 2; Curtin Matheson Scientific, Houston, Texas), distilled into H_3BO_3, and titrated with standard H_2SO_4. Total P was measured with a spectrophotometer after digestion with concentrated $HClO_4$ and HNO_3, and color development with combined reagent (United States Environmental Protection Agency 1974). During 1971 and 1972, NH_4-N and (NO_2 + NO_3)-N were measured with the steam distillation method (Bremner 1965). During 1973, NH_4-N and (NO_2 + NO_3)-N were measured with a Technicon Auto-Analyzer II, using Technicon's NH_3 in water and wastewater, and NO_2 and NO_3 in water and wastewater methods, respectively. Orthophosphorus was measured with a spectrophotometer after color development using the combined reagent. Concentrations of K, Na, Ca, and Mg were determined by atomic absorption spectroscopy (Issac and Kerber 1971). Organic N was determined by subtracting NH_4-N from Kjeldahl N, and organic P (including hydrolyzable P) was determined by subtracting orthophosphorus from the total P. Chemical oxygen demand was determined by oxidation with $K_2Cr_2O_7$ in 50% (volume/volume) H_2SO_4 solution at reflux temperature (United States Environmental Protection Agency 1974).

Nutrient movement from one watershed component or into the next component was determined as the product of nutrient concentration and flow amount for time periods from 2 h to 2 wk. Amounts were then adjusted to an area basis (kilograms per hectare) depending on their use as output or input terms. For instance, interflow leaving the upland was adjusted for the area of the upland, but when used as an input term to the bog, it was adjusted for the area of the bog. The short-term amounts were summed for annual values.

Water and nutrient flow was partitioned into an upland and peatland portion for each of 3 yr. The layer of upland (presented as an unknown box in terms of internal nutrient cycling) evaluated for nutrient retention and leaching includes the organic, A2, and A and B horizons collectively. We consider herbaceous and woody uptake, litter fall, and decomposition as internal processes. The bog (unknown cycling box) evaluated for nutrient retention and leaching is the peat deposit and a portion of mineral soil surrounding it. Again, we consider herbaceous and woody uptake, litter fall, and decomposition to be internal processes.

Water years were selected on the basis of natural events, thus specific dates varied from year to year. Precipitation input began with the start of snow accumulation in mid-November and ended with the same the following year. Water output started with surface runoff resulting from snowmelt in late March and ended with the cessation of streamflow in January. Once the snowpack begins to accumulate in mid-November, it stays until the major spring melt. However, fall rains stored in the bog contribute to streamflow as late as January by flowing underneath the snowpack.

Nutrient flow was separated into three segments each year based on natural events so that seasonal impacts

TABLE 3. Gross watershed nutrient budget for Watershed Number 2, Marcell Experimental Forest and other selected sites.

Reference Budget item	Nutrient ($kg \cdot ha^{-1} \cdot yr^{-1}$) Total N	Total P	K	Ca	Mg	Na	Annual precipitation (cm)
This paper	Marcell Experimental Forest, Minnesota						80
Input*	7.5	0.50	1.1	3.6	0.7	1.1	
Streamflow output†	2.2	0.15	2.1	3.3	1.2	0.7	
Deep seepage output*	1.0	0.07	0.7	3.7	1.2	1.2	
Total output	3.2	.22	2.8	7.0	2.4	1.9	
Net gain or loss	+4.3	+0.28	−1.7	−3.4	−1.7	−.8	
Schindler et al. 1976	Experimental Lakes Area, Ontario						83
Input	6.4	0.32	1.1	3.8	0.9	1.6	
Output	0.9	0.05	1.2	6.0	2.4	3.7	
Net gain or loss	+5.5	+0.27	−0.1	−2.2	−1.5	−2.1	
Likens et al. 1977	Hubbard Brook Experimental Forest, New Hampshire						130
Input	20.7	0.04‡	0.9	2.2	0.6	1.6	
Output	4.0	0.02	2.4	13.9	3.3	7.5	
Net gain or loss	+16.7	+0.02	−1.5	−11.7	−2.7	−5.9	
National Academy of Science 1974 Swank and Waide 1980	Coweeta Hydrologic Laboratory, North Carolina						185
Input	8.8	. . .	3.2	6.2	1.3	5.4	
Output	3.2	. . .	5.2	6.9	3.1	9.7	
Net gain or loss	+5.6	. . .	−2.0	−0.7	−1.8	−4.3	
Crisp 1966	Rough Sike Catchment, England						213
Input	8.2	0.6	3.1	9.0	. . .	25.5	
Output	3.0	0.4	9.0	53.8	. . .	45.2	
Net gain or loss	+5.2	+0.2	−5.9	−44.8	. . .	−19.7	
Viro 1953	Finland (national average)						57
Input	6	0.1	2.4	2	1	2	
Output	2	0.3	4.6	12	4	6	
Net gain or loss	+4	−0.2	−2.2	−10	−3	−4	

* 1971–1973 average.
† 1969–1973 average.
‡ PO_4-P only.

on nutrient retention or leaching could be seen. The first yearly segment is called "spring" and is defined as the period from the start of snowpack accumulation until nighttime temperatures were >0°. Nominally, this is mid-November to mid-May and reflects a period of overwinter precipitation storage and the cold, wet, flushing period following snowmelt. "Summer" is defined as the period from night temperatures >0° until deciduous leaves fall. Nominally, this is mid-May to mid-September and reflects the warm, high rainfall, high evapotranspiration period. "Fall" is defined as the time from deciduous leaf fall to the start of snow accumulation and reflects the cool, fall recharge period. Streamflow that occurs under the snowpack as late as January results from fall rains and is considered in the fall segment.

RESULTS AND DISCUSSION

The water balance

Based on 3-yr averages, the total watershed and its upland and bog components lose water vapor at or near potential rates (Table 1). There are errors in all the separate determinations of the water balance as discussed by Winter (1981) and Federer (1970). It is unlikely that estimates of areal evapotranspiration (ET) by the water budget method are closer than ±15% of the true value.

For the total watershed, potential evapotranspiration (PET) approximates water balance ET within 8% on an annual basis and within 1% on a 3-yr basis. For the bog and upland components, PET is within 12% of balance ET except for 1972. PET is 19% less than the upland, and 33% more than the bog balance ETs in 1972. These differences probably resulted from a large storm on 11 and 12 July which produced 12.83 cm of rain in 27 h. Upland soils may have produced deep seepage not accounted for until the next year, while the bog produced a large amount of immediate runoff from a small area.

Normal precipitation for north central Itasca County is 70 cm; however, normal precipitation measured at the Marcell Experimental Forest is 76 cm and consistently runs higher than National Oceanic and Atmospheric Administration gages. During the 3-yr study it averaged 80 cm. Our gages are within 8 km of the Hudson Bay–Gulf of Mexico divide and may receive

TABLE 4. Upland nitrogen input, output, and retention, Marcell Experimental Forest, Minnesota, USA. Average of 1971, 1972, and 1973.

Nitrogen form	Season	Input: Net precipitation	Output: Interflow	Output: Deep seepage	Output: Surface flow	Output: Total	Retention: Absolute	Retention: Relative
		(kg·ha⁻¹·yr⁻¹)						(%)
Nitrate N	Spring	0.813	0.014	0.013	0.115	0.142	0.671	83
	Summer	0.686	0.007	0.023	0.004	0.034	0.652	95
	Fall	0.237	0.009	0.010	0.002	0.021	0.216	91
	Annual	1.736	0.030	0.046	0.121	0.197	1.539	89
Ammonium N	Spring	0.397	0.033	0.028	0.191	0.252	0.145	37
	Summer	1.168	0.022	0.027	0.003	0.052	1.116	96
	Fall	0.405	0.024	0.014	0.002	0.040	0.365	90
	Annual	1.970	0.079	0.069	0.196	0.344	1.626	83
Organic N	Spring	0.672	0.477	0.407	1.218	2.102	−1.430	−213
	Summer	3.049	0.143	0.365	0.027	0.535	2.514	82
	Fall	1.063	0.411	0.162	0.005	0.578	0.485	46
	Annual	4.784	1.031	0.934	1.250	3.215	1.569	33
Total N	Spring	1.882	0.524	0.448	1.524	2.496	−0.614	−33
	Summer	4.903	0.172	0.415	0.034	0.621	4.282	87
	Fall	1.705	0.444	0.186	0.009	0.639	1.066	63
	Annual	8.490	1.140	1.049	1.567	3.756	4.734	56

more precipitation than lower areas because of a slight orographic effect.

Whole watershed water yield (streamflow plus deep seepage) averages 27.5 cm. Published maps for Minnesota show 21.6 cm of annual runoff for our area (Baker et al. 1979), and long-term streamflow records for the Little Fork and Big Fork River basins adjacent to our area average 20.8 and 16.5 cm, respectively (Helgesen et al. 1976, Lindholm et al. 1976). These differences may be due to 10–16 cm of additional precipitation at the Marcell site, which is partitioned into more streamflow and evapotranspiration near potential levels.

For the 3-yr average, the total watershed converted 34% of the precipitation to streamflow and deep seepage and 65% to water vapor. The remaining 1% went to changes in soil moisture and water table storage. The upland component also converts 34% of precipitation to water yield (surface flow, interflow, and deep seepage). The bog converts 55% of its inputs (precipitation, surface flow, and interflow) to water yield (stream and deep seepage). These differences in water yield conversion should not be attributed to some special characteristic of peatland, but rather to the bog's topographic position in relation to the upland. The added inputs to the peatland from the upland pass through because both upland and peatland evapotranspire at potential rates. If upland inputs are discounted, the peatland converts 36% of its precipitation to water yield, or nearly the same as the upland.

Our data are for a climate where precipitation exceeds PET and where both upland and bog areas evapotranspire near potential rates. Surface and interflow from the upland is generally restricted to spring or late fall periods, as is streamflow from the bog and total watershed, unless very large storms occur during the summer (Bay 1967, Boelter and Verry 1977). During these high water table periods, the bog can transmit flow much quicker than the mineral soil.

Deep seepage rates, because they are calculated from deep-well records, are the same for both upland and bog (Table 1). In fact, they may differ during dry years or during large storms occurring after a dry period when the bog has saturated soils but the upland does not. However, the deep seepage term is necessary to balance the hydrologic equation; because hydraulic conductivities of well-decomposed peat and glacial till are similar, the seepage rates over long periods probably are similar. Thus this small watershed is not "tight"; one-third of the liquid water leaving the area is by deep seepage.

Groundwater recharge through the mineral soils surrounding the bog occurs as unsaturated flow to the regional water table. Groundwater recharge from the bog may occur under similar conditions at the bog edges and underneath the extensive shallower areas of the peat, but saturated flow may occur directly under the bog at its lowest point (<5% of the bog area). If the latter condition exists, the bog cannot be called perched (Bay 1967) even though its water table is 8 m above the regional water table. The bog may represent a groundwater mound with a narrow hydraulic connection to the regional water system (Winter and Carr 1980).

Streamflow and total watershed nutrient yield

Nutrient yield in streamflow is used as a required component in assessing lake trophic status (Dillon

TABLE 5. Upland phosphorus input, output, and retention, Marchell Experimental Forest, Minnesota, USA. Average of 1971, 1972, and 1973.

Phosphorus form	Season	Input: Net precipitation	Output: Interflow	Output: Deep seepage	Output: Surface flow	Output: Total	Retention: Absolute	Retention: Relative
		(kg·ha⁻¹·yr⁻¹)						(%)
Orthophosphorus	Spring	0.054	0.006	0.005	0.119	0.130	−0.076	−141
	Summer	0.494	0.003	0.004	0.003	0.010	0.484	98
	Fall	0.172	0.004	0.003	0.001	0.008	0.164	95
	Annual	0.720	0.013	0.012	0.123	0.148	0.572	79
Organic P	Spring	0.133	0.025	0.022	0.095	0.142	−0.009	−7
	Summer	0.470	0.011	0.023	0.003	0.037	0.433	92
	Fall	0.164	0.014	0.009	0.000	0.023	0.141	86
	Annual	0.767	0.050	0.054	0.098	0.202	0.565	74
Total P	Spring	0.187	0.031	0.027	0.214	0.272	−0.085	−45
	Summer	0.965	0.014	0.027	0.005	0.046	0.919	95
	Fall	0.335	0.018	0.012	0.002	0.032	0.303	90
	Annual	1.487	0.063	0.066	0.221	0.350	1.137	76

1975). This is a "nutrient-added" technology whether lakes are fertilized for fish production or nutrient pollution is reduced to prevent algal growth. However, adoption of trophic-state models has been hampered by a lack of measured variation in that most reported data are for 1 yr at one location (Uttormark et al. 1974). We can provide some insight to watershed nutrient yield variability, using the 3 yr of data from the present study plus an additional 2 yr of streamflow output data and an average year of data reported earlier for the same watershed.

Watershed Number 2 on the Marcell Experimental Forest was used to calculate kilogram per hectare nutrient yields with 3–15 water samples/yr and continuous flow records for 1968–1972 (Verry 1975). Nutrient concentrations at a given flow rate were integrated with long-term flow duration curves to produce an annual nutrient yield. In the present study, 35–76 water samples were taken each year, and their average nutrient concentration between two sample times was multiplied by the amount of streamflow between these sample times to calculate nutrient yield. The 1968–1972 and 1969–1973 samples were completely different, and analyses and laboratories were completely different. The annual nutrient yield values for 1969–1973 are listed in Table 2 with measures of central tendency and

TABLE 6. Upland metal input, output, and retention, Marcell Experimental Forest, Minnesota, USA. Average of 1971, 1972, and 1973.

Metal	Season	Input: Net Precipitation	Output: Interflow	Output: Deep seepage	Output: Surface flow	Output: Total	Retention: Absolute	Retention: Relative
		(kg·ha⁻¹·yr⁻¹)						(%)
Potassium	Spring	1.075	0.264	0.231	2.829	3.324	−2.249	−209
	Summer	10.643	0.134	0.350	0.070	0.554	10.089	95
	Fall	3.781	0.145	0.087	0.068	0.300	3.481	92
	Annual	15.499	0.543	0.668	2.967	4.178	11.321	73
Calcium	Spring	1.984	1.681	1.449	4.276	7.406	−5.422	−273
	Summer	10.252	0.695	1.630	0.078	2.403	7.849	77
	Fall	3.651	1.038	0.593	0.031	1.662	1.989	54
	Annual	15.887	3.414	3.672	4.385	11.471	4.416	28
Magnesium	Spring	0.390	0.546	0.475	1.206	2.227	−1.837	−471
	Summer	2.301	0.216	0.518	0.020	0.754	1.547	67
	Fall	0.816	0.341	0.198	0.009	0.548	0.268	33
	Annual	3.507	1.103	1.191	1.235	3.529	−0.022	−1
Sodium	Spring	0.254	0.463	0.402	0.428	1.293	−1.039	−409
	Summer	0.790	0.271	0.627	0.005	0.903	−0.113	−14
	Fall	0.275	0.347	0.192	0.000	0.539	−0.264	−96
	Annual	1.319	1.081	1.221	0.433	2.735	−1.416	−107

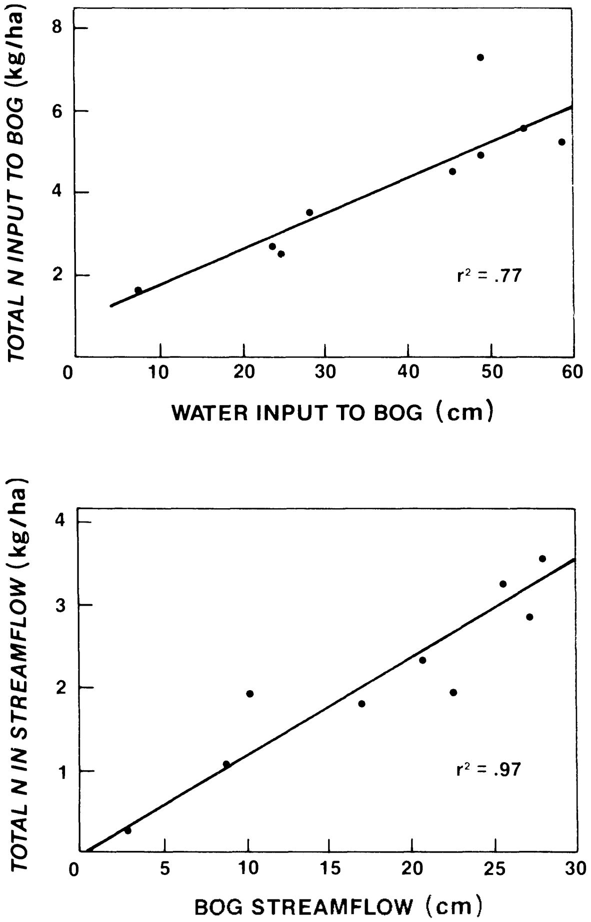

FIG. 3. Seasonal total N input and output in relation to the amount of water carrying it.

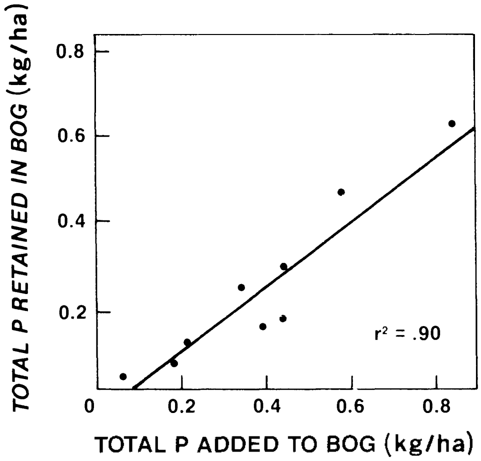

FIG. 4. Seasonal total P added to and retained by the bog.

variation along with the average annual value for the 1968–1972 periods.

Total N, total P, Ca, Mg, and COD exhibit coefficients of variation (CV-8–12) which are similar to the coefficient of variation for annual streamflow amount (CV-11). Breakdowns into forms of nitrogen and phosphorus exhibit greater variation (CV-18–63% presumably caused by the movement of nutrients between inorganic and organic forms. K and Na are more variable (CV-21 and 18% respectively) than streamflow amount. This additional variation may reflect the relative ease of leaching of these two metals and the stronger interaction of temperature and water cycles on their leaching. The annual loading rates of total N, total P, Ca, Mg, and COD will vary the same as streamflow amounts vary. For precipitation nutrients entering lakes, their annual loading will vary the same as snow and rainfall amounts vary (Verry 1976, Verry and Timmons 1977). It is fortunate that total N and total P are the most frequently used nutrients in assessing lake eutrophication.

COD (that portion of the organic matter oxidized by a strong oxidant) leaves the watershed in large amounts, as is obvious from the dark-colored streamflow. Two hundred and three kilograms per hectare leave the entire watershed, but the upland contributes 110 kg/ha (Timmons et al. 1977), and the bog contributes 389 kg/ha.

The low-intensity sampling results (1968–1972) agree with the intesive sampling results (1969–1973) only for total N and Ca. In general, yields of total nutrients from the low-intensity sample are within ±47% of the high-intensity means. Thus nutrient yields are best measured by more intensive nutrient sampling and concomitant flow volumes unless precise concentration–flow rate relations can be established. We averaged 46 samples/yr for a 30-wk ice-free sampling period in 1969–1973. The frequency of sampling was roughly proportional to flow rates, with emphasis given to active snowmelt periods and large storms.

The gross watershed nutrient budget is presented in Table 3 along with similar budgets from five other areas. Like most other watersheds, the complex upland peatland watershed in this paper shows a net gain for N and P and a net loss of K, Ca, Mg, and Na. And the amounts of input, output, and net gain or loss are strikingly similar to a small Precambrian lake basin in the Experimental Lakes Area (ELA) of southwest Ontario, located 170 km north-northwest of the Marcell Experimental Forest. Both areas are similar in climate and vegetation, but the ELA watershed is tight with shallow soils over bedrock, and the Marcell watershed leaks through deep glacial drift of tills and sands over similar bedrock.

The upland–peatland watershed is typical of many watersheds in the northern Lake States and southern Canada. It appears that in this climate regime the flow of most nutrients from these areas is proportional to streamflow, because the peatland is the lower topographic unit and thus streamflow emanates from a saturated environment. This proportionality of water and

TABLE 7. Peatland nitrogen input, output, and retention, Marcell Experimental Forest, Minnesota, USA. Average of 1971, 1972, and 1973.

Nitrogen form	Season	Input: Net precipitation	Input: Interflow	Input: Surface flow	Input: Total	Output: Stream flow	Retention: Absolute	Retention: Relative
		(kg·ha⁻¹·yr⁻¹)						(%)
Nitrate N	Spring	0.558	0.029	0.231	0.818	0.107	0.711	87
	Summer	0.904	0.013	0.007	0.924	0.105	0.819	89
	Fall	0.278	0.018	0.003	0.299	0.066	0.233	78
	Annual	1.740	0.060	0.241	2.041	0.278	1.763	86
Annonium N	Spring	0.308	0.066	0.382	0.756	0.239	0.517	68
	Summer	1.065	0.044	0.006	1.115	0.277	0.838	75
	Fall	0.328	0.047	0.003	0.378	0.190	0.188	50
	Annual	1.701	0.157	0.391	2.249	0.706	1.543	69
Organic N	Spring	0.413	0.952	2.437	3.802	2.054	1.748	46
	Summer	2.625	0.287	0.054	2.966	2.234	0.732	25
	Fall	0.807	0.823	0.009	1.639	1.100	0.539	33
	Annual	3.845	2.062	2.500	8.407	5.388	3.019	36
Total N	Spring	1.280	1.047	3.049	5.376	2.403	2.973	55
	Summer	4.594	0.343	0.067	5.004	2.614	2.390	48
	Fall	1.412	0.888	0.016	2.316	1.357	0.959	41
	Annual	7.286	2.278	3.123	12.696	6.374	6.322	50

nutrient flow does not hold in arid watersheds where soil water conditions are more seasonably variable (Leonard et al. 1979).

The upland waterborne nutrient flow is characterized by large additions in summer and fall when the export of water is low because of high ET losses, but inputs are high because of the annual precipitation distribution and the large amounts of nutrients leached from the forest canopy. Waterborne nutrient export is highest in the spring period because nutrients are readily available, soils are near field capacity, and vegetation growth is limited to root activity and bud swelling. The export part of the spring period is the time from snowmelt until night temperatures are >0°C. It is also the time before tree leafout and the greening of grasses, which begin about mid-May. Conditions in the peatland portion of the watershed are different.

Organic soil peatland.—The bog, its vegetation, and an undefined portion of mineral soil near its edges annually retain 55% of all the waterborne nutrients that enter it. Nutrients are supplied to the bog in approximate proportion to the amount of water supplied as the sum of net precipitation under black spruce, upland surface flow, and upland subsurface flow. Nutrients leave the bog in streamflow in approximate proportion to the amount of streamflow (Tables 7–9). Fig.

TABLE 8. Peatland phosphorus input, output, and retention, Marcell Experimental Forest, Minnesota, USA. Average of 1971, 1972, and 1973.

Phosphorus form	Season	Input: Net precipitation	Input: Interflow	Input: Surface flow	Input: Total	Output: Stream flow	Retention: Absolute	Retention: Relative
		(kg·ha⁻¹·yr⁻¹)						(%)
Orthophosphorus	Spring	0.015	0.012	0.237	0.264	0.047	0.217	82
	Summer	0.075	0.005	0.005	0.085	0.078	0.007	8
	Fall	0.023	0.008	0.003	0.034	0.029	0.005	15
	Annual	0.113	0.025	0.245	0.383	0.154	0.229	60
Organic P	Spring	0.116	0.051	0.191	0.358	0.116	0.242	68
	Summer	0.283	0.021	0.005	0.309	0.134	0.175	57
	Fall	0.087	0.028	0.001	0.116	0.058	0.058	50
	Annual	0.486	0.100	0.197	0.783	0.308	0.475	61
Total P	Spring	0.131	0.063	0.428	0.622	0.163	0.459	74
	Summer	0.358	0.026	0.011	0.395	0.212	0.183	46
	Fall	0.110	0.036	0.004	0.150	0.085	0.065	43
	Annual	0.599	0.125	0.443	1.167	0.460	0.707	61

TABLE 9. Peatland metal input, output, and retention, Marcell Experimental Forest, Minnesota, USA. Average of 1971, 1972, and 1973.

Metal	Season	Input: Net precipitation	Input: Interflow	Input: Surface flow	Input: Total	Output: Stream flow	Retention: Absolute	Retention: Relative
		(kg·ha⁻¹·yr⁻¹)						%
Potassium	Spring	0.368	0.528	5.652	6.548	2.963	3.585	55
	Summer	2.813	0.268	0.139	3.220	1.872	1.348	42
	Fall	0.864	0.291	0.136	1.291	1.285	0.006	0
	Annual	4.045	1.087	5.927	11.059	6.120	4.939	45
Calcium	Spring	0.743	3.363	8.551	12.657	3.332	9.325	74
	Summer	3.483	1.390	0.156	5.029	3.792	1.237	25
	Fall	1.070	2.076	0.062	3.208	2.014	1.194	37
	Annual	5.296	6.829	8.769	20.894	9.138	11.756	56
Magnesium	Spring	0.074	1.091	2.412	3.577	1.382	2.195	61
	Summer	0.943	0.433	0.040	1.416	1.534	−0.118	−8
	Fall	0.290	0.682	0.019	0.991	0.912	0.079	8
	Annual	1.307	2.206	2.471	5.984	3.828	2.156	36
Sodium	Spring	0.224	0.927	0.857	2.008	0.974	1.034	51
	Summer	0.746	0.542	0.008	1.296	0.958	0.338	26
	Fall	0.229	0.693	0.001	0.923	0.461	0.462	50
	Annual	0.199	2.162	0.866	4.227	2.393	1.834	43

3 illustrates these observations with total nitrogen for each of nine seasons.

Annually, 86% of NO_3 69% of NH_4 and 36% of organic-N inputs to the bog are retained (Table 7). The high calculated retention of inorganic nitrogen compared with the upland component is probably due to a combination of microbial denitrification of NO_3^- to $NO_2^=$ followed by a chemical conversion of $NO_2^=$ to gaseous nitrogen, which leaves the bog (Broadbent and Clark 1965, Chen et al. 1972). For total nitrogen the annual retention is 50%. About 60% of ortho- and organic phosphorus is retained annually, and thus 61% of the total phosphorus is retained. Annual metal retention is 45% K, 56% Ca, 36% Mg, and 43% Na. Bogs are nutrient traps.

The amount of nutrients retained increased as the amount of nutrients added increased (Fig. 4). Thus, the bog was not saturated with nutrients and probably could have taken more. However, the amount lost in streamflow also increased. The increase of all nutrient budget items in seasonal bog values may simply define the low end of a similar trend along the ecologic gradient from bog to strong fen (Moore and Bellamy 1974).

Seasonally, bog nutrient retention differs from the upland. Like the aspen input, black spruce net precipitation nutrients are greatest in summer; however, surface and subsurface flow from the upland combine to make the spring period the largest in nutrient input to the bog (Tables 7–9). While nutrient output from the upland is very strong in spring, output from the bog is variable. The greatest amounts of nutrient retention occur in the spring for metals, orthophosphorus, organic P, total P, and organic N. The greatest amount of NO_3 and NH_3 is retained during the summer period. The inorganic nitrogen is "retained" well (converted to N gas) in all seasons on a relative basis (86–69% retention). Seasonal retention efficiency is variable and lower for organic nitrogen, averaging 36%. Orthophosphorus is best retained in the bog during spring (82% retention), in striking contrast to the upland. Organic-P retention efficiency is more evenly spread around 60% throughout the year. Total P is best retained in spring. Potassium retention efficiency varies by season, with fall being a pass-through condition. Calcium has a high retention efficiency in spring (74%) and averages 56% for the year. The efficiency of Mg retention is best in spring (61%), but bogs during summer or fall periods occasionally exhibit a flow-through or negative retention, as the upland consistently does. The bog, in marked contrast to the upland, retains Na at 43% efficiency throughout the year.

In terms of nutrient retention efficiency or amount, the bog and upland are fortuitously out of synchronization. The upland in spring, because of overwintered dead vegetation and high water flow, is in a nutrient flush condition. The bog in spring is in a high nutrient retention condition. In contrast to the upland, the bog is actively growing. The spruce canopy is actively transpiring. Ericaceae shrubs are green, and *Sphagnum* moss is actively growing while remnants of the snowpack still exist. *Sphagnum* normally will grow 10 cm during this cold moist period. Fall (and late summer) is a time of dying plants in both the upland and bog, but upland soils are not sufficiently recharged for large flows to occur, while those in the bog, with its high water table, are.

Our nutrient flow accounting is for an upland and peatland with a continental climate typical of the northern Lake States. In areas with higher precipitation or diffferent seasonal distribution, interactions may be different. The observations do, however, provide us with insight for nutrient-added management situations. We are concerned specifically with forest fertilization and on-land sewage treatment. These two practices differ in nutrient content and in amount of water added with the nutrient. Fall (after mid-September) is not a good time to add nutrients, especially with water, if nutrient retention and plant uptake is a management goal. Nutrient additions to the upland should be delayed until after the spring period (mid-May) or until grasses green and leaves flush. Nutrient additions to the bog during spring offer the possibility of high nutrient retention. Water levels, however, should not exceed an average hummock height in order to assure intimate water contact with the vegetation.

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