MODIFICATION OF RUNOFF FROM UPLAND WATERSHEDS - THE INFLUENCE OF A DIVERSE RIPARIAN ECOSYSTEM

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Abstract - Both forested and herbaceous wetlands modify surface and subsurface water, but there is little information on how water is modified as it moves through different habitats within wetlands. Nutrient flux studies of the Rhode River system have shown that a diverse wetland (Mill Swamp) has a significant impact on nutrient runoff from upland watersheds. In this paper we present data to demonstrate how water quality parameters change as surface and subsurface water moves through different habitats within Mill Swamp.

Mill Swamp can be divided into three habitats: (1) a floodplain forest that has been hydrologically modified and floods regularly, (2) a floodplain forest that rarely floods, and (3) a wetland that is primarily dominated by herbaceous vegetation.

While there are seasonal changes in all surface water quality parameters, few changes occur as surface water moves through the two forested habitats. In contrast, all parameters change temporally and spatially as surface water moves into and through the herbaceous habitat. Ammonium and phosphate concentrations decrease during spring and winter months and increase during summer months. Nutrient changes in the herbaceous habitat are especially pronounced during summer months when periods of anoxia occur in the water column. Nitrate-nitrite and pH also decrease as surface water moves through the herbaceous habitat. There are also changes in nutrient concentrations in subsurface water, especially nitrate-nitrite and total Kjeldahl nitrogen, in the forested area that rarely floods.

After two years of data collection, it appears that surface water chemistry is primarily controlled by changes that occur as water moves through the herbaceous portion of Mill Swamp. Changes in groundwater chemistry appear to be associated with forested areas which are not regularly flooded with surface

water and where the watertable elevation fluctuates widely during the year.

INTRODUCTION

Swamps and riparian forests are habitats in which nutrients in surface water and groundwater are modified (Brinson et al., 1984; Kitchens et al., 1975; Lowrance et al., 1984). Changes in nutrient concentrations may be associated with biological processes (Brinson et al., 1984; Peterjohn and Correll, 1986), physical processes such as sedimentation (Cooper et al., 1986), or biological uptake (Fail et al., 1986; Kitchens et al. 1975). Except for a few studies of nutrient changes along transects (Peterjohn and Correll, 1984 and 1986; Lowrance et al., 1983 and 1984; Fail et al., 1986; Todd et al., 1983), there have been few investigations of nutrient changes as water moves through different habitats within riparian or swamp forest ecosystems.

This paper presents preliminary results of studies designed to quantify the fluxes of nutrients through a diverse wetland, hereafter referred to as Mill Swamp. Mill Swamp is part of the Rhode River upland-estuarine system (38^o 51'N, 76^o 32'W) that is located near Annapolis, Maryland. Jordan et al. (1986) have shown that Mill Swamp has a significant impact on runoff from the largest watershed that drains into the Rhode River, a subestuary of Chesapeake Bay. However, data from that monitoring study could not be used to determine where within Mill Swamp nutrient changes were occurring.

Mill Swamp (Fig. 1A) can be divided into three habitats based on hydrology and vegetation. West of MD Route 468, the forested wetland is inundated when the quantity of water flowing into it is greater than the amount of water that can pass through two culverts under the road (Fig. 1B). Hydrologically, this portion of Mill Swamp is now more similar to a regularly flooded floodplain forest (Mitsch and Rust, 1984) than to alluvial swamp forests as described by Brinson et al. (1984) and Yarbro (1983). East of the road is a forested habitat that rarely floods and an area dominated by herbaceous vegetation (Fig. 1A). Flooding of the forested area has been almost completely eliminated because of flow restrictions through the culverts under the road. However, one part of the forested area does flood during high flow conditions when the herbaceous area is completely inundated (Fig. 1B). Under low flow conditions, standing water occurs only in the downstream end of the herbaceous

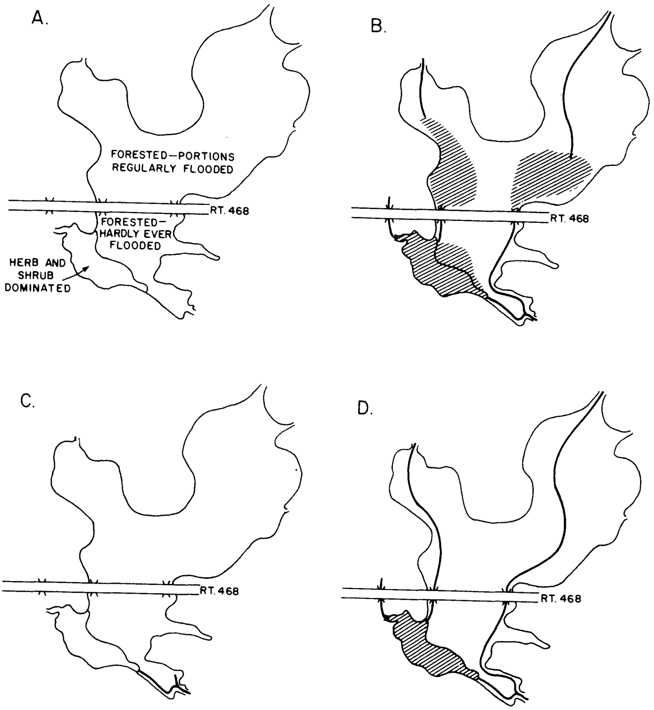

Fig. 1. Diagrammatic representation of Mill Swamp under different hydrologic conditions. Part A shows the 3 major habitats within Mill Swamp. Streams are designated as thicker solid lines and flooded areas are represented by the shaded areas. Flow conditions shown in B, C, and D are described in the text.

habitat (Fig. 1C). Under extremely dry conditions, such as those occurring in the summer of 1985, there is no water in any of the stream channels except tidal water which flows into the stream channels at sampling sites 4 and 5 (Fig. 2) during flood tide. Under normal flow conditions (Fig. 1D) water flows in all streams and the surface of most of the herbaceous area is flooded. There are few historical data to determine how long the herb dominated area has been in existence, but an aerial photograph of the Rhode River area shows that it was present in 1921.

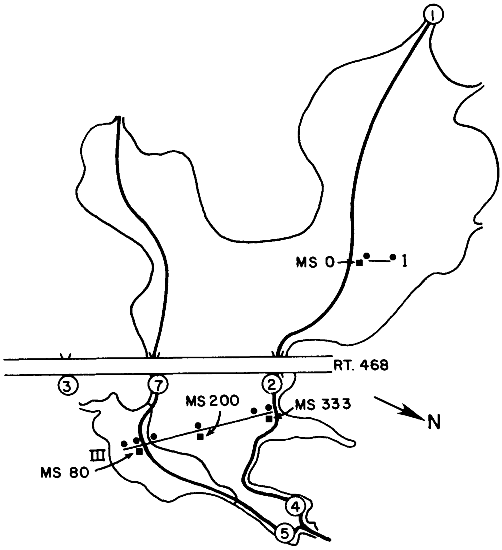

Fig. 2. Sampling sites in Mill Swamp. Surface water collection sites are designated as circled numbers. Subsurface water transects are indicated in roman numerals and sampling stations along the transects are shown as solid circles. Groundwater monitoring stations are indicated with a MS followed by the distance (m) from the origin of the transect.

The canopy of the two forested habitats is dominated by Fraxinus americana, Acer rubrum, Ulmus americana, and Betula nigra. The understory is dense and dominated by Cornus amomum and Viburnum dentatum. The herbaceous area can be divided into four vegetation zones based on species dominance: (1) Typha latifolia and Saururus cernuus, (2) Carex sp. and Leersia oryzoides, (3) Leersia oryzoides and Saururus cernuus, (4) Hibiscus palustris and Saururus cernuus.

MATERIALS AND METHODS

Surface water - Surface water collection sites were chosen to determine if nutrient concentrations changed as water moved into and through each of the three habitats (Fig. 2). Site 1, located upstream of Mill Swamp, was chosen to be representative of water that entered the system. Sites 2 and 7, located at culverts going under the road, were chosen to represent water that had passed through the frequently flooded portion of Mill Swamp. Water flowing past Site 2 remains in the stream channel and flows through the forested area east of the road without coming into contact with the surface of the forested wetland. Water flowing past Site 7 enters the herb dominated area where it mixes with water that flows past Site 3. Site 3 samples water from a small subwatershed before it enters the herb dominated portion of Mill Swamp. Sites 4 and 5 sample water that has flowed through the forested and herb dominated areas east of the road. Sites 4 and 5 can be tidally influenced under low flow conditions in Mill Swamp and when extreme high tides occur in the Rhode River.

Samples are collected bimonthly in acid washed polyethylene bottles. They are returned to the laboratory, acidified with 36 N sulfuric acid, filtered (0.45 micron), and refrigerated prior to analysis as described below. A separate sample is collected in nonacidified polyethylene bottles, and returned to the laboratory for pH measurements.

Subsurface water - Water levels are monitored at four locations using digital recorders that take readings at 15 minute intervals (Fig. 2). One recorder (MS 0) is located in the frequently flooded area about 200m west of the road. The other three recorders were located east of the road. MS 80 is in the herbaceous wetland and MS 333 on the bank of the stream flowing through the forested area that hardly ever floods (Fig. 2). MS 200 is in a portion of the forested area that is inundated under high flow conditions (Fig. 1B and 2).

Subsurface water is sampled from clusters of wells distributed along the two transects shown in Fig. 2. The transects are perpendicular to the direction of stream flow and each ground water well symbol in Fig. 2 represents a cluster of 3 wells. Transect I is 40 meters long and has clusters of wells, hereafter referred to as Sites 0 and 40, at both ends. Wells at Site 0 are approximately 5-10 meters from the stream channel. Transect III is 333 meters long and has five clusters of wells. Two clusters, Sites 60 and 80, are in the herb and shrub dominated area (Figs. 1 and 2). The site 80 cluster is close to water level recorder MS 80 (Fig. 2). Another cluster of wells, Site 200, is near water level recorder MS 200 (Fig. 2). Two sets of clusters (Sites 300 and 333) are near water level recorder MS 333. Site 333 wells are on the levee of the creek that flows through the forested area east of the road (Fig. 2). Wells are constructed from PVC pipes that are capped on the bottom and have holes drilled in a band around the pipe to sample water from 15 to 30 cm below the substrate surface.

Subsurface water samples are collected monthly. The wells are pumped dry with a vacuum pump the day before samples are collected. On the sampling day, water that has percolated into the wells is pumped into a glass collecting jar, transferred to acid washed polyethylene bottles, and returned to the laboratory for analyses as described below.

Analytical procedures - The filtered portion of each surface water sample is analyzed for orthophosphate (PO_4), ammonia-N (NH_4), and nitrate plus nitrite-N hereafter referred to as nitrate (NO_3). Orthophosphate is measured colorimetrically using the stannous chloride technique (American Public Health Association 1976). The level of NH_4 was analyzed by oxidizing ammonia and labile amino compounds to nitrite which is then measured colorimetrically (Richards and Kletsch, 1964). Nitrate is reduced to nitrite with amalgamated cadmium and analyzed as above (American Public Health Association, 1976).

The nonfiltered portion of each sample is used to measure total phosphorus (TP), total Kjeldahl nitrogen (TKN), and organic matter (OM). Total phosphorus is digested with perchloric acid (King, 1932) and then measured using the stannous chloride technique (American Public Health Association, 1976). The TKN method measures both NH_4 and organic nitrogen, but does not include nitrate or nitrite nitrogen. The samples are digested to ammonia salts using sulfuric acid and hydrogen peroxide with hengar boiling chips as catalysts (Martin, 1972). The ammonia is then distilled and measured by Nesslerization (American Public Health Association, 1976).

Organic carbon is measured by drying samples at 60^{o}C then digesting with 67% sulfuric acid and potassium dichromate in a water bath at 100^{o}C for three hours (Maciolek, 1962). This is done in the presence of mercuric sulfate to complex halides (Dobbs and Williams, 1963). The excess dichromate is then measured colorimetrically and chemical oxygen demand (COD) is determined (Gandy and Rananathan, 1964). COD is multiplied by 3.4 to convert to Calories (g-cal/liter). Acidity is measured with a Cole-Parmer Model 5800-00 pH meter.

Subsurface water collected from wells along transects described above is analyzed using the same techniques as with surface water with two exceptions: the water is not acidified and all analyses are performed on filtered samples.

RESULTS

Surface water - Analysis of variance and discriminant analysis (Ray, 1982) were applied to log transformed data to test for site, season (month), and year differences. ANOVA was also used to test for two-way interactions, but three-way interactions could not be considered because samples were not replicated at each site. Site relationships from the canonical discriminant analysis are shown in Fig. 3. The first two canonical variables were significant ($P<.0001$ and $P<.003$, respectively) and separated sampling sites into the forested (Sites 1, 2, 4) and herbaceous (Sites 3, 5, 7) parts of Mill Swamp.

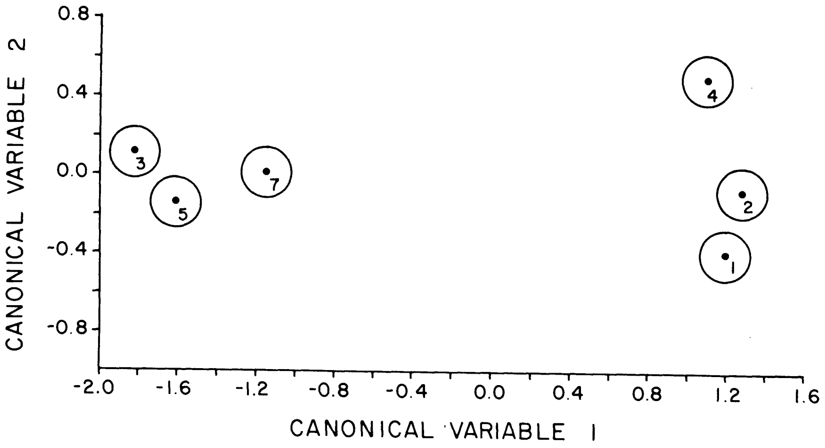

Fig. 3. Results of canonical discriminant analysis of surface water quality data. Sampling locations are shown on Fig. 2. The circles around each station are 95% confidence limits.

pH, TP, PO_4, TKN, and NO_3 had the highest F values and had significant impacts in discriminating between sites (Table 1). pH had the highest canonical correlation coefficient on the first axis and was the variable most responsible for separation of sites into the forested and herbaceous areas. Total Kjeldahl nitrogen had the highest canonical correlation coefficient on the second axis (Table 1). The discriminant analysis not only separated the sites into two groups, but the sites were all significantly different from each other at the 95% confidence level. ANOVA also separated the sites into two groups, but produced results that were more readily interpretable.

There were significant site (P>.0001) and seasonal (P>.0001) effects for all variables. Significant year differences were found only for NO_3 and OM. Season X site and site X year interactions were significant (P>.005) for all variables. Season X year interactions were significant for only PO_4, NO_3, and pH. Sites, given in parentheses, in Table 2 are arranged in the sequence generated by the ANOVA and are from the highest means on the left to the lowest on the right. Means, expressed as antilogs, not significantly different at the P>.05 level share the same superscript. While no two variables are arranged in the same left to right sequence, it is possible to discern general relationships between sites.

ANOVA also divided the sites into two groups. Sites 1, 2, and 4 are not significantly different for any of the variables (Table 2) suggesting that nutrient concentrations change little as water moves through the forested portions of Mill Swamp. Sites 3, 5, and 7 are ranked closest to each other for all but 2 of the variables. Site 5 is significantly different from either Site 3 or 7 for 4 of the variables (Table 2). This suggests that surface water nutrient composition changes as it moves through the herbaceous portion of Mill Swamp. Mean pH, PO_4, TP, TKN, and OM concentrations increase while NO_3 decreases as water moves through the herbaceous portion of Mill Swamp (Table 2).

Based on results of the ANOVA and discriminant analyses, we have chosen to describe temporal variations by combining sites into two groups: the forested area (Sites 1, 2, and 4) and the herbaceous area (Sites 3, 5, and 7). Figures 4 and 5 suggest that temporal patterns are more pronounced in water that flows through the herbaceous portion of Mill Swamp. Seasonal (monthly) differences and seasonal interactions are also obvious in Figs. 4 and 5. Phosphate concentrations increase in the summer months and decline in the colder months (Fig. 4). There appears to be an inter-annual shift in the time when the increases and declines occur, but the general pattern has held during each of the three years that we have been sampling surface water. Organic matter concentrations (Fig. 5) also increase during the summer, but unlike phosphate, there are no differences between the herbaceous and forested areas

Table 1. Results of canonical discriminant analysis of surface and subsurface water. Variables used in the analysis are listed along with their standardized canonical coefficients, F, and P values.

VARIABLE	CANONICAL VARIABLE 1	CANONICAL VARIABLE 2	F	P
	SURFACE WATER			
pH	1.52	0.55	71.81	0.0001
TP	0.48	0.47	4.31	0.0008
PO_4	0.05	-0.61	5.68	0.0001
TKN	-0.23	1.04	4.97	0.0002
NO_3	-0.13	0.30	2.47	0.0327
NH_4	0.03	-0.57	1.81	0.1105
OM	-0.25	0.52	4.16	0.0011
	SUBSURFACE WATER			
pH	1.28	-0.86	79.61	0.0001
TP	-0.59	-0.07	4.21	0.0004
PO_4	0.26	0.12	5.97	0.0001
TKN	0.30	-0.09	31.09	0.0001
NO_3	-0.29	-0.92	26.39	0.0001
NH_4	-0.04	0.22	26.99	0.0001
OM	0.08	0.64	25.18	0.0001

during the remainder of the year.

Subsurface water - In addition to seasonal patterns of surface flooding and fluctuations in the groundwater table, there are distinct intra- and interhabitat differences (Fig. 6). Groundwater levels are lowest in late summer and fall and highest in the winter and spring. West of the road (MS 0 in Fig. 6), watertable heights are always elevated above those measured east of the road. There was also less depression of the groundwater at that site during dry periods such as the one between June and September of 1984. Figure 6 suggests that the area west of the road has received large amounts of sediment because the surface elevation at the monitoring site is more than 2 meters above surface elevations of the three recorders east of the road.

Table 2. Results of ANOVA for surface water variables. Sites are given in parentheses. Means for each site are antilogs as the ANOVA was performed on log transformed data. Means that share the same superscript are not different based on Tukey's Studentized Range Tests. Values are parts per billion for all variables except OM and pH. OM units are g-cal/l. Site locations are given in Fig. 2.

VARIABLE	SITES AND MEANS					
TP	199^{a} (1)	189^{a} (4)	186^{a} (2)	113^{b} (5)	105^{b} (7)	91^{b} (3)
PO_4	139^{a} (1)	127^{a} (2)	122^{a} (4)	65^{ab} (5)	61^{b} (7)	46^{c} (3)
TKN	339^{a} (4)	316^{abc} (2)	287^{ab} (1)	286^{ab} (7)	280^{ab} (5)	262^{b} (3)
NO_3	276^{a} (7)	210^{ab} (4)	193^{ab} (2)	184^{ab} (1)	115^{b} (3)	75 (5)
NH_4	73^{a} (1)	64^{a} (2)	61^{ab} (4)	47^{b} (7)	28^{c} (5)	27^{c} (3)
OM	49^{a} (5)	48^{ab} (4)	48^{ab} (3)	44^{ab} (7)	41^{ab} (2)	40^{b} (1)
pH	6.71^{a} (2)	6.71^{a} (4)	6.64^{a} (1)	5.86^{b} (7)	5.75^{bc} (5)	5.67^{c} (3)

Substrates in the portion of Mill Swamp west of the road are almost always waterlogged.

The herbaceous habitat is also waterlogged for long periods of time as shown by the watertable data in Fig. 6 (MS 80). In the forested area east of the road (MS 200 and MS 333 in Fig. 2), the groundwater is almost always below the surface, especially near the stream channel (MS 333 in Fig. 2) during the growing season months. As noted earlier, MS 200 is flooded under high flow conditions (Fig. 1B) when water spreads into the forested area from the herba-

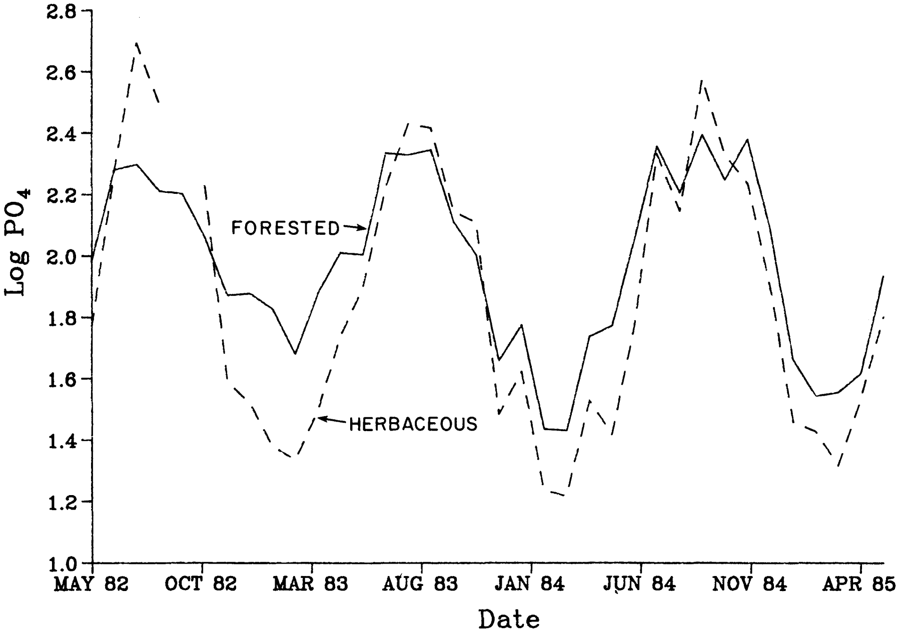

Fig. 4. Seasonal patterns of phosphate concentrations in surface water in the forested and herbaceous portions of Mill Swamp.

ceous area. Watertable fluctuations in the forested areas suggest that substrate conditions alternate between aerobic and anaerobic at MS 200 and that conditions are almost always aerobic at MS 333.

Site relationships for subsurface water were analyzed by discriminant analysis (Fig. 7). The first four canonical variables were highly significant ($P>.0001$), but the first two variables had much higher F values (15.27 and 7.33) for the first and second variables compared to 4.16 and 3.55 for the third and fourth. Sites 0 and 300 were separated by the first canonical variable which was most influenced by pH (Table 1). The second canonical variable separated the sites further (Fig. 7) with pH, NO_3, and OM having the highest canonical coefficients (Table 1). Sites 300 and 333 have about the same position on the second canonical axis as do Sites 0 and 80. A second grouping is formed by Sites 40, 60, and 200. These two groupings coincide with a gra-

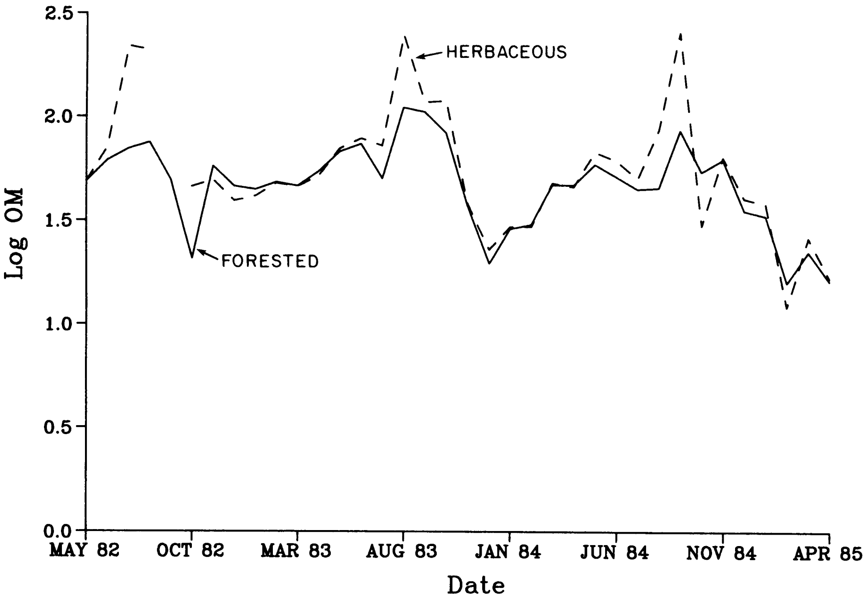

Fig. 5. Seasonal patterns of organic matter concetrations in surface water in the forested and herbaceous portions of Mill Swamp.

dient of decreased flooding and increased fluctuations in the groundwater table. Sites 0 and 80, are in areas where surface flooding is most frequent and groundwater is near the surface for longer periods of time. Those well clusters correspond to the locations of groundwater monitors MS 0 and MS 80 (Fig. 2). Wells at Sites 40, 60, and 200 are at slightly higher elevations and flood less frequently and the groundwater table fluctuations are probably more similar to those found at recorder site MS 200 (Fig. 2). Wells at Sites 300 and 333 are in areas that rarely flood and the watertable is almost always below the wetland surface (Fig. 6).

ANOVA and Tukey's Studentized Range Tests comparisons of water quality data from the wells are shown in Table 3. The ANOVA model was based on main effects due to site, season, and year. All two- and three-way comparisons were made with replicates being the set of 3 wells at each site. Similar to

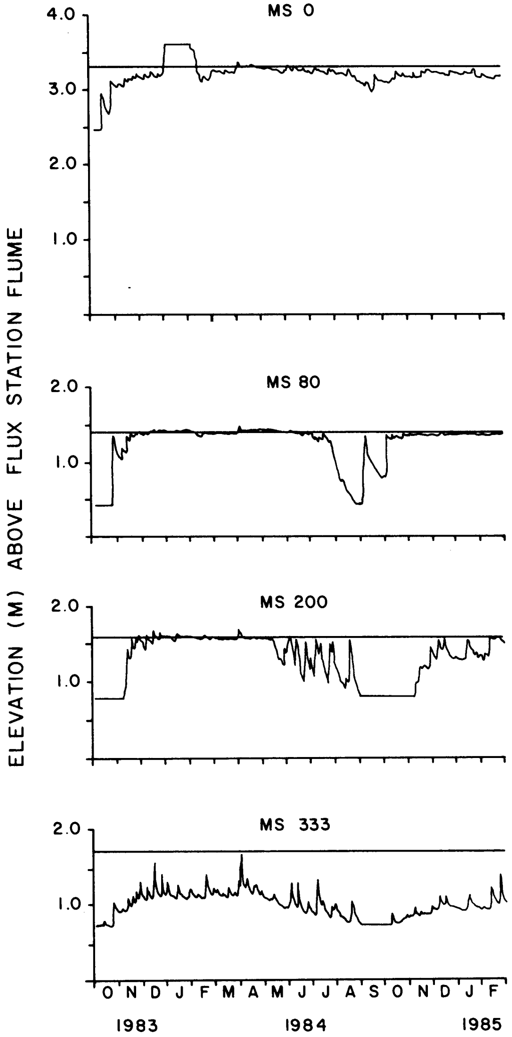

Fig. 6. Subsurface water elevations at the four monitoring stations shown in Fig. 2. All data are shown as elevation (m) above the base of the flux station that is used to continuously monitor water flux through Mill Swamp. The solid horizontal line on each graph represents the elevation of the surface relative to the base of the water flux monitoring station.

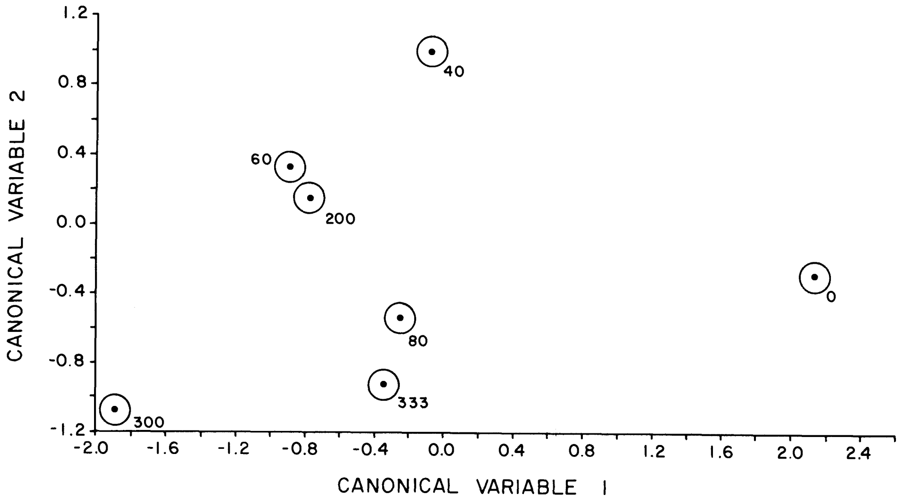

Fig. 7. Results of canonical discriminant analysis of subsurface water quality data. Wells 0 and 40 are on Transect I while the other wells are on Transect III (Fig. 2). Circles around each station are 95% confidence limits.

surface water data, none of the variables have the same left to right alignment of sites and none of the variables have the same statistical between site relationships. There were significant Site ($P>.0001$) effects for all variables. Significant seasonal and yearly differences occurred for all variables except PO_4 (season) and TP (year). Two-way interactions were significant in all variables except TKN and NH_4.

Comparison of Table 3 and Fig. 7 show slightly different site relationships. Sites 0 and 40 are almost always statistically similar and Sites 60, 80, and 200 form a second group (Table 3). The discriminant analysis grouped Site 0 with 80 and Sites 40 and 60 with 200. Sites 300 and 333 form a separate group in both the ANOVA (Table 3) and discriminant analysis (Fig. 7). Phosphate and NO_3 concentrations are highest in areas that flood less frequently and where groundwater fluctuations are greatest. Organic matter, TKN, and NH_4 show the opposite pattern (Table 3).

We have chosen to demonstrate temporal variations and interactions by combining the well data into 3 groups. Group 1 combines data from wells 0 and

Table 3. Results of ANOVA for subsurface water variables. Sites are given in parentheses. Means for each site are antilogs as the ANOVA was performed on log transformed data. Means that share the same superscript are not different based on Tukey's Studentized Range Tests. Values are parts per billion for all variables except OM and pH. OM units are g-cal/l. Site locations are given in Fig. 2.

VARIABLE	SITES AND MEANS						
TP	49^{a} (333)	33^{ab} (40)	29^{b} (200)	28^{b} (300)	21^{b} (60)	21^{b} (80)	20^{b} (0)
PO_4	43^{a} (333)	24^{ab} (300)	22^{bc} (40)	20^{bcd} (200)	13^{cde} (80)	12^{de} (60)	11^{e} (0)
TKN	684 (0)	450 (40)	262^{a} (60)	257^{a} (80)	213^{ab} (200)	155^{bc} (333)	138^{c} (300)
NO_3	495^{a} (300)	240^{ab} (333)	236^{b} (80)	92^{c} (60)	65^{cd} (200)	38^{d} (0)	14 (40)
NH_4	285 (0)	148 (40)	66^{a} (80)	59^{ab} (200)	57^{ab} (60)	38^{b} (333)	35^{b} (300)
OM	64^{a} (0)	54^{a} (40)	34^{b} (60)	31^{bc} (200)	30^{bc} (80)	24^{cd} (333)	22^{d} (300)
pH	6.34 (0)	5.81^{a} (333)	5.75^{a} (80)	5.68^{bc} (40)	5.49^{bc} (60)	5.44^{bcd} (200)	5.39^{cd} (300)

80 which are in areas that flood most frequently. Group 2 combines data from wells in locations that are hydrologically intermediate (40, 60, and 200). Group 3 combines data from the driest locations (300 and 333). Organic matter and NH_4 concentrations are higher in the summer months in wells that are in areas where the groundwater is near the surface (Figs. 8 and 9). The pattern was similar in 1983 and 1985, but was not as obvious in 1984. Nitrate (Fig. 10) and phosphate (Fig. 11) are clearly highest in areas which flood less.

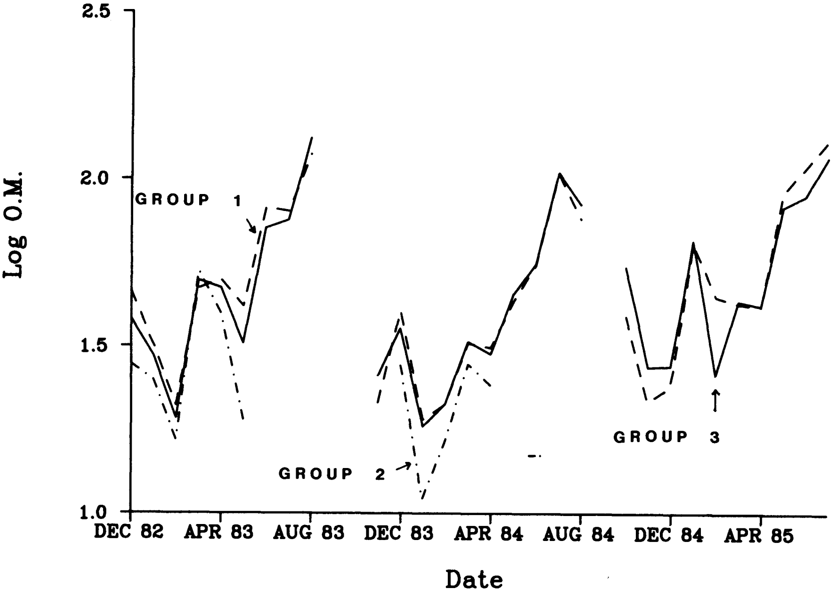

Fig. 8. Seasonal patterns of organic matter in subsurface water. Values are means for data combined into three groups as discussed in the text.

Both parameters show clear seasonal differences. Similar to NH_4 and OM, there are clear annual patterns, but with less obvious seasonality in 1984.

DISCUSSION

Results of this study demonstrate within wetland differences in surface and subsurface water quality parameters. Surface water changes occur primarily in the herbaceous area. We cannot yet completely evaluate within habitat patterns for subsurface water because we only have enough data from groundwater wells along transects I and III. Three other transects are now being sampled, but we have very few data because of the dry conditions that have persisted since the summer of 1984. Data from transects I and III, however, do demonstrate between habitat differences that are related to drawdown of the watertable. The watertable is most often near the surface in the forested area west of the road. As the results for both surface and subsurface

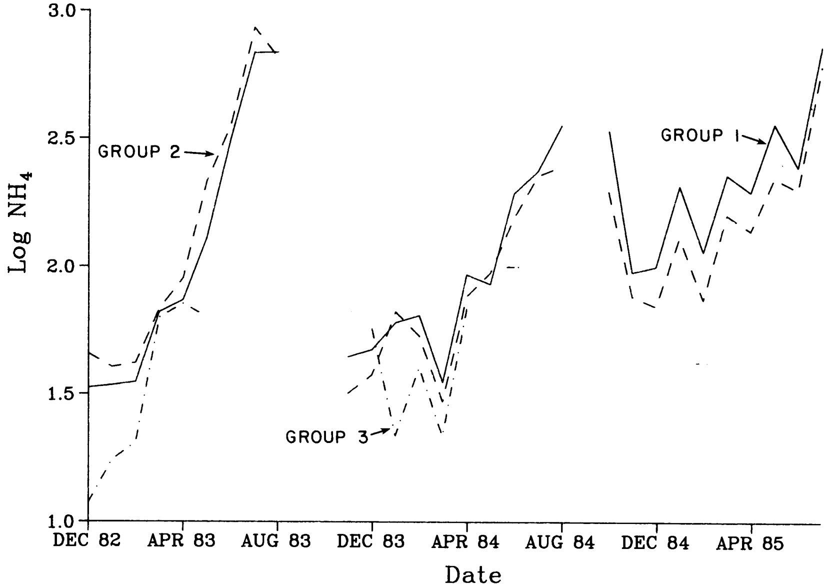

Fig. 9. Seasonal patterns of ammonia in subsurface water. Values are means for data combined into three groups as discussed in the text.

water are preliminary and we have not yet conducted experimental manipulations in Mill Swamp, explanation of the patterns can only be inferred from results of other studies.

Surface water - We have not detected any impact of either of the forested portions of Mill Swamp upon any of the surface water quality paramaters. East of the road, surface water in the forested area is almost always contained within the stream corridor and we have not recorded any surface flooding events during the 3 years that we have been collecting data from the recorder at MS 333 (Fig. 2). The stream is completely shaded during the growing season, supports no macrophytes, and contains very few riffle and pool habitats. These conditions are all thought to be important if significant nutrient processing is to occur in streams. West of the road, because the stream channels are small and very shallow, surface flooding occurs more frequently. During the period that watertable data have been collected at MS 0, (Fig. 2) the wetland surface has flooded on numerous occasions. In 1984, a comparatively wet

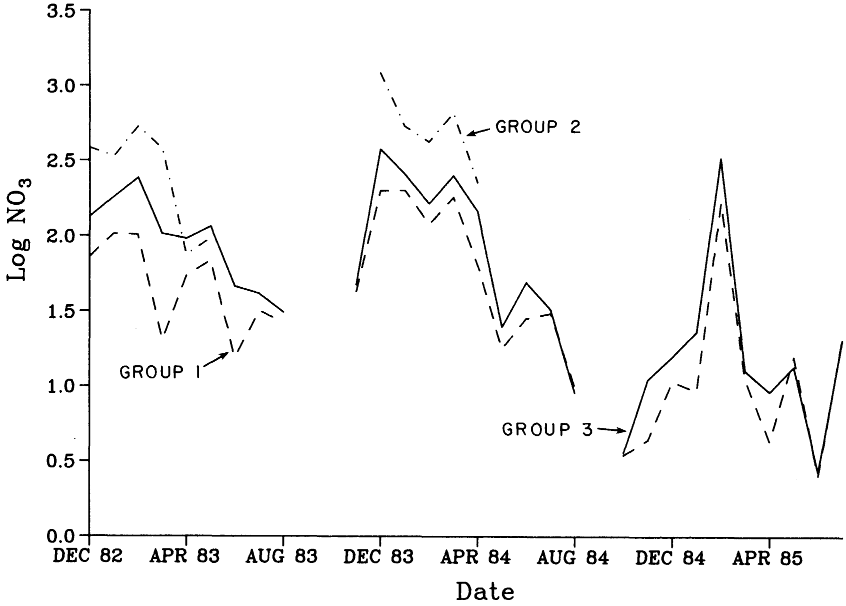

Fig. 10. Seasonal patterns of nitrate in subsurface water. Values are means for data combined into three groups as discussed in the text.

year in the winter and spring, the surface was flooded for several months (Fig. 6). We believe that any significant changes in surface water would be restricted to flooding conditions, especially in the late winter and spring when the water contains large amounts of sediment. We combined watertable data and surface water quality data to compare periods of time when the area west of the road flooded to a comparable time when the area did not flood. Data from that comparison show that greater changes in nutrient concentrations occur between Sites 1 and 2 during periods of flooding (Table 4). Concentration changes between Sites 1 and 2 were more pronounced for NH_4, TP, PO_4 and NO_3 during the period of flooding from December, 1983 through February, 1984 than they were during the same time period in 1984 and 1985 when surface water was restricted to channel flow. All of the variables except NO_3 declined between Site 1 and Site 2. During the second time period, nitrate concentrations increased between the two sites.

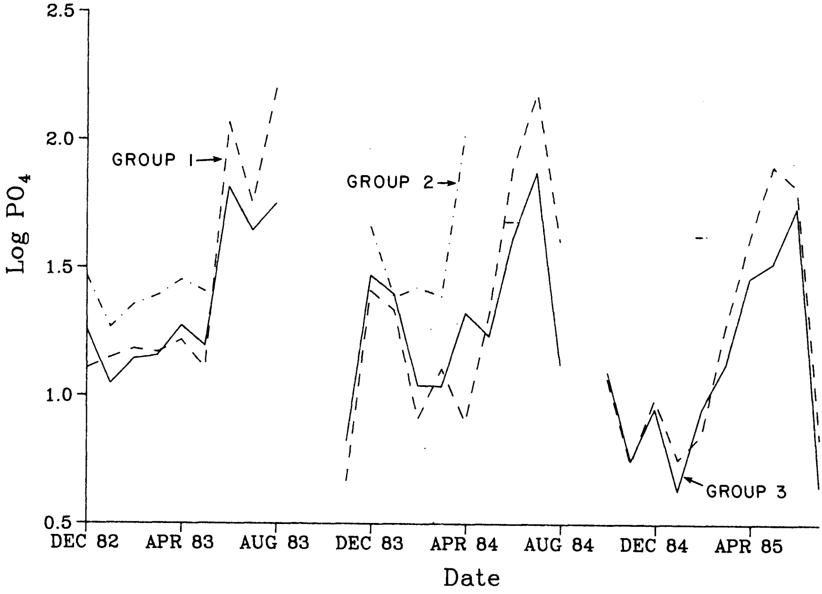

Fig. 11. Seasonal patterns of phosphate in subsurface water. Values are means for data combined into three groups as discussed in the text.

Although we have not conducted any detailed studies of water quality changes during flooding events, data from a study of litter decomposition also demonstrates that nutrient interactions between flooding water and surface litter occur in the area west of the road. The decomposition study was conducted in several upland and wetland habitats to compare changes in the nutrient status of litter and rates of decomposition (Whigham and O'Neill, Unpublished). Litter bags accumulated large amounts of sediment in the riparian forest studied by Peterjohn and Correll (1986), but the amount of sediment that accumulated in the litter bags in the flooded portion of Mill Swamp was an order of magnitude higher (Fig. 12). The amount of phosphorus contained in the litter bags in Mill Swamp was much greater than the amount of phosphorus contained in litter bags at any of the other sites (Fig. 13). Nitrogen followed the same pattern. These findings support the results shown in Table 4 and those of Cooper et al. (1986) who found that larger sediment particles are deposited in riparian forests while finer sediments that contain high phosphorus levels are transported further downstream and deposited in swamps and/or floodplain areas.

Nutrient transformations in the herbaceous area are most likely caused by interactions between the water and wetland vegetation, litter, and microbes. The importance of the litter zone and its microbial community has been demonstrated in estuarine wetlands (Wolaver and Zieman, 1984; Jordan and Whigham, 1985), and freshwater tidal wetlands (Whigham and Simpson, 1978). The importance of the litter-microbial community in altering water quality has been demonstrated by including it into the development of wastewater management systems that use overland flow systems to treat sewage effluent (Smith and Schroeder, 1985). Nutrient retention can be further augmented by the physical presence of macrophytes which cause water velocity to decline and sediment deposition to be increased (Burton, 1982). Perennial emergent macrophytes

Table 4. Changes in concentrations between Sites 1 and 2 (Fig. 2) during a period of continuous flooding (12/83-2/84) and the same time period a year later (12/84-2/85) when surface flow was restricted to stream channels. Values are antilogs of means that were based on log transformations. All values are parts per billion except for OM which is g-cal/l.

VARIABLE	SAMPLE SITE	FLOODED	NOT FLOODED
TP	1	145	126
	2	110	118
PO_4	1	85	85
	2	59	66
TKN	1	195	240
	2	195	229
NO_3	1	427	170
	2	363	186
NH_4	1	79	93
	2	62	83
OM	1	25	30
	2	27	31

probably have a greater influence on subsurface water as they have been shown to alter the chemistry of interstitial water through the assimilation of nutrients from the substrate and the translocation of large amounts of material from belowground structures (Jayne and Carpenter, In press; Klopatek, 1975; Shaver and Melillo, 1984).

Annual species of vascular plants, in contrast, probably have a large impact on water quality during the growing season. Annuals that occur in the herbaeous portion of Mill Swamp (Polygonum arifolium, Polygonum saggitatum, Impatiens capensis) cannot tolerate anaerobic conditions and their root systems develop in the narrow aerobic zone at the wetland surface. As the plant canopy develops, lower leaves of the annuals senesce and adventitious roots develop at the nodes (Whigham, personal observation). By the middle of the growing season, the annuals have formed a dense mat of adventitious roots

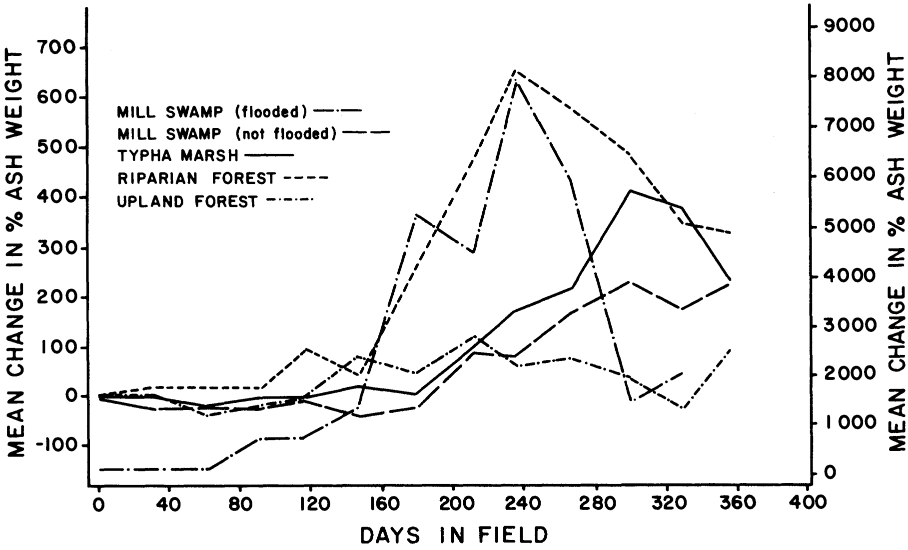

Fig. 12. Changes in the ash content, expressed as a percentage of the original, in leaf litter for several vegetation types on the Rhode River watershed. Site designations are as shown on the figure. The scale for the flooded portion of Mill Swamp is on the right.

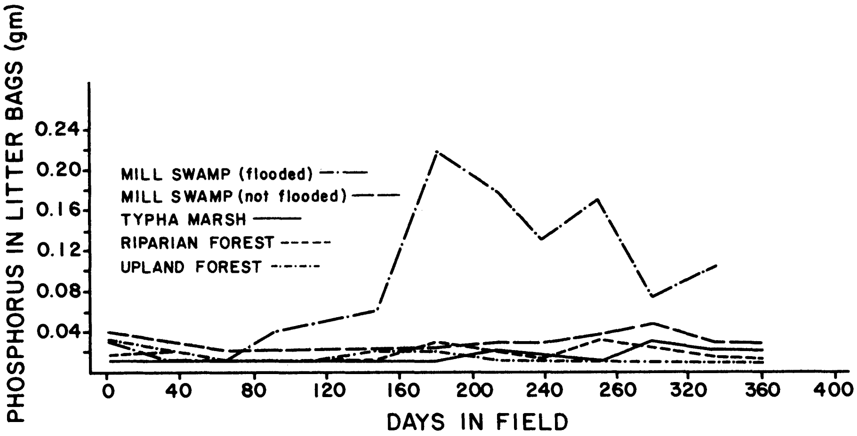

Fig. 13. Temporal changes in the amount (gm) of phosphorus in litter bags. Site designations are as shown on the figure.

on the wetland surface. The root mat is bathed by surface water and we believe that it plays an important role by assimilating nutrients from the surface water. Nutrient retention at other times of the year is most likely controlled by interactions between the water and the litter-microbial community. These interactions are most important in the spring, prior to emergence of the vascular plants, when bacterial growths and algal mats are present on the litter (Whigham, personal observation; Whigham et al. 1980). The litter-microbial community interactions are also important in the fall following dieback of the vascular plants.

Each summer there are increases in phosphate concentrations of water leaving the herbaceous portion of Mill Swamp (Fig. 4). An oxygen monitor in that area recorded frequent overnight anoxia. Phosphorus fluxes probably coincide with those events.

Subsurface water - The nutrient composition of subsurface water, interstitial water near the wetland surface, appears to be primarily controlled by the annual pattern of flooding and drawdown. Brinson and his colleagues (Brinson et al., 1983 and 1984) have studied the interaction between surface and subsurface water in a North Carolina alluvial swamp forest. They found that nitrate and ammonium interactions were closely coupled to denitrification, the ability of ammonium to be adsorbed on cation exchange sites during periods of flooding, and the conversion of ammonium to nitrate during periods of drawdown. During periods of drawdown, nitrate did not increase in subsurface water due to denitrification. Ammonium did not accumulate in subsurface water suggesting that microbial assimilation was not very important in the alluvial swamp system. Yarbro et al. (1984) found different results in North Carolina swamps that had been drained. Nitrogen and phosphorus losses were greater in drained swamps with continuously lowered watertables. The results of those two North Carolina studies demonstrate the importance of fluctuating watertables. Annual flooding is necessary in swamp systems because flooding replenishes nutrient supplies and organic matter needed to drive denitrification (Peterjohn and Correll, 1986). Surface flooding is also important if swamp systems are to retain phosphorus (Brinson et al., 1984). Drawdown periods cause alternating periods of aerobic and anaerobic conditions that are important to both organic matter decomposition and nitrogen loss through nitrification and denitrification (Brinson et al., 1984; Reddy and Patrick, 1975).

CONCLUSIONS

This preliminary research into nutrient processing in Mill Swamp has shown that there are differences between habitats and also differences between surface and subsurface water. However, we still do not know much about mechanisms responsible for the patterns nor do we know the impact that each of the habitats has on overall nutrient flux and retention. We are now in the process of building additional monitoring stations in Mill Swamp to quantify hydrologic fluxes through each of the habitats. We will then be able to more clearly define the role that the three habitats play in nutrient processing within Mill Swamp.

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DISCUSSION: Whigham Paper

Comment (Correll): I am struck by some similarities with some of the things that Gilliam was talking about in terms of the influence of regulating the water table height on the nutrient dynamics. I am wondering how similarly this system responds as compared with some of the North Carolina coastal plain areas that are being regulated artificially for crop production. Could we see similar patterns if we knew enough about this system?

Question (Gilliam): How wide is this swamp where the road goes across?

Answer: Well, I guess in the upper part it might be 600 - 700 m across. At the road probably 400 m.

Question (Gilliam): How big an area are you talking about?

Comment (Correll): The total area is about 60 hectares.

Comment (Gilliam): In our situation we would consider that mostly riparian vegetation on a creek. An area that size down where we are, I don't believe would be called a swamp. We are talking about swamps that are much bigger.

Answer: I think the reason we call it a swamp is that historically that is what it was called. If it wasn't for the road going across it, I think it would just be a riparian zone. It would be a continuation of the riparian zone found further up the gradient.

Comment (Gilliam): One of the things we have noticed is that road beds turned out to be very effective dams to hold the water and to channelize it and create swamps upstream which are quite effective filters. These roads have done quite a bit for water quality downstream.

WATERSHED RESEARCH PERSPECTIVES

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