FINAL REPORT

TO

CITY OF CLERMONT

FLORIDA

# REMOVAL OF NUTRIENTS FROM TREATED MUNICIPAL WASTEWATER BY FRESHWATER MARSHES

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# EXECUTIVE SUMMARY

TO

CITY OF CLERMONT

FLORIDA

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# EXECUTIVE SUMMARY

## Introduction

This report presents the results of two years of application of secondarily treated wastewater into a freshwater marsh on the outskirts of the city of Clermont, Florida. Figure 1 is a photograph of the four enclosed experimental plots connected by a boardwalk to the dike surrounding the Clermont Sewage Treatment Plant Percolation Pond. The entire project was funded by city and county agencies. The objective of the study was to determine at what rate and in what manner secondarily treated wastewater could be applied to a freshwater marsh with minimal effect on the marsh and surrounding waters.

This study utilized four 0.5 acre (2000 $m^2$) plots. Three of these received secondarily treated wastewater at the low, medium, and high rates of 0.6 in./wk (1.5 cm/wk), 1.5 in./wk (3.7 cm/wk), and 3.8 in./wk (9.6 cm/wk), respectively. A fourth plot used as a control received 1.7 in./wk (4.4 cm/wk) of fresh water from a municipal well. Collected data included the following: standing crop of vegetation; phosphorus and nitrogen content of aboveground and soil water, applied wastewater, and vegetation; volume of rainfall and wastewater or fresh water loadings; and water table elevation.

## Experimental Results

1. A two-year study on the effects of application of secondarily treated wastewater to a freshwater marsh in central Florida showed no significant release of nutrients from any plot to the environment adjacent to or below the experimental plots.

Figure 1. Aerial photograph of the Clermont Marsh Study Area. The north direction is from the upper right corner to the lower left corner. The Palatlakaha River is shown in the foreground.

2. Data collected from wells in experimental plots showed a concentration of phosphorus that was not significantly greater than the concentrations observed in wells located in the natural marsh (approximately 0.1 mg/l). This represented only 3% of the applied phosphorus. There was negligible export of phosphorus out of any plot in the surface water. During the dry year, the bulk of the applied phosphorus appeared to have been adsorbed by the soil complex. During the wet year the soil complex may not have stored phosphorus. The large concentration of phosphorus (avg. 7.3 mg/l) in the standing water in the high rate loading plot (3.8 in./wk) was presumed to originate from the applied water as well as being released from the soil complex.
3. All forms of nitrogen in applied secondarily treated wastewater approached average background concentrations of the marsh in both standing water and exported soil water. These results were obtained under all loading rates for both wet and dry conditions. The bulk of the applied nitrogen was lost to the atmosphere in gaseous form (as $N_2$ and $N_2O$); a small amount was deposited as new peat. Of the inorganic nitrogen applied to the high rate loading plot (3.8 in./wk), 94% was removed by the marsh system during the dry year. The wet year value was 96%.
4. Applied secondarily treated wastewater stimulated the growth of semiwoody plants in the dry marsh; specifically, marsh hibiscus and buttonbush. Algae and duckweed grew in the vicinity of wastewater application pipes when standing water was present.

## Application of Results to Other Areas

1. Any secondarily treated wastewater applied to the marshland must pass through the peat for maximum removal of phosphorus to occur. The marsh-treatment system should therefore be designed so as to insure passage of all applied wastewater through the peat substrate. In this study, 97% removal of phosphorus and 95% removal of total inorganic nitrogen were obtained in a marsh having a peat depth of 1.5 m.

2. based on the results of this study, an application rate of 1.5 in./wk should not produce detrimental water quality impacts in groundwater or adjacent water bodies provided the treated wastewater passes through the peat.

3. The long-term effects (greater than five to ten years) are unknown for this marsh since the study covered only two years. A recent study in Wildwood, Florida, indicated that a small marsh/shrub area within a wooded swamp was still functioning to remove phosphorus after approximately 20 years.

## Application Methodology

1. The experimental plots received secondarily treated wastewater once a week over a 24-hr period. This provided a six-day "restoration" period during which time the marsh could assimilate the applied load. A similar "restoration" period should be considered in the design of the proposed wastewater treatment system.

2. Application of the wastewater was achieved via a low pressure piping system that provided a relatively uniform distribution over the interior portion of the experimental plots. All efforts should be made to achieve a similar distribution in the proposed application system.

# INTRODUCTION

## Overview

The ability of a freshwater marsh to assimilate the phosphorus and nitrogen in secondarily treated municipal wastewater was evaluated in this study. The evaluation of a natural ecosystem, which is to be utilized for advanced waste treatment, raises several important ecological and engineering issues. One of the important aims of this research was to determine the structural and functional responses of the system to the water and nutrient subsidies. The marsh system may build structure to accumulate the input nutrients. Further, the treated wastewater subsidies may increase the overall flows of water and nutrients through the system. From an engineering standpoint, it is important to consider the ultimate fate of the applied nutrients and the rate at which the treated wastewater can be applied without overloading the marsh system. Marsh systems may provide a very attractive alternative to expensive, fossil fuel-subsidized advanced waste treatment plants.

There exists a variety of natural systems that have the capability of providing advanced waste treatment. The common characteristic of these ecosystems is their ability to assimilate and store nitrogen and phosphorus in plant tissue or in the soil. Sopper and Kardos (1973) illustrated the potential of recycling sewage effluent using terrestrial systems. Secondarily treated municipal wastewater was applied to forage crops, red pine plots, and white spruce stands. Annual crop yields and tree growth were significantly greater with effluent irrigation. Renovation of the wastewater was particularly successful in the reed-canary forage grass plots. The annual crop of reed-canary grass removed 35% of the phosphorus applied and 97% of the nitrogen. The remaining 65% of the phosphorus was retained by the soil. There are two drawbacks to extensive use of terrestrial systems. The treated wastewater pumping and distribution costs may be prohibitively high. In addition, the water stress imposed by the treated wastewater could limit widespread or long-term use.

Wetlands provide a possible alternative to the use of terrestrial systems. Marshes and swamps are adapted to flooded soil conditions, and the distribution problem is minimized since the effluent can be spread by the movement of the already existing standing water in the system. Marshes and swamps are also two of the most productive ecosystems in the world (Lieth 1975). This high growth rate suggests an equally high assimilation of nutrients in plants.

The suitability of swamps to act as nutrient sinks has been studied extensively in Florida. Cypress domes in central Florida receiving primary wastewater have shown increased growth. The plant community together with the soil compartment proved to be an efficient filter for the applied phosphorus and nitrogen (Odum and Ewel 1977). Boyt et al. (1976) found that primarily treated sewage underwent a 98.0% reduction in the phosphorus concentration and a 89.7% reduction in the nitrogen concentration after passing through a mixed hardwood swamp. Growth rates for the cypress trees in the swamp were also found to be higher than for trees in a control area. Likewise, trees in a cypress strand receiving raw sewage for the past 40 years grew significantly more than trees in a control area (Nessel 1978). The phosphorus concentration of the effluent was significantly reduced after flowing through the cypress strand.

Wisconsin freshwater marshes have been studied extensively with regards to cycling of nutrients under natural conditions together with studies that emphasized the water quality role of the marsh ecosystem (Fetter et al. 1978; Klopatek 1975; Lee et al. 1975). In Florida, marsh research has centered on the functioning of the Everglades vegetation under both natural and enriched conditions (Davis 1978; Steward and Ornes 1975a, 1975b).

Marshes in a variety of other geographic areas have also been studied to determine their effectiveness in wastewater renovation. Michigan peatlands, freshwater tidal marshes, saltmarshes, and man-made marshes have each been sites for treated wastewater disposal research. In a Michigan sedge-willow peatland subjected to nearly 6 cm/wk of secondary effluent Kadlec et al. (1977) found that the marsh functioned as a nutrient sink for both nitrogen and phosphorus. Within 30 m of the effluent discharge point in the peatland, 99% of the nitrate-nitrite nitrogen, 95% of the total dissolved phosphorus, and 71% of the ammonia was removed from the effluent. Increased plant standing crops and higher levels of plant tissue phosphorus were found in a band extending the length of the effluent discharge pipe. Higher concentrations of both nitrogen and phosphorus were also measured in the soil along the discharge pipe. Denitrification appeared to be an important sink for the applied nitrogen.

In a preliminary study to determine the nutrient renovation capability of a Delaware River freshwater tidal marsh, experimental plots have been subjected to a maximum of 12.7 cm/day of secondary effluent (Whigham and Simpson 1976). Numerous studies have been made to determine the effect of increased nutrient loads on saltmarsh vegetation. In Louisiana, the effect of supplemental inorganic nitrogen and phosphorus on stands of Spartina alterniflora have been measured (Patrick and Delaune 1976). Valiela et al. (1975) have reported that application of sewage sludge to S. alterniflora stands on the coast of Massachusetts caused an increase in the annual maximum standing crop. On Long Island, New York, a marsh system has been artifically constructed to determine the feasibility of its use in the renovation of raw sewage (Small 1977). Results indicate that the system removes the major portion of nitrogen and orthophosphate in sewage applied to it (Small 1978).

Whigham and Bayley (in press) reviewed studies of nutrient absorption in wetlands to determine what ecosystem parameters were most important in determining the waste treatment capacity of any particular wetland. They compared the amounts of nitrogen and phosphorus that accumulated annually in aboveground vegetation in different wetlands. They also compared the removal of nutrients by different wetlands as demonstrated by mass balance studies in those systems. They found that the type of substrate, organic versus inorganic, was potentially important in determining the nutrient assimilation capacity of a wetland. Wetlands with organic peat substrates, though accumulating less nitrogen and phosphorus in their annual production of aboveground vegetation, appeared to be more capable of processing wastewater than wetlands with inorganic substrates.

## Project Objective

In this study, secondarily treated wastewater was applied to a freshwater marsh ecosystem located near the city of Clermont in central Florida from May 1, 1977 through June 1, 1979. The main questions posed and addressed were the following:

Does the nutrient subsidy in the treated wastewater result in an increased level of annual net production? Under treated wastewater application is there a corresponding increase in belowground production as well as aboveground production? Does application of treated wastewater and freshwater significantly alter the hydrology of the plots as compared to the undisturbed marsh? What is the quality of the treated wastewater after flowing through the marsh system? How much phosphorus and nitrogen is exported from the plots compared to the amount of nutrients applied? What are the major phosphorus and nitrogen sinks in the marsh? Does the marsh act as an efficient tertiary treatment facility? What loading rate provides the most efficient and practical treated wastewater renovation?

## Description of the Study Area

The research site lies in the northward flowing Palatlakaha River watershed, part of the St. Johns River Basin (Fig. 2). The site is located within the city of Clermont (population 4800), 40 km to the west of Orlando, Florida. The Palatlakaha chain of lakes is known for its clear, clean, low productivity waters and is fed by the Green Swamp located to the south of Clermont (Wilkes and Kaleel 1972). The experimental marsh is located in 32 hectares (ha) of marsh immediately south of Lake Hiawatha, and it is adjacent to the city of Clermont's 0.6 mgd sewage treatment plant. The chief land uses in the Clermont area are either residential or agricultural (primarily citrus groves).

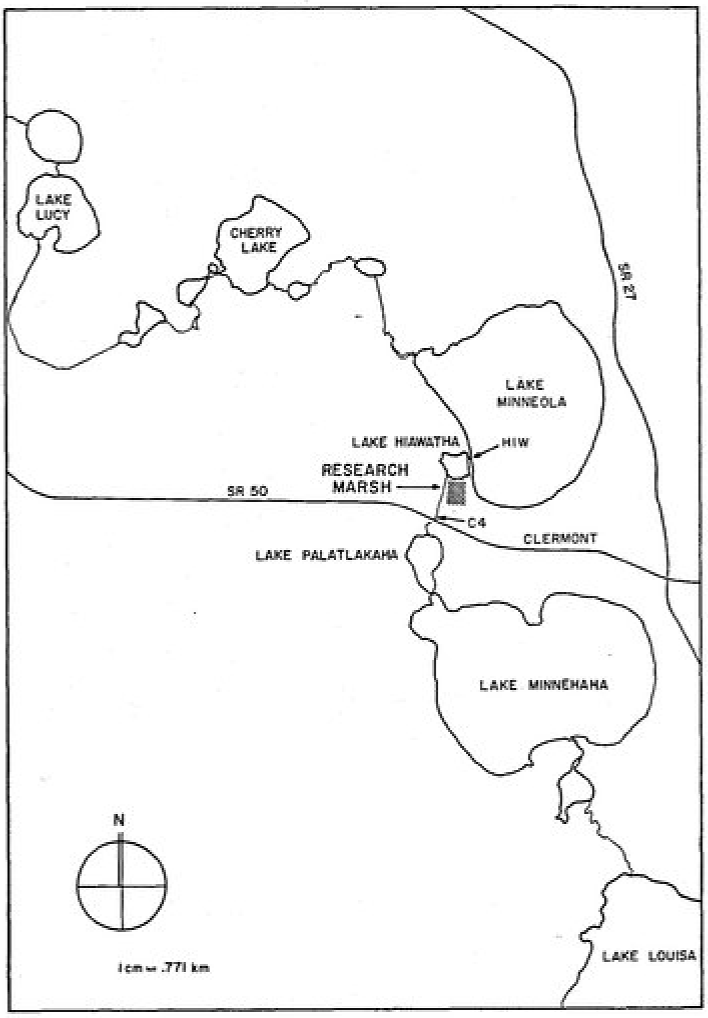



Figure 2. Map showing location of research marsh in relation to the City of Clermont and the Palatlakaha chain of lakes.

## Marsh Vegetation and Substrate

The vegetation in the experimental plots was primarily composed of emergent aquatic macrophytes. Sagittaria lancifolia (arrowhead), Pontederia cordata (pickeral weed), Panicum spp. (panic grass), and Hibiscus spp. (marsh hibiscus) were the dominant species. Table 1 is a listing of the dominant species present in the experimental site. Davis (1946) characterized a marsh dominated by these species as a flag pond marsh. When standing water was present in the marsh, various species of blue-green algae, green algae and diatoms, as well as Lemna sp. (duckweed), were present in that standing water.

The general physical structure of the marsh is schematically illustrated in Fig. 3. The top layer, approximately 1.5 m thick, consists of the highly organic, Brighton series, peat soil (USDA 1975). This organic matter was composed of both undecomposed and decomposing herbaceous plant material. The peat soils are very acidic; the pH ranges from 4.15 to 4.78 (Davis 1946). A zone of saturated coarse sand is found below the peat layer. A confining layer of kaolinite clay and sand separates the marsh soil water from a direct connection with the underlying Floridan Aquifer (Knochenmus and Hughes 1976).

Table 1. Dominant marsh plants of the research site.

| Species | Common Name |
|---|---|
| *Sagittaria lancifolia* | Arrowhead |
| *Pontederia cordata* var. *Lancifolia* | Pickerel weed |
| *Panicum* spp. | Panic grass |
| *Hibiscus* spp. | Marsh hibiscus |
| *Peltandra* sp. | --- |
| *Ludwigia peruviana* | Primrose willow |
| *Cephalanthus occidentalis* | Buttonbush |
| *Mikania* sp. | Climbing hempweed |
| *Ludwigia* spp. | --- |
| *Cladium jamaicense* | Sawgrass |

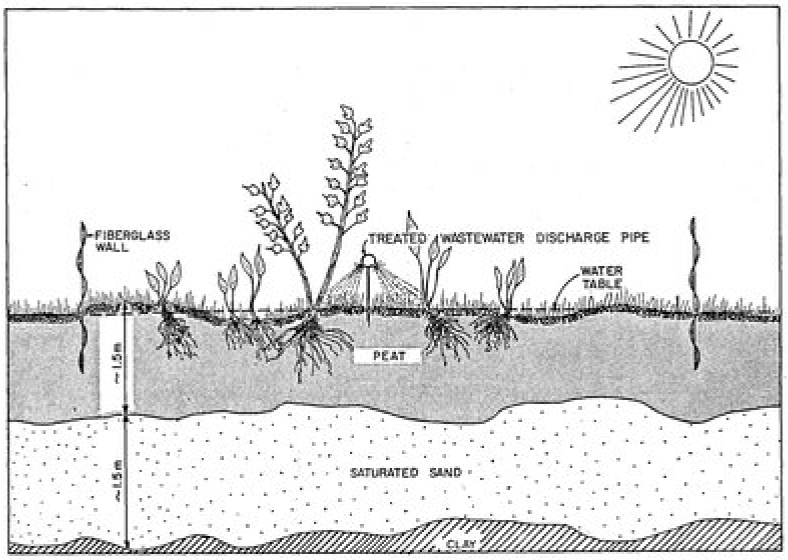



Figure 3. Illustration of the structure of the experimental plot, marsh vegetation, and the physical structure of the marsh.

# METHODS

## Experimental Plots

Four 2000 $m^2$ experimental plots were constructed in the 32-ha marshland just south of Lake Hiawatha. The layout of the experimental site is shown in Fig. 4. The structural details of each plot were shown in Fig. 3. The perimeter of each plot consisted of corregated fiberglass panels supported by wooden posts. The panels were placed to a depth of 0.6 m in the peat and extended 1.5 m above the peat surface. Joints and corners were sealed with caulking compound. The purpose of the wall was to constrain applied surface water within the area of each plot.

While secondarily treated wastewater was delivered to three of the experimental plots, a fourth plot recieved municipal fresh water pumped from a nearby groundwater well. Water was delivered to each of the plots via a 30 m-long perforated PVC pipe suspended 1.5 m above the peat surface. The pipes were oriented south-to-north through the center of each plot. Water was jetted out of the perforated pipe, under pressure, in a downward direction. Applied water contacted the marsh surface within a 3 m corridor directly beneath each application pipe. Since the water was not sprayed, evaporative loss was minimized. This simplified the eventual development of a hydrologic budget.

Each plot received its water loading over a 24-hour period once each week. Plot C, the control plot, received 4.4 cm/wk of fresh water. Plot L, the lowest-rate plot, received 1.5 cm/wk of treated wastewater. Plot M received an intermediate rate, 3.7 cm/wk treated wastewater. Plot H received the highest loading rate, 9.6 cm/wk.

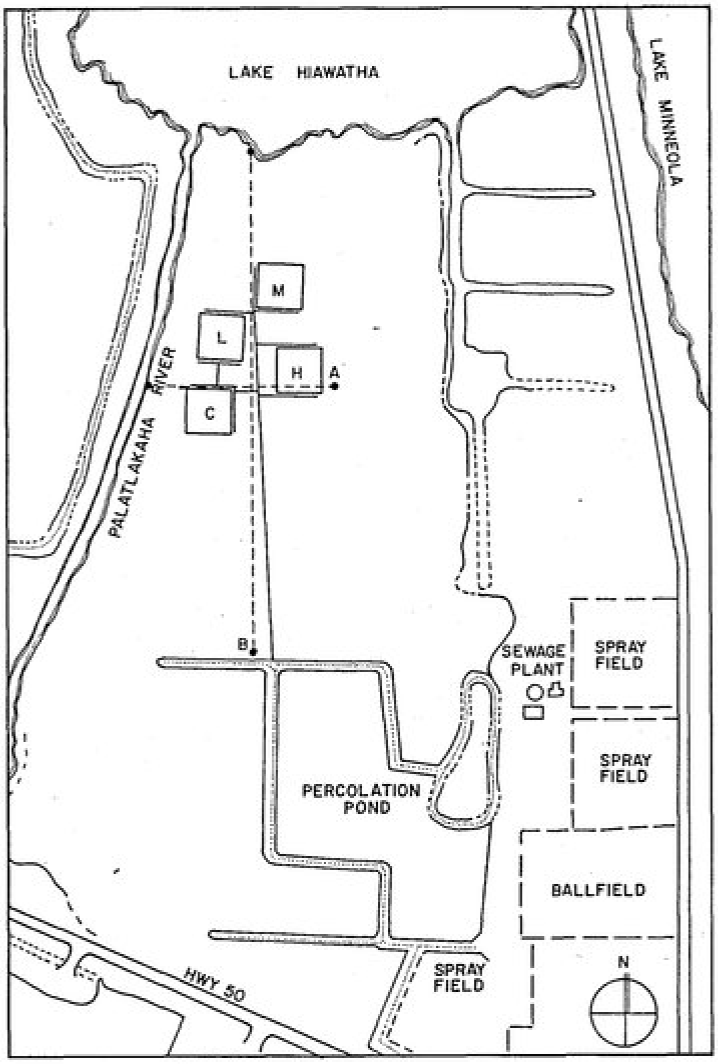



Figure 4. Map showing the four experimental plots in relation to Lake Hiawatha and Clermont's sewage treatment plant together with the orientation of the two water table transects (A and B). Plot C receives 4.4 cm/wk freshwater. Plots L, M, and H receive 1.5, 3.7, and 9.6 cm/wk treated wastewater respectively.

Application was initiated on May 1, 1977 and continued through June 1, 1979.

Figure 4 shows the location of the groundwater wells, surface water sampling stations, water level recorders, and the rain gauge. Wells consisted of 1.5 in. diameter PVC pipe with approximately 0.25 m of 1.0 in. diameter slotted PVC screening at the bottom. Shallow wells were placed to a well bottom depth of 0.5 m. Medium depth wells were placed to the bottom of the peat layer, which was approximately 1.5 m deep. Deep wells were installed in the sand layer, 2.5 m below the marsh surface.

A hydrographic survey indicated that the water table, when below the surface of the peat, sloped in a northwesterly direction (See Appendix). Medium depth wells (W21M, W22M, W23M, W24M) were placed in the northwest corner of each plot. Water samples from the wells were considered representative of renovated water leaving each of the respective plots. A medium depth well located several hundred feet to the north of the experimental plots (W2M) served as a natural background control well for water at the bottom of the peat layer. Deep wells placed along a transect between the percolation pond and the experimental plots (see Figs. 2 and 5) monitored possible contamination of the sand layer by the percolation pond and regional, upland seepage.

When the water table was above the surface of the peat, surface water samples were collected in the marsh. The location of each surface sampling point is shown in Fig. 5. As shown, sets of three samples each were collected along north-south transects beneath the application pipe and approximately 3 m from the western boundary within each plot. Another three-sample transect was located 10 m west of Plot H. Two sets of three samples each were collected near well W2M; samples within each of these two sets were taken within a 3 m radius.

A recording rain gauge (Belfort weighing rain gauge) and four eight-day water level recorders (Stevens Type F recorder) were positioned in the marsh as shown in Fig. 5. The recorders in Plots C and H operated continuously throughout the study. The recorder in the natural area of the marsh, to the north of the plots, was

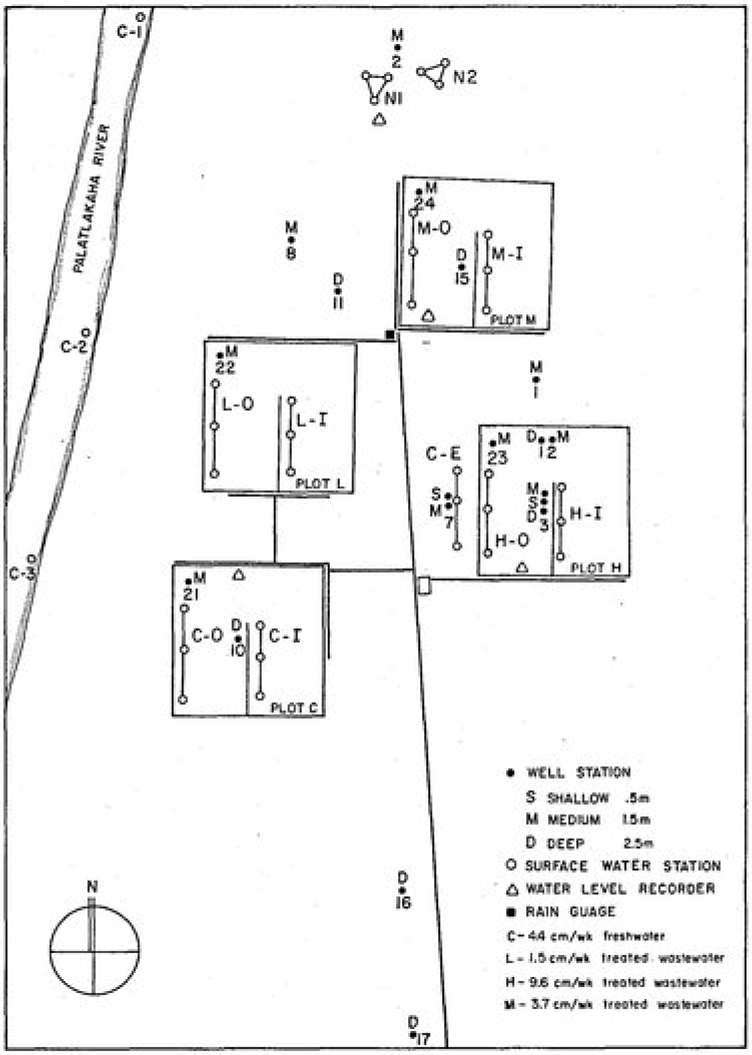



Figure 5. Detailed map of the experimental plots, the location and depths of the groundwater wells, and the location of the surface water sampling stations.

Well numbers hereafter are preceded by a W and followed by an M (indicating a medium-depth well) or a D (indicating a deep well).

operated from November 14, 1978, through the end of the study. The recorder in Plot M was operated from May 31, 1978, through the end of the study.

## Water Chemistry

Grab samples of applied treated wastewater were obtained periodically during each weekly application date. Each time a grab sample was obtained, a portion of the sample was added to a monthly composite frozen sample. Freezing prevented interconversion of the several nitrogen species prior to analysis. Another portion of each grab sample was added to a monthly composite unfrozen sample, used for phosphorus analyses.

Wells and surface water stations were sampled monthly, 24 hours after the end of the most recent treated wastewater application. Samples were collected in acid-washed plastic bottles. All wells were pumped out using a portable hand pump. After May 3, 1978, all medium and shallow depth wells were pumped dry and allowed to recharge before taking a sample. All deep wells were flushed by pumping out 3 liters of water prior to sampling.

Surface samples collected in the marsh were obtained using 150 ml acid-washed plastic bottles. Water was sampled immediately below the surface. The three 150 ml samples in each set described above were combined into one composite sample for that set. All samples were transported back to the lab and immediately refrigerated. Surface samples were filtered immediately upon return to the lab using a Reeve Angel 934 AH glass-fiber filter to remove any suspended algae or floating plants.

After September 1977, all samples were filtered through a Reeve Angel 934 AH glass-fiber filter prior to analysis. Measurements of pH were performed within three hours of sampling and again just prior to analysis using a Corning model 12 pH meter with a catalogue number 476022 electrode. Samples were analyzed for the following parameters: nitrate nitrogen, nitrite nitrogen, ammonia nitrogen, total Kjeldahl nitrogen, orthophosphate, and total phosphorus. Organic nitrogen values were obtained by subtracting the ammoniacal nitrogen value from the total Kjeldahl nitrogen value for each sample. Total nitrogen was taken as equal to nitrate plus nitrite plus total Kjeldahl nitrogen. The procedures used for these analyses followed those in APHA (1976). Analysis for ammoniacal nitrogen was performed using the automated colorimetric phenate method. Concentrations of nitrate nitrogen and nitrite nitrogen were determined using the automated cadmium reduction method. Total Kjeldahl nitrogen (free ammonium plus organic nitrogen) was measured using the automated phenate method. Concentrations of total phosphorus and orthophosphate were determined by the stannous chloride method described in APHA (1976).

## Hydrologic Measurements

One important goal of this study was to construct an input-output mass balance for nitrogen and phosphorus in the marsh plots. Such a mass balance requires estimates of hydrologic flows into and out of the system. The boundary between the peat and sand layers was chosen as the lower boundary of the marsh system; flux measurements for water were derived for the peat and plant community lying above this lower boundary. The significant fluxes into the system were applied treated wastewater or fresh water, rainfall, and inflowing water from the adjoining channel and lake. The significant outward fluxes were evapotranspired water and outflow to the adjoining channel and lake. Water flux is summarized in Fig. 6.

### Specific Yield

The changes in volume of water contained within the marsh plots over time were derived from water level records made by the continuous strip chart recorders placed inside the plots (see Fig. 5 for recorder locations). The volume change represented by a drop or rise in the water table is a function of the specific yield of the peat. Specific yield is the ratio of the volume of gravity-drainable

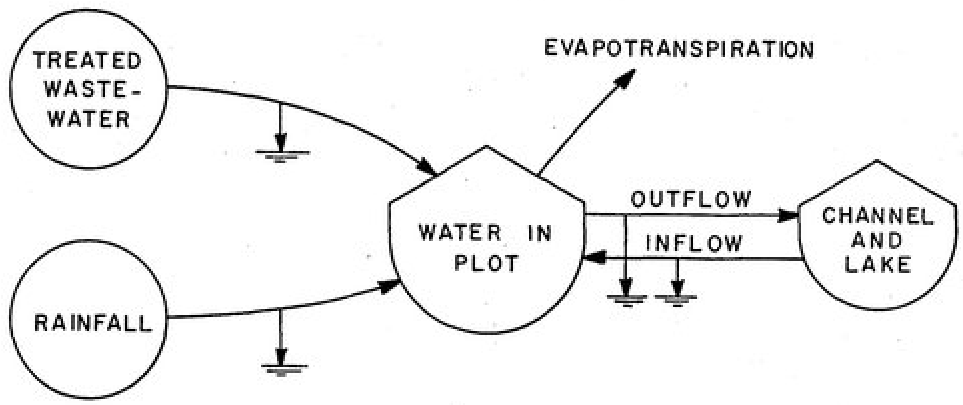



Figure 6. Summary of significant water flows into and out of each experimental plot in the marsh. See Appendix for a description of symbols.

water to the volume of soil that contains that water. Gravity-drainable water is that water free to move under the influence of hydrostatic pressures in the soil. The remainder of the water is held immobile by electrostatic forces within the soil complex, though it may evaporate under dry conditions. Specific yield may vary with depth in a soil. Specific yield was calculated in this study by measuring the rise in the water table elevation associated with brief (less than 1 hour) rainfall events of 1 cm or more.

The ratio of the depth of rainfall (R) to the increase in water table elevation (W) was considered representative of the specific yield (S) at the original depth of the water table (d) in the peat soil:

$$S_d = (R/W)_d$$

The calculated specific yield values ($S_d$) were found to be linearly correlated with their respective depths (d). Separate correlations were performed for the two water level recorders in Plots C and H. This produced a specific yield depth function both for Plot C and for Plot H. This function was applied to obtain specific yield values when the water table was less than 2.10 cm above the surface of the peat in Plot H, and less than 6.13 cm above the surface of the peat in Plot C. Above these heights, which represent the values at which the respective specific yield equations yielded a value of 1.0, actual specific yield in the plots was assumed to be 1.0.

Evapotranspiration

During those periods when the water table was below the surface of the peat in the marsh, the continuous water level records were utilized to obtain estimates of evapotranspiration (Heimberg 1976). The rise or fall of the water table observed during nighttime hours represented net flow of water to or from the marsh due to hydrostatic forces alone. The rate of change in water table elevation during each night was extrapolated up to noon of the following day and back to noon of the previous day. These noon elevations represented where the water table would be if no evapotranspiration had occurred over the whole 24-hour period centered on each successive night. The difference between the elevation extrapolated from the previous night and the elevation extrapolated from the following night represented the water loss due to evapotranspiration during that day. An illustration of this procedure is given in Fig. 7. The method was applied to the water level recorders in Plots C and H, respectively, for clear, rainless days. Rain obscured the water table drop. The observed elevation change due to evapotranspiration was multiplied by an appropriate specific yield value to get the actual volume of water lost by evapotranspiration that day. To obtain specific yield, the water table elevation observed in the plot at noon of that day was entered into the specific yield depth equation derived for that particular plot.

The daily evapotranspiration values calculated using the recorders in Plots C and H represented the average transpiration of the entire marsh area on that day, rather than evapotranspiration specific to each plot. This was due to the strong hydraulic connection between each plot and the surrounding area of the marsh. All the daily evapotranspiration estimates calculated from the recorders in Plots H and C during a particular month were averaged together to yield an evapotranspiration rate estimate (in cm/day) for that month. This method of empirically estimating evapotranspiration could only be applied during those months when the water table was either below or near the surface of the peat. When larger amounts of standing water were present in the marsh, the water surface was contiguous with the water flowing in the adjacent channel. Due to a sufficiently strong hydraulic connection, any evapotranspired water was almost immediately replenished by the adjacent waters of the channel. Thus, no drop attributable to daily evapotranspiration was seen in the water level records on days when the water table was high. After June 1978, the water table was too high to employ the method. Before this month, the method was consistently applied except for December 1977.

Empirical evapotranspiration estimates were thereby available for only the first 13 months of the study, May 1, 1977 - May 31, 1978. These monthly evapotranspiration rate averages

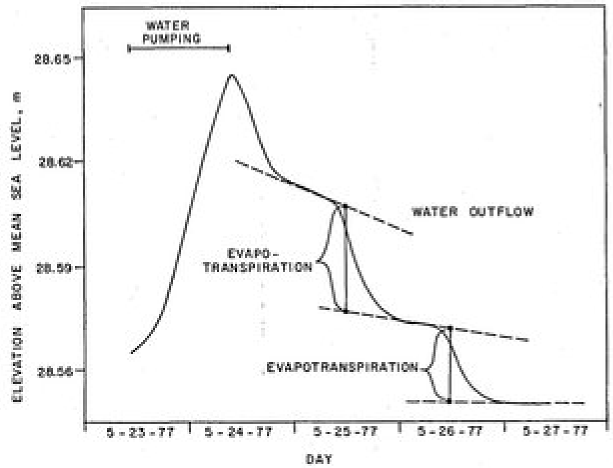



Figure 7. Four day record of the water table elevations in Plot C (4.4 cm/wk freshwater). The effect of evapotranspiration, water pumping, and water outflow on the water table is indicated.

($ET_{ave}$) were determined to be linearly related to the product of aboveground live biomass (B) and saturation deficit (SD) for each respective month:

$$ET_{ave} = (K_1 \times B \times SD) + K_0$$

This model of evapotranspiration is illustrated in Fig. 8. The coefficients $K_1$ and $K_0$ in the equation were determined by linear regression of the empirical estimates of evapotranspiration, derived from the water level records, to measured values of average natural marsh live biomass and meteorologic data obtained from regional summaries. For monthly aboveground live biomass the averages of values obtained for the outside regions of all four plots were used. This was done because no significant difference in aboveground live biomass ($\alpha$ = .01) was detected among the plots' outside areas during either the first or second years. (See live aboveground biomass section). Hence outside area averages were considered the best available estimate of natural marsh biomass for both years.

The model of evapotranspiration so derived from the first 13 months' worth of data was subsequently applied to get separate evapotranspiration estimates for Plot C, Plot H, and the natural area of the marsh during that 13-month period. Linear interpolation between successive biomass measurements was performed to obtain a biomass estimate for the middle of each month. Saturation deficit values for each month were derived using monthly means of daytime temperature and monthly means of the relative humidity occurring at 4:00 p.m., as given in NOAA (1977, 1978) for Orlando, Florida. Orlando is located 32 km (20 mi) to the west of Clermont. The Smithstonian Meterological Tables (1951) were employed to get the saturation moisture content of air at each mean monthly temperature. The average aboveground live biomass values for the entire area of Plot C were employed to get monthly evapotranspiration rates for Plot C. This same procedure was applied for Plot H. (See the plant community measurements section for details on how "entire-area" averages were calculated.) The average values for the outside regions of all

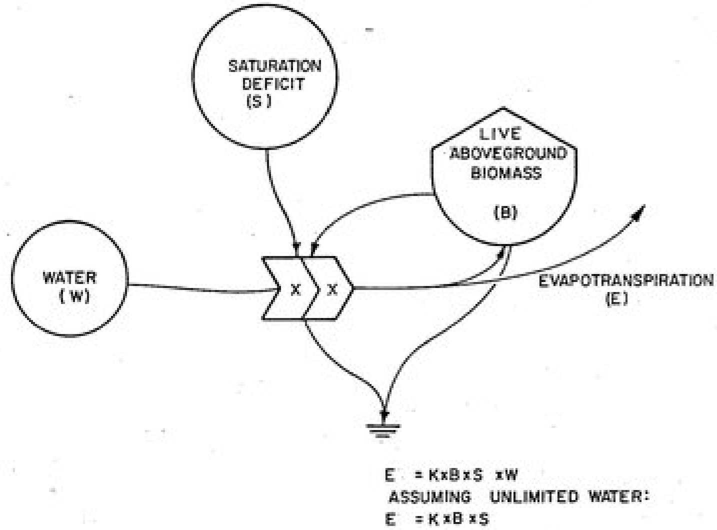



Figure 8. Evapotranspiration model and equation which describes the interaction. See Appendix for description of symbols.

plots were employed as representative of the natural marsh biomass. Linear interpolation between successive biomass values was applied as needed to get averages of biomass for each area for each month.

To estimate evapotranspiration during the second year for Plot C, Plot H, and the natural area, the same model equation was used as for the first year. This was necessary since no empirical estimates were available for evapotranspiration during the second year. Biomass values for the entire areas of Plots C and H and the average values for the outside regions of Plots C, M, and H were employed in the model equation for Plot C, Plot H, and the natural marsh area, respectively.

To derive model coefficents and to predict evapotranspiration from the model, the woody component of total live biomass in all areas was excluded from the total live biomass value obtained on sampling dates December 3, 1977, February 20, 1978, December 15, 1978, and February 18, 1979. This was done because negligible leaf area was observed on woody species during those sampling periods. The contribution of such species to marsh evapotranspiration was probably negligible for those periods. Eliminating the live wood component helped reduce the variance of biomass estimates within plots during those periods for use in the evapotranspiration model.

Outflow

Total monthly outflow from each of the plots was computed by the continuity equation:

$$O = W + R - ET - \Delta S$$

where O is the total outflow during the month, W is the volume of treated wastewater or fresh water applied that month, R is the volume of rainfall for that month, ET is the evapotranspiration as derived from the evapotranspiration model, and $\Delta S$ is the change in water storage in the plot between the beginning and end of the month.

## Distribution of Applied Water

Throughout the study there was a major concern for the effective distribution of applied treated wastewater throughout the plots. In particular, strong assurance was required that applied treated wastewater flowed past the northwest corner medium depth wells of Plots L, M, and H. Treated wastewater applied to the plots was known to contain higher levels of chloride than were present in the undisturbed areas of the marsh. Chloride is believed to be a passive, conservative element in biological systems; it is largely unused by microbes and plants and does not bind significantly to soil. Therefore, chloride in applied treated wastewater was used as a tracer in Plots L, M, and H.

A three-day experiment was conducted to investigate applied treated wastewater distribution in Plot H. A matrix of nine pairs of wells was placed within and just exterior to Plot H. Nine of the wells were installed at the bottom of the peat layer (medium depth wells), and nine were installed in the sand layer (deep wells) at the same locations as the medium wells (see Fig. 9). The wells were sampled via hand pumps on three consecutive days, just prior to, during, and 24 hours after a weekly pumping of treated wastewater. All medium depth wells were pumped dry and allowed to refill prior to sampling. Deep wells were flushed by pumping out 2 liters of water prior to sampling. A sample of applied treated wastewater was also collected. The experiment was conducted from March 27, 1978 to March 29, 1979, at which time the water table was 2.4 cm above the surface of the peat. All samples were analyzed for chloride according to APHA (1976) procedure.

Between February 9, 1978 and November 10, 1978, all water samples collected in the marsh, plus the treated wastewater samples collected each month, were analyzed for chloride content. This provided further information on the distribution of applied treated wastewater (under changing hydrologic regimes) throughout the plots in surface water and groundwater.

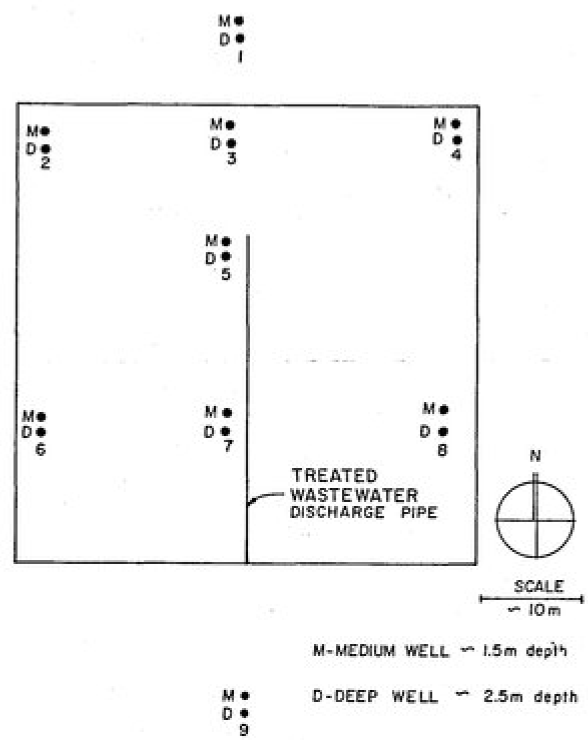



Figure 9. Map showing location of the 18 wells used in the chloride tracer study conducted in Plot H (9.6 cm/wk treated wastewater).

## Plant Community Measurements

### Biomass Measurement

In order to determine the effects of added nutrients on plant growth and plant nutrient storage, periodic harvest of aboveground live, aboveground dead, and belowground live plus dead biomass samples was carried out in the experimental plots. Harvested areas were defined using randomly placed 0.25 $m^2$ quadrats. At the outset of the study, it was observed that plants were more affected by applied treated wastewater in the area immediately surrounding the application pipe. To achieve smaller variance within sampled populations a stratified sampling procedure was used in each plot. Three randomly chosen 0.25 $m^2$ squares were harvested from a 462 $m^2$ area defined by a perimeter 7.21 m to either side of the application pipe, and 5.15 m from the northern tip of the pipe. This area was designated as the "inside"(I) region for the plot.

Three randomly chosen 0.25 $m^2$ squares were harvested from the rest of the plot, in the area further away from the application pipe. This area was designated as the "outside" (O) region for the plot. Areas within 2.1 m of each plot's fiberglass border were excluded from sampling to avoid any influence of the wall on measured growth. Areas within 1.0 m of the pipe were excluded as well to avoid any influence of this structure on measured growth.

In dealing with biomass data for the experimental sites average values were often desired for the entire area of a plot. Area-weighted averages were derived in such cases. The inside region comprised 25% of the total area of a plot, while the outside region comprised 75% of the total area. Thus, area-weighted averages for the entire plot were computed by :

$$B_{\text{entire area}} = (0.25 \times B_{\text{inside area}}) + (0.75 \times B_{\text{outside area}})$$

Aboveground live biomass was harvested by clipping plants with lawn shears down to the surface of the peat. Loose litter was gathered up by hand; any litter that had become incorporated into the peat-root mat was excluded. Beginning with the June 28, 1978 sample, a hand rake was employed in gathering litter to help dislodge litter enmeshed between plant stalks.

Belowground biomass, when harvested, was always taken from the same 0.25 $m^2$ areas harvested for aboveground biomass. Using a flat blade shovel, the 0.25 $m^2$ area of peat was removed to a depth of approximately 30 cm. This depth appeared to include nearly all of the live root biomass. On April 25, 1978, June 25, 1978, September 18, 1978, and February 17, 1979, all of the 0.25 $m^2$ areas harvested for aboveground biomass were harvested for belowground biomass as well.

All harvested above and belowground biomass was returned immediately to the laboratory where it was stored at 10°C. Aboveground plant material was separated into live and dead components as a preliminary step. Prior to the April 15, 1978 sample live aboveground biomass was separated by species and plant part. The separation categories were: 1. Sagittaria leaves; 2. Sagittaria stems; 3. Pontedaria leaves; 4. Pontedaria stems; 5. Panicium and other grasses; 6. Hibiscus leaves; 7. Hibiscus wood; 8. unidentifiable herbaceous material; and 9. unidentifiable woody material. Dead material was separated into: 1. dead herbaceous and 2. dead wood. Beginning with the April 15, 1978 harvest, the categories used for separation were : 1. live herbaceous excluding grass; 2. live grass; 3. live wood; 4. dead herbaceous; and 5. dead wood.

Collected root samples with associated peat were immediately transported back to the laboratory and stored at 10°C prior to washing. The samples were washed gently with tap water over a 1 mm nylon-mesh screen to remove the finely divided peat enmeshed in the roots. All root matrerial that did not pass through the screen was included in subsequent weight and nutrient measurements. For the June 25, 1978, September 18, 1978, and February 17, 1979 harvest, roots were given preliminary washing with municipal fresh water in the field. This preliminary washing removed the bulk of the weighty peat, thus simplifying transport. No separation of live from dead roots was attempted in this study, as there was no simple, clear-cut method available for distinguishing between these two categories. Thus, each root sample represents both live and dead roots, and includes all tubers, rootlets, and fine roots that did not pass through the 1mm mesh screen.

Both belowground and aboveground plant materials were dried in a forced draft oven for at least 72 hours until no further weight change was observed. Root samples generally required more drying time than aboveground materials due to the lower surface to volume ratio of tubers. Dried samples were weighed immediately upon removal from the drying oven to preclude weight gain via absorption of atmospheric moisture.

All aboveground categories and belowground stock for each quadrat were individually ground and subsequently analyzed for nitrogen and phosphorus content. Representative subsamples consisting of approximately 25% of the total root biomass from each sampled quadrat were ground, rather than grinding the entire root sample. All ground samples were stored in covered styrofoam cups prior to nutrient analysis.

Nitrogen analyses of biomass were performed using acid digestion followed by micro-Kjehldahl steam distillation (Jackson 1962, as modified by the School of Forestry, University of Florida, Gainesville). Three milliliters of concentrated sulfuric-acid were added to 0.1 g of sample and a catalyst consisting of 10 g $K_2SO_4$ and 0.3 g $CuSO_4$. The mixture was boiled in a 30 ml Kjehldahl flask until all the sample was dissolved by the acid. The contents of the flask were then brought up to 30 ml with distilled water. Two 5-ml subsamples, each amended with 4 ml of 40% KOH solution, were distilled on a Kjehldahl apparatus into boric acid indicator solution. The indicator solution was subsequently titrated with 0.01 N HCl. The total phosphorus concentration in the plant materials was analyzed by a procedure developed at the School of Forestry, University of Florida. A 1 g sample of dried plant material was ashed for 8 hours at 550°C. Three milliliters of concentrated hydrochloric acid (HCl) were added to the ashed sample, which was dried at 90°C. One milliliter of 6.25 N HCl was added to the dry sample and the volume of the sample was brought up to 25 ml with deionized water. This sample was filtered through a #42 Whatman filter. The concentration of phosphorus in the sample was determined by the ascorbic acid method as described in APHA (1976).

Net annual aboveground production was defined in this study as the peak aboveground live standing crop measured during the growing season. Estimates of aboveground production using peak live standing crop data will be lower than estimates made using other methods. This is so because plant mortality, herbivory, and respiration of plants use production before it can be measured (Odum and Odum 1976; Westlake 1963). Any tissues that develop after the peak harvest are likewise not included in this production estimate. If different species present in the marsh attain their peak biomass at different times during the year, the peak value for total biomass of all species combined will necessarily be lower than the sum of individual species' true peak values (Whigham et al. 1978). Despite these factors, the net production values derived from peak biomass provided a useful indicator of the effects of treated wastewater input on growth in the marsh and of the net amounts of nutrients removed by live vegetation growth during the year.

## Decomposition Measurements

During the first year of this study, three sets of approximately 50 litter bags, each containing freshly cut *Sagittaria* stems, *Sagittaria* leaves, and *Panicum* grass, respectively, were spread out in an undisturbed area of the marsh site. Five bags from each set were returned immediately on the date of set placement in the marsh. These were dried in a forced-draft oven at 70°C for 72 hours and weighed to obtain average percent moisture content. Subsequently, they were ground in a Wiley Mill and analyzed for average initial total phosphorus and nitrogen content, using the previously described methods for analysis of phosphorus and nitrogen in vegetation. Subsets of five bags each from the three sets were collected at intervals and returned to the lab. Initially, litter bags were collected every two weeks. After December 3, 1977, bags were collected less frequently. A summary of the sampling schedule for biomass, water, litter bags, and soil is given in Table 2. Returned bags were dried, weighed, and analyzed for total phosphorus and

Table 2. Summary of sampling dates for biomass, water samples, peat soil, litter bags, water level, and rainfall in the marsh.

| Type of Sample | Sample Location | | 4/25/77 | 6/10/77 | 7/8/77 | 8/11/77 | 9/15/77 | 12/3/77 | 2/20/78 | 4/15/78 | 6/25/78 | 9/18/78 | 12/15/78 | 2/17/79 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIOMASS | | | | | | | | | | | | | | |
| Aboveground | | | | | | | | | | | | | | |
| live and dead | Plot C | Inside | x | x | x | x | x | x | x | x | x | x | x | x |
| | | Outside | x | x | x | x | x | x | x | x | x | x | x | x |
| | Plot L | Inside | x | x | x | x | x | x | x | x | | | | |
| | | Outside | x | x | x | x | x | | | x | | | | |
| | Plot M | Inside | x | x | x | x | x | x | x | x | x | x | x | x |
| | | Outside | x | x | x | x | x | | | x | x | x | x | x |
| | Plot H | Inside | x | x | x | x | x | x | x | x | x | x | x | x |
| | | Outside | x | x | x | x | x | x | x | x | x | x | x | x |
| Belowground | Plot C | Inside | | | | x | | | x | x | x | x | | x |
| | | Outside | | | | | | | | x | x | x | | x |
| | Plot L | Inside | | | | x | | | | | | | | |
| | | Outside | | | | | | | | | | | | |
| | Plot M | Inside | | | | | | | | x | x | x | x | x |
| | | Outside | | | | | | | | x | x | x | x | x |
| | Plot H | Inside | | | | x | | | x | x | x | x | | x |
| | | Outside | | | | | | | | x | x | x | | x |

Table 2 Continued.

PEAT SOIL

| | | 3/16/78 | 9/11/78 | 2/17/79 |
|---|---|---|---|---|
| Plot C | Inside | x | x | x |
| | Outside | | x | x |
| Plot M | Inside | | x | x |
| | Outside | | x | x |
| Plot H | Inside | x | x | x |
| | Outside | | x | x |
| Natural Marsh | | x | x | x |

DECOMPOSITION

| Fresh-Cut Plant Litter Bags | 7/28/77 | 8/17/77 | 8/25/77 | 9/19/77 | 10/6/77 | 10/24/77 | 11/9/77 | 12/3/77 | 1/11/78 | 2/9/78 | 5/15/78 | 7/6/78 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Sagittaria* | | | | x | x | x | x | x | x | x | x | x |
| *Panicum* | x | x | x | x | x | x | x | x | | x | x | x |

| Dead Biomass Litter Bags | 7/16/78 | 8/3/78 | 8/18/78 | 10/12/78 | 1/26/79 | 4/16/79 |
|---|---|---|---|---|---|---|
| Plot C | x | x | x | x | x | x |
| Plot M | x | x | x | x | x | x |
| Plot H | x | x | x | x | x | x |

Table 2 Continued.

| WATER SAMPLES | 6/1/77 | 6/29/77 | 8/3/77 | 8/31/77 | 10/6/77 | 11/7/77 | 1/11/77 | 2/9/78 | 3/16/78 | 4/14/78 | 5/3/78 | 5/31/78 | 6/24/78 | 7/6/78 | 8/3/78 | 9/11/78 | 10/12/78 | 11/10/78 | 12/15/78 | 1/19/79 | 2/17/79 | 3/16/79 | 4/13/79 | 5/11/79 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Medium Depth Wells | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Deep Wells | | | | | | | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| River | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Surface Water | | | | | | | | | | | | | | | x | x | x | x | | x | x | x | x | x |

Treated Wastewater--------------------(Monthly Composites)---------------------

Table 2 Continued.

| WATER LEVEL RECORDERS | 5/1/77 | | 4/31/79 |
|---|---|---|---|
| Plot C | ├ | Continuously | ┤ |
| Plot H | ├ | | ┤ |
| Natural Marsh | ├ | | ┤ |

| RAIN GAUGE | 5/1/77 | | 12/27/78 | | 3/28/78 | 4/31/79 |
|---|---|---|---|---|---|---|
| | ├ | | ┼ | - - - | ┼ | ┤[a] |

[a]Daily measurements of rainfall collected by treatment plant personnel were utilized for the period 12/27/79 - 3/28/79.

nitrogen content as described above. Average dry weight remaining, average total phosphorus and nitrogen concentration, and average fraction of initial phosphorus and nitrogen content remaining were computed for each group for each collection date. Rates of decomposition were then derived from the weight loss values.

During most of the second year of this study, the water table in all areas of the marsh was above the surface of the peat. Rates of decomposition were expected to change for each species under wet vs. dry conditions and to vary between control and treated wastewater plots. In order to obtain an average rate of decomposition for litter derived from the whole range of species in each plot, subsamples of the aboveground dead material harvested on June 25, 1978, were placed in 1 mm mesh nylon litter bags. Six sets of six bags were derived from the litter harvested in each of Plots C, M, and H. Each six-bag set contained one litter subsample from each of the six 0.25 $m^2$ areas harvested on June 15, 1978. The bags were placed in the marsh on July 6, 1978. In each case bags were returned to the plot where their litter was harvested. One of the sets from each plot was returned immediately to the laboratory on July 6, 1978, and analyzed for average moisture content and total nitrogen content by the methods described above for the first year's decomposition study. Litter bag sets were subsequently collected on the dates shown in Table 2. Each sample was analyzed for dry weight loss, total nitrogen concentration, and fraction of original nitrogen content remaining.

## Peat Soil Measurements

Core samples of the peat substrate were taken from several locations in the marsh on the dates shown in Table 2. The cores were obtained using a post hole digger with blades 0.25 m long; the resultant core was 0.125 in. in diameter. Samples were obtained for the depth intervals: 0-25 cm, 25-50 cm, 50-75 cm, and 75-100 cm. After March 20, 1978, the 75-100 cm core was excluded at each sampling location. On March 20, 1978, cores were taken at four randomly chosen locations in the inside regions for each of Plots C, L, and H. Four coring stations were also randomly chosen from a natural area of the marsh, north of the experimental plots. On September 15, 1978, and February 17, 1979, during biomass harvest, cores were taken within 1 m of each of the 0.25 $m^2$ areas harvested. Subsamples of approximately 100 g each were obtained from the central portion of each of the cores for each depth interval. These were dried in a forced-draft oven at 70°C for at least 72 hours, until no further weight loss was observed. Dried peat samples were ground into fine powder using a mortar and pestle, and then sifted through a 1 mm mesh nylon screen. Rhizomes and large roots were trapped by the screen.

The powdered peat that passed through the screen was analyzed for total nitrogen content via acid digestion and subsequent micro-Kjehldahl steam distillation. As with the biomass samples, 0.1 g of powdered peat soil was used in the nitrogen analysis. The same analysis procedure was used for both peat and biomass samples. Peat in this marsh was found naturally to contain large quantities of nitrogen, which obscured any possible differences in nitrogen content due to treated wastewater application. Adsorption of ammonium onto the cation exhange sites of the peat was subsequently investigated. The full set of cores obtained on September 18, 1978, and February 17, 1979, was analyzed for exchangeable ammonium using the KCl extraction technique described in Black (1970). Two 100 g subsamples were obtained from each of the cores for each depth interval. One of the subsamples was dried in a forced-draft oven at 70°C for at least 72 hours, until no further weight loss was observed. Percent moisture content of the wet peat sample was calculated from the observed weight loss. The remaining 100 g subsample was shaken mechanically for one hour with 100 ml of 2 N KCl. Suspended peat was then filtered out using Whatman #4 (fast) filter paper. The filtrate was analyzed for ammonium using the MgO method of micro-Kjehladahl steam distillation (Black 1970). Filtrate was stored in plastic vials at 10°C prior to analysis. The 100 g subsamples from September 18, 1978 cores were frozen for storage, prior to KCl extraction. The 100 g subsamples from February 17, 1979 cores were stored at 10°C prior to KCl extraction.

The total phosphorus concentration of the peat soil was determined by the use of a procedure developed at the Soil Science Department, University of Florida. A 1 g sample of dried soil was dried at 550°C for eight hours. Five milliliters of concentrated HCl were added to the ashed sample. The samples were then dried at 70°C. The volume of the sample was brought up to 25 ml by the addition of 0.1 N HCl and vigorously shaken. The sample was filtered through a Whatman #42 filter. The phosphorus concentration of the sample was determined by the ascorbic method as described in APHA (1976).

The potential adsorption capacity of the peat soil for phosphorus was measured via adsorption isotherms. Two sets of isotherms were performed on soils representative of the natural marsh at varying depths (0-25, 25-50, 50-75 cm). The first isotherm was a time study to determine solution/soil equilibrium times. The second study entailed adsorption of varying concentrations of orthophosphate.

The soils were ground in a blender to create a relatively homogeneous sample. These samples were then autoclaved to reduce biological activity within the soil. After autoclaving, samples equivalent ot 0.4 g dry soil were placed in 250 ml Erlenmeyer flasks.

Phosphorus solutions of varying concentrations and composition were autoclaved to create sterile conditions. The concentrations for orthophosphate were 6.3, 12.6, 57.3, 87.3, and 110.7 mg/l. The pH of each solution was adjusted to 7.0 with 0.2 N NaOH. This pH was representative of the surface water pH in each of the experimental plots. After pH adjustment, the conductivity of each solution was adjusted to 670 mhos/cm with saturated KCl to eliminate any ionic strength inequalities caused by variation in phosphorus concentration and NaOH addition.

The isotherm tests were conducted by adding 40 ml of the prepared phosphorus solution to the wet soil previously placed in the 250 ml Erlenmeyer flasks. The soil-water samples were sealed with parafilm and shaken continuously for 48 hours, which had been determined to be the time necessary to reach equilibrium. After 48 hours, the samples were removed from the shaker table and filtered. Filtration took place in two steps; the sample was passed through a Whatman qualitative filter and the filtrate was subsequently passed through a 0.45 mm filter. The filtrates were evaluated for phosphorus by the ascorbic acid method outlined in standard methods (APHA 1976). The percent adsorption was determined by calculating the difference between initial phosphorus concentration and the 48- hour concentration.

## Nitrification and Denitrification Studies

### Preliminary Nitrification Studies in Marsh Water

Marsh surface water collected at Clermont was incubated at 25°C for 30 days. Half of the samples were amended with ammonium (as ammonium sulfate) to a concentration of 25 mg/l $NH_4$-N. Half of the amended and unamended samples were aerated after the air was humidified by pumping through 400 ml deionized water in a 500 ml Erlenmeyer flask to reduce evaporation. The humidified air was routed to the individual replications by a network of tygon tubing and syringe needles (Fig. 10). Twenty-five-milliliter samples were taken periodically for analysis. Dissolved oxygen was determined immediately, and phenyl mercuric acetate (PMA) was added to prevent microbial growth. The samples were stored at 4°C until pH, ammonium, and nitrate were determined.

The second study compared nitrification in water from Lake Alice on the University of Florida campus to standing water in the experimental marsh. Yellow-colored, dissolved organic compounds, commonly called tannins, were removed from half of the marsh water by adding powdered, activated charcoal, mixing for one hour, and filtering through a Whatman #42 filter paper. A suspension of nitrifiers was obtained by shaking a mixture containing 100 g of soil known to contain nitrifiers with 150 ml of water for one hour and allowing the soil to settle out. Ten-milliliter aliquots were used

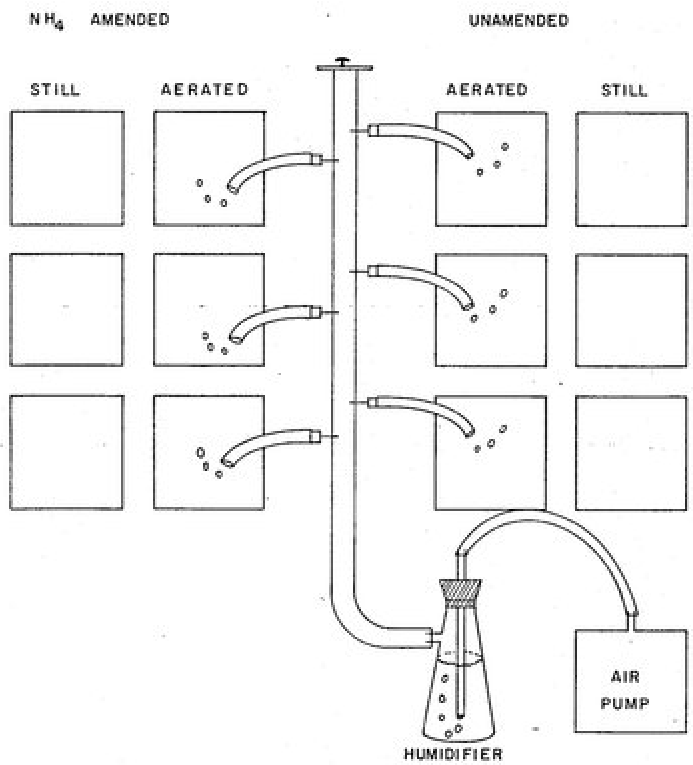



Figure 10. Experimental design for preliminary nitrification study.

as nitrifier inoculum for half of the filtered samples and for half of the unfiltered samples. Twenty-milliliter samples of each treatment group were stored and analyzed as described previously.

## Preliminary Denitrification Studies

Initial laboratory studies using test tubes of nitrate-amended solutions and marsh soil were designed to ascertain if denitrification was occurring. Solutions of calcium nitrate in deionized water and potassium nitrate were made in deionized water, in oxidation pond water from the Clermont sewage treatment plant, and in marsh water (standing water in the experimental marsh prior to the plots' existence). A 10-ml aliquot of each solution was gently added to a test tube (eight replications) containing 6.0 $\pm$ 0.2 g marsh soil obtained in bulk from the experimental marsh and incubated at 25°C for 11 days. The same design without the soil was also employed to see if denitrification would occur in the water alone. Sampling involved gently pouring off the solution and analyzing it for ammonium and nitrate.

## Nitrification and Denitrification Studies Using Soil:Water Columns

In order to better simulate actual marsh conditions, additional experiments for both nitrification and denitrification were conducted using intact soil:water columns. Intact soil columns, half with and half without *Sagittaria lancifolia* were obtained from randomly selected sites outside plots in the experimental marsh area. The columns were 70 X 10 cm diameter PVC pipes, which were sealed at the bottom with knockout test caps (Fig. 11) after obtainaing 45 cm of soil. Once in the lab, the columns were placed in wooden racks and allowed to stand for stabilization for two to four weeks while receiving only enough deionized water to keep the soil saturated. (Those containing plants were placed under a window.) Several days before a study began, those columns that required lime received 10.0 g

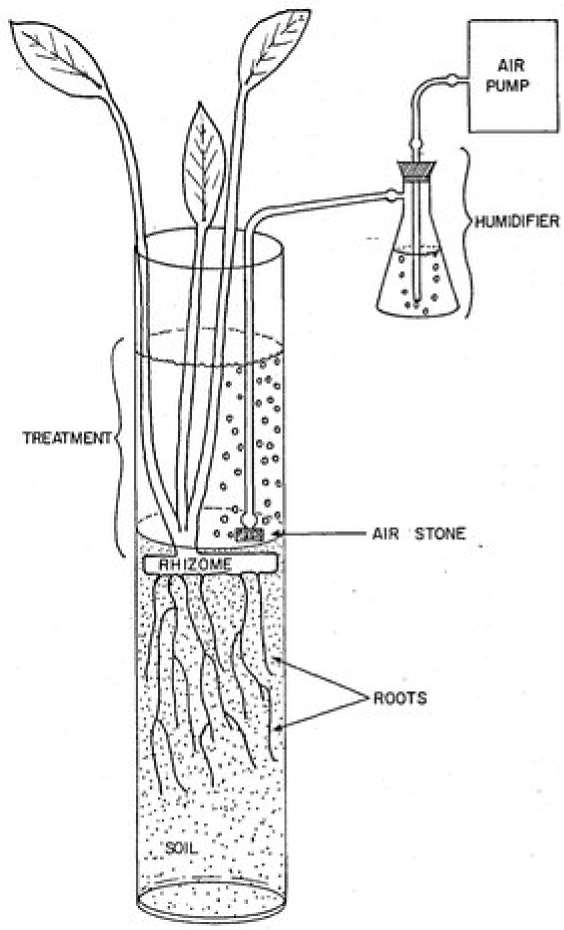



Figure 11. Experimental setup for nitrification and denitrification studies using soil:water columns.

powdered $CaCO_3$ applied to the surface of the soil. (The lime dosage was calculated using Yuan's (1974) double buffer method to bring the top 15 cm of soil to a pH of 7.0.) Treatments in the nitrification and denitrification studies were the same and involved the water level overlying the soil (Fig. 11). The following treatments (two replications) were used with and without plants: 1. Control; treated wastewater to 15 cm depth. 2. Water depth 15 cm; treated wastewater to a 15 cm depth. 3. Water depth 30 cm; treated wastewater to 30 cm depth. 4. Fluctuating water depth; treated wastewater to 30 cm depth, empty (0 cm) for two weeks, after which fresh treated wastewater reapplied to a 30 cm depth. 5. Water depth 15 cm, pH adjusted; treated wastewater to a 15 cm depth over 10 g $CaCO_3$.

In all cases, water lost by evaporation and transpiration was replaced two to four times weekly by adding deionized water to maintain the appropriate depth. Columns were aerated in a manner similar to that described for the previous nitrification study. About 15 ml of the overlying water in the columns was sampled at mid-depth, i.e., 7.5 and 15 cm, respectively. PMA was added and the sample was stored at 4°C until ammonium, nitrate, and pH were determined, usually within 24 hours.

In the nitrification study, ammonium was added to the treated wastewater obtained from the Clermont sewage treatment plant as ammonium sulfate. In the denitrification study, nitrate was added to the treated wastewater as potassium nitrate. Ammonium and nitrate were added to appropriate columns at least once more in column studies. The second and third application of the appropriate form of nitrogen was added as a more concentrated solution to the individual soil:-water columns without changing the treated wastewater except in the fluctuating columns.

Ammonia Volatilization Study

In order to quantify volatilization of ammonia during column studies, another soil:water column experiment was conducted.

Columns were packed with 30 cm of marsh soil (no plants), and 30 cm of ammonium-amended treated wastewater was added. The columns (four replications) were sealed at both ends with knock-out test caps and aquarium seal. Air going into the columns was bubbled through a boric acid indicator solution to scrub off any atmospheric ammonia and humidify the incoming air. Air leaving the columns was forced through a boric acid indicator (in test tubes) to trap any volatilized ammonia. Care was taken to prevent contact of tygon tubing with the boric acid indicator solution since it was found that the indicator solution reacted with tygon. The boric acid was titrated and replaced after 1, 3, 7, and 20 days and the column water was analyzed at the beginning and end of the study for pH, ammonium, and nitrate.

### In Situ Nitrification and Denitrification Studies

For the purpose of obtaining natural nitrification and denitrification rates an in situ study was conducted. Eno (1960) and more recent work by Struble (1977) found polyethylene bags acceptable for this type of study due to their permeability to gases, specifically oxygen and carbon dioxide, and impermeability to ions such as nitrate and ammonium. Polyethylene bags were filled with 100 g marsh soil and subjected to the following treatments:

1. Control, shallow; soil in bags buried in top 8 cm.
2. Control, deep, lime; soil plus lime in bags buried at 30 cm.
3. Nitrification, shallow; soil amended with ammonium in bags buried at 30-cm depth.
4. Nitrification, deep; soil amended with ammonium in bags buried at 30-cm depth.
5. Denitrification, shallow; soil amended with nitrate in bags buried in top 8 cm.
6. Denitrification, deep; soil amended with nitrate in bags buried at 30 cm depth.

7. Denitrification, deep, lime; soil amended with nitrate plus lime in bags buried at 30-cm depth.

Bags were flattened to maximize surface area and heat sealed. Nitrification bags were amended with ammonium as ammonium chloride to bring the final concentration to about 35 mg/l $NH_4$-N. The denitrification bags were similarly amended with nitrate as potassium nitrate. Control bags received no nitrogen. Lime used in all cases was 0.85 g of finely powdered calcium carbonate per bag, which was the amount extrapolated from an earlier application of Yuan's double buffer method and was intended to bring the pH of the soil to 7.0.

Bags were retrieved at selected intervals. Temperature, pH, and dissolved oxygen readings were taken at each site. After the bags were removed, the sample pH was determined, and the contents of each bag were extracted. The extractant was analyzed for ammonium and nitrate.

## Microbial Studies: Total, Nitrifying, and Denitrifying Populations

Shallow soil samples (top 8 cm) were taken in areas with dense root growth as well as areas with lesser root growth to determine qualitatively the rhizosphere effect on total bacteria, autotrophic nitrifier, heterotrophic nitrifier, and denitrifier populations. Similar analyses were done on rootless soil samples taken at about a 30 cm depth.

Microbial populations from the shallow and deep samples were further compared with populations existing after 27 days of in situ incubation in polyethylene bags. This was accomplished by compositing 2 g wet weight subsamples from each of the three replicates of the following treatments: 1. Control, shallow; total and denitrifiers; 2. Control, deep, lime; total and denitrifiers; 3. Denitrification, deep; total and denitrifiers; 4. Nitrification, shallow; total and heterotrophic and autotrophic nitrifiers. A single

2 g wet weight subsample of each treatment was used for each population type. A pooled 10 g wet weight sample was used in the natural marsh studies for plating, 2 g for each of five samples.

Since available carbon is often a factor in bacterial population growth, extractable carbohydrates were determined on duplicate samples from the natural marsh (shallow with roots and deep without) as well as from the polyethylene bag study (control, deep, lime).

Analytical Methods for Nitrification-Denitrification Study

Ammonium and nitrate plus nitrite determinations were done by steam distillation as described by Bremmer and Keeny (1965) and involved collection of the distillate in boric acid indicator and subsequent titration with $H_2SO_4$ solution. An Orion 701 or 401 meter was used to measure pH, in conjunction with a Fisher combination pH electrode. A YSDL model 54 Oxygen meter with a YSI model 5419 probe was used to determine concentrations of dissolved oxygen.

Ammonium, nitrite, and nitrate were extracted from the soil in the polyethlylene bags in the in situ study by transferring the 100 g of wet organic soil into a polyethylene sample bottle, adding 100 ml of 2 N KCl solution, shaking briefly and then allowing the suspension to stand for two hours. The mixture was shaken again before filtration through a Whatman #40 filter and finally stored with PMA at 4°C until inorganic nitrogen was determined (Bremner 1965).

The total soil bacterial population count was determined by a dilution plate technique with five plates per 10-fold dilution on a tryptone, glucose yeast agar (TGY) as developed by Ou et al. (1978). The dentrifier population was determined by the most probable number method of Focht and Joseph (1973) and the autotrophic nitrifiers by a similar method described by Alexander and Clark (1965). The heterotrophic nitrifier population was estimated by a method adapted from Tate (1977) and involved subculturing 100 randomly selected colonies from the total bacterial count plates into Difco nutrient broth amended with ammonium sulfate at 0.5% The available organic carbon was quantified as extractable carbohydrate in a two-step process. Five grams of oven-dry soil were treated with 50 ml of 0.02 M

$CaCl_2$ at 100°C for one hour and then filtered through a Whatman #40 filter paper (Stanford, 1975). One milliliter of the filtrate was used in the anthrone method of total carbohydrate determination (Loewus, 1952; Morris, 1948).

# RESULTS

## Characteristics of the Peat Soil

### Moisture Content, Organic Matter Content, and Bulk Density

The peat soil of the research marsh was approximately 1.5 m in depth. Down to a depth of 75 cm the peat was matted, coarsely fibrous, and generally brown in color. Below 75 cm the color of the soil turned brown-black and became more finely fibered. The darker color at the greater depth possibly indicated a higher degree of decomposition (Davis and Lucas 1959).

The moisture content, weight loss on ignition, and the bulk density of peat samples is shown in Table 3. The moisture content represents the amount of water bound in the soil complex. There was no large variation in the moisture content from the surface to the 1 m depth. Approximately 90% of the wet weight of the peat soil was water. The weight loss on ignition values are estimates of the total organic content of the soil. Successive increases in bulk density were found in the 0-25, 25-50, and 50-75 cm depth intervals. These results indicate that each cubic meter of the peat soil contains approximately 930 kg of water and 70 kg of dry matter.

Davis (1946) provided extensive physical data for Florida peats. The peat of the marsh research site generally had greater quantities of organic matter than most of the Florida peats. The average organic matter content of Everglades peat from Broward County was 74%. The average organic matter content of the upper 75 cm of the Clermont peat was 89%. This greater organic matter content may reflect the low sediment loading from the Palatlakaha River. Lower organic matter values are found in those peats underlying streams or lakes which contain a high sediment load. The moisture content of the Clermont peat was also generally higher

Table 3. Three physical characteristics of the peat soil: moisture content, weight loss on ignition, and bulk density. Samples were collected from an undisturbed portion of the research marsh. Mean ± Standard Error, sample size = n.

| Depth (cm) | Moisture Content, % | n | Weight Loss on Ignition | n | Bulk Density (g dry matter/cm$^3$) | n |
|---|---|---|---|---|---|---|
| November 1977 | | | | | | |
| 0-25 | 89.0±0.6 | 6 | 81.7±1.2 | 8 | 0.060±0.005 | 4 |
| 25-50 | 92.0±0.2 | 6 | 88.5±0.6 | 8 | 0.070±0.002 | 4 |
| 50-75 | 91.2±0.6 | 6 | 93.5±0.9 | 8 | 0.082±0.003 | 4 |
| 75-100 | 86.0±0.4 | 6 | 72.6±3.1 | 8 | --- | -- |
| July 1978 | | | | | | |
| 0-25 | 90.7 | 6 | 88.1 | 3 | --- | |
| 25-50 | 91.5 | 6 | 88.3 | 3 | --- | |
| 50-75 | 90.6 | 6 | 91.9 | 3 | --- | |

than that measured for other Florida peats. Both the organic matter content and the vegetation type are important in determining a peat's water-holding capacity.

Specific Yield

The specific yield of the peat soil was measured through paired observations of rainfall volume and water table rise (see Methods). Water level recorders in Plots C and H were utilized for these observations. A paired t-test indicated that the water table rise per rainfall event was significantly higher ($\alpha = .05$) in Plot C than in Plot H. The results for Plot C and Plot H were plotted separately (Figs. 12 and 13). A significant linear relationship was found between the water table rise per rainfall event and the depth to the water table in Plot C and Plot H. The water table rise per centimeter of rainfall increased as the depth to the water table increased. This result was consistent with the finding that the density of the soil increased with depth. With less pore space at the deeper soil depths a centimeter of water fills up a greater volume of the soil.

The inverse of the water table rise per rainfall event observations represents the specific yield of the soil. Table 4 shows representative specific yield values based upon the water table rise per rainfall event correlations. The specific yield decreases with depth. The major differences between the specific yield values for Plot C and Plot H were evident in the upper 10 cm of the soil profile. The specific yield at the top of the soil was not equal to 1.0 due to the presence of dead and live plant matter, which occupied volume and depressed the specific yield values until the water table was several centimeters above the ground surface. The lower specific yields found near the surface in Plot H as compared to Plot C possibly were a consequence of the larger aboveground and belowground biomass of Plot H.

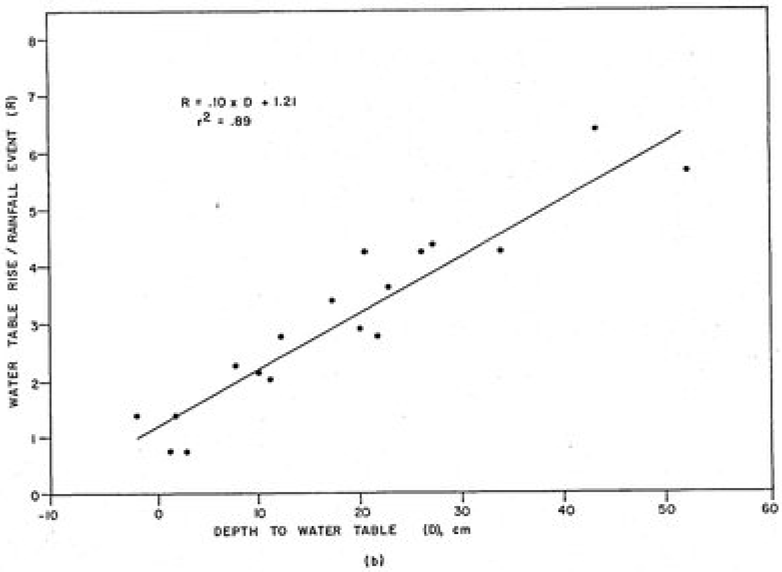
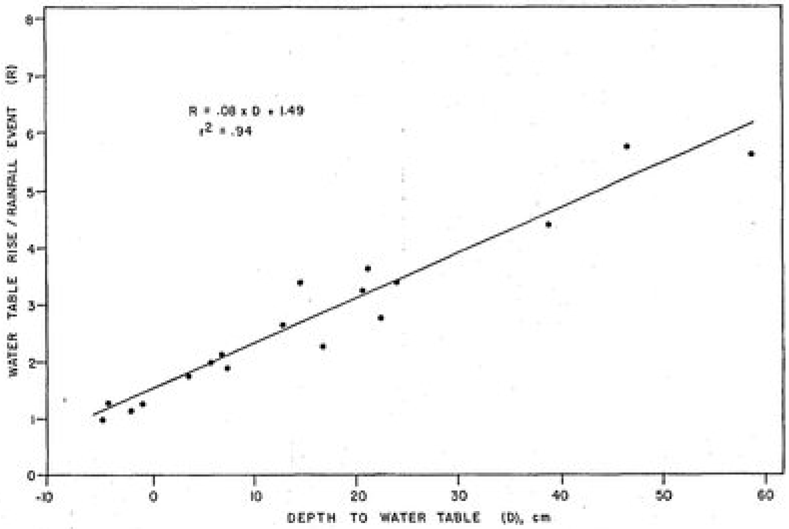



Figure 12. Ratio of water table rise to rainfall event versus the depth to the water table in Plot C (4.4 cm/wk freshwater). The straight line represents the least squares regression equation.




(a)

Figure 13. Ratio of water table rise to rainfall event versus the depth to the water table in Plot H (9.6 cm/wk treated wastewater). The straight line represents the least squares regression equation.

Table 4. Representative specific yield values for Plots C and H. Values were calculated from water table rise per rainfall event and depth to water table observations.

| Water Table Depth (cm) | Specific Yield | |
|---|---|---|
| | Plot C | Plot H |
| 0 | 0.83 | 0.67 |
| 10 | 0.45 | 0.44 |
| 20 | 0.31 | 0.32 |
| 30 | 0.24 | 0.26 |
| 40 | 0.19 | 0.21 |
| 50 | 0.16 | 0.18 |

## Hydrologic Considerations

### Seasonal Water Table Fluctuations and Hydrologic Inputs

Water table elevations. The water table elevations from the recorders in Plots C and H are presented in Fig. 14. Except for a short period in August and September the water table was below the peat surface for the entire growing season of the first year. During the winter months of the first year, the water table rose to the surface or slightly above the surface, and remained near or above the surface of the peat from mid-July of the second year through the end of the study. The water level record of Plot C tracked very closely to the water level record of Plot H over the entire study. There are no major differences between the seasonal water table elevations in Plot C and Plot H.

Long-term hydrographic records of Lake Minnehaha are shown in Figs. 15 and 16. This lake is located near the experiment site (see Fig. 2). The stage-duration curve for Lake Minnehaha (Fig. 15) was computed from average daily water levels. The curve indicates that lake levels near the experimental marsh were above the present average peat surface roughly 82% of the time between June 1945 and September 1964. Thus "dry" conditions prevailed 18% of the time, assuming no appreciable changes in peat depth over that time interval. Average yearly water levels for Lake Minnehaha (USGS 1979) are shown in Fig. 16 for 1946-1978. It should be noted that after 1959, a dam regulated outflow from the chain of lakes, including Lake Minnehaha. Apparently the water surface was generally above the experimental marsh peat surface both prior to and after the installation of the dam. Thus "wet" conditions have prevaled more often than "dry" condititons in the marsh over the past thirty years.

Hydrologic inputs. Rainfall data, including historical averages for north central Florida, are shown in Table 5. Rainfall was 58% lower than the historical averages during the interval February to July 1977. The water table of the marsh was belowground during this interval. The rainfall was also low during September and October of 1977, which was reflected in the marsh water table record.

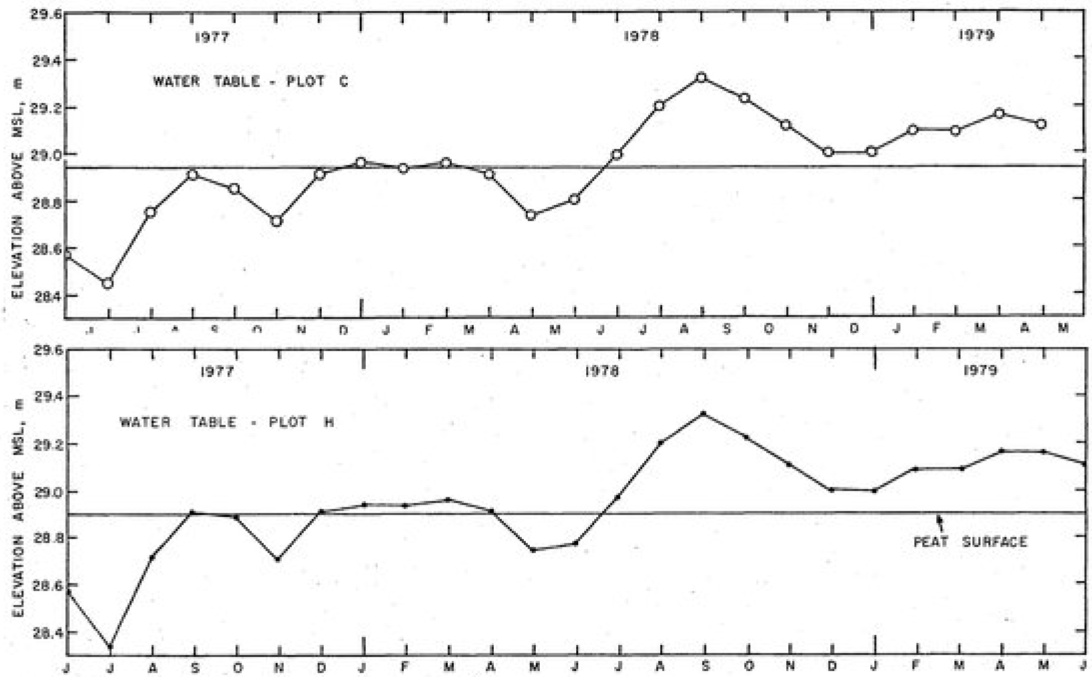



Figure 14. Seasonal water table elevations in Plot H (9.6 cm/wk of treated wastewater) and Plot C (4.4 cm/wk of fresh water).

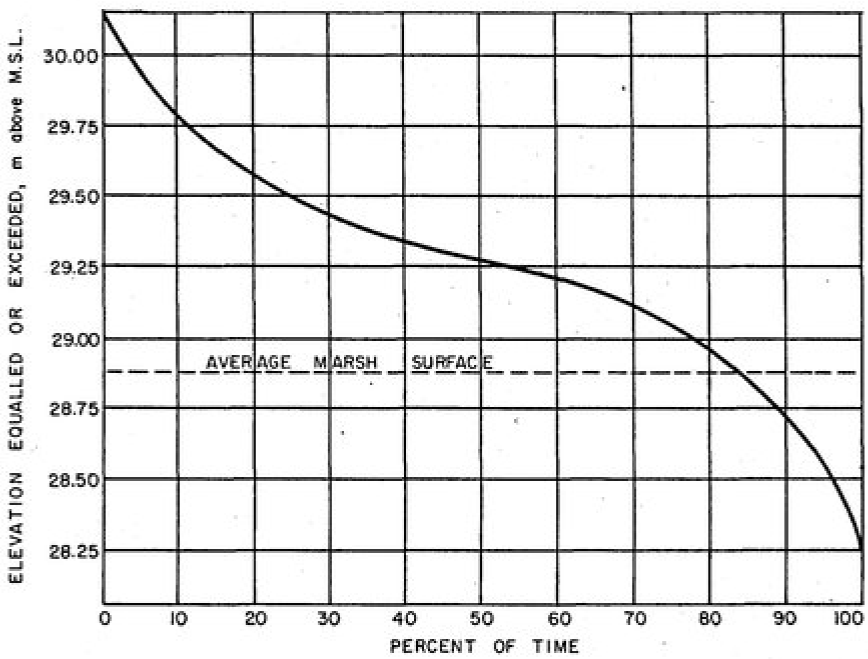



Figure 15. Stage-duration curve, Lake Minnehaha, Lake County, June 1945 - September 1964. (Adapted from Bishop 1967).

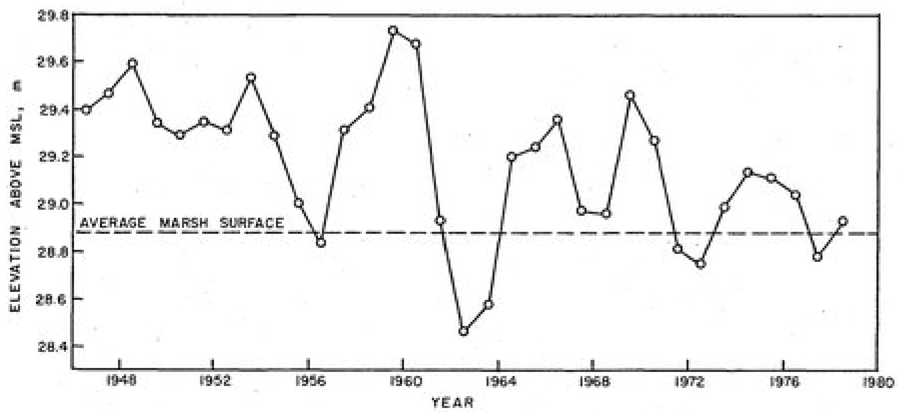



Figure 16. Mean annual water level elevations in Lake Minnehaha, 1946-1978. Data obtained from USGS (1979).

Table 5. Historical monthly rainfall averages for north central Florida, observed rainfall in north central Florida, and observed rainfall in the research marsh. All values are expressed as cm $H_2O$.

| Month | Historical Average[a] (cm) | North Central Florida Observed[a] (cm) | Research Marsh Observed (cm) |
|---|---|---|---|
| January 1977 | 6.1 | 9.1 | 7.5[a] |
| February | 7.8 | 7.2 | 5.2[a] |
| March | 9.9 | 3.7 | 4.2[a] |
| April | 7.0 | 1.1 | 0.4[a] |
| May | 8.0 | 4.6 | 2.1 |
| June | 17.9 | 7.6 | 5.5 |
| July | 20.8 | 17.4 | 21.8 |
| August | 19.5 | 22.4 | 16.2 |
| September | 18.4 | 16.6 | 13.9 |
| October | 10.7 | 2.9 | 2.8 |
| November | 4.6 | 7.7 | 8.2 |
| December | 5.6 | 10.1 | 10.4 |
| January 1978 | 6.1 | 9.7 | 7.2 |
| February | 7.8 | 14.9 | 14.9 |
| March | 9.9 | 8.9 | 6.6 |
| April | 7.0 | 3.2 | 1.8 |
| May | 8.0 | 10.0 | 14.4 |
| June | 17.9 | 18.6 | 27.6 |
| July | 20.8 | 24.8 | 32.8 |
| August | 19.5 | 14.5 | 6.5 |
| September | 18.4 | 8.6 | 7.9 |
| October | 10.7 | 4.8 | 4.6 |
| November | 4.6 | 0.3 | 0.0 |
| December | 5.6 | 10.9 | 8.9 |
| January 1979 | 6.1 | 16.1 | 17.8 |
| February | 7.8 | 5.6 | 5.0 |
| March | 9.9 | 8.7 | 10.0 |
| April | 7.0 | | 13.3 |
| | 303.4 | | 277.5 |

[a] Reference, NOAA 1977, 1978, 1979. The North Central Florida values are an average of 14 stations in this region.

During the winter months of 1977-1978, with lower evapotranspiration and above average rainfall, the marsh water table was near the surface. The rainfall observed directly in the research marsh was typical of the north central Florida observations during the first year of the study.

Rainfall in the marsh was below average in March and April of 1978 and the water table dropped at this time. In June and July of 1978 rainfall was considerably higher than either the historical average or the concurrent north central Florida average. During this time the surface water rose to a height of approximately 0.4 m above the surface of the peat in the marsh. The marsh water surface became contiguous with the channel and lake surface water during this period. For August through November 1978, rainfall was below the historical average. The water table was observed to fall between September and December 1978 to a level near the surface of the peat. Above average rainfall for December 1978 through April 1979 caused the water table to rise once more, to a height of approximately 0.2 m above the peat at the termination of the study.

Rainfall and water table elevations were below normal in 1977, with the period May 1977 - April 1978 being designated as a "dry year" for this study. In 1978, rainfall and water table elevations were average compared with the long-term mean. The period May 1978 - April 1979 was designated as a "wet year" for comparitive purposes, since the water table was above the peat surface after June 1978.

The input of treated wastewater or fresh water to the experimental plots is shown in Table 6. Wastewater or fresh water inputs represented 385% and 175% of rainfall input to Plots H and C, respectively, during the period May 1, 1977 - April 31, 1979. Treated wastewater monitoring for Plots L and M was discontinued after September 1978.

## Evapotranspiration

Evapotranspiration from the research marsh. Empirical estimates of evapotranspiration were calculated for the first 13 months of the study using the diurnal water table fluctuations as described

Table 6. Quantities of treated wastewater and fresh water applied to experimental plots. All values expressed as cm $H_2O$.

| Month | Plots | | | |
|---|---|---|---|---|
| | C (cm fresh water) | L (cm wastewater) | M (cm wastewater) | H (cm wastewater) |
| May 1977 | 15.3 | 5.1 | 15.3 | 41.5 |
| June | 19.8 | 6.4 | 19.3 | 50.9 |
| July | 15.5 | 5.2 | 15.2 | 40.7 |
| August | 15.8 | 5.1 | 15.2 | 49.6 |
| September | 19.1 | 6.4 | 19.3 | 51.1 |
| October | 18.8 | 5.1 | 15.0 | 42.2 |
| November | 14.9 | 5.1 | 15.2 | 41.2 |
| December | 19.2 | 6.4 | 19.3 | 50.9 |
| January 1978 | 15.2 | 5.1 | 15.2 | 40.7 |
| February | 15.2 | 5.1 | 15.2 | 40.7 |
| March | 15.4 | 5.1 | 15.4 | 21.8 |
| April | 15.4 | 5.1 | 15.4 | 41.4 |
| May | 21.7 | 13.6 | 25.0 | 46.2 |
| June | 16.0 | 15.1 | 5.0 | 45.9 |
| July | 15.4 | 5.1 | 15.4 | 41.1 |
| August | 19.3 | 6.4 | 19.3 | 51.3 |
| September | 15.4 | 5.1 | 15.4 | 41.1 |
| October | 15.4 | --- | --- | 41.1 |
| November | 15.4 | --- | --- | 41.1 |
| December | 15.4 | --- | --- | 41.1 |
| January 1979 | 15.4 | --- | --- | 41.1 |
| February | 34.9 | --- | --- | 32.7 |
| March | 34.9 | --- | --- | 32.7 |
| April | 34.9 | --- | --- | 32.7 |

in the Methods section. A paired t-test showed no significant difference between the evapotranspiration rates calculated from each recorder located in Plots C and H. Table 7 presents the average monthly evapotranspiration values determined from May 1, 1977 - April 31, 1978, and includes the combined data from both recorders. The range of daily values found during each month is also shown.

Evapotranspiration was approximately 0.5 cm/d throughout the growing season of 1977 (May through September). During late fall, evapotranspiration began to decline and reached the lowest measured values during January and February of 1978. Values rose through the spring of 1978. An evapotranspiration rate of 1.0 cm/day was the largest single observed value, and this value was recorded during September 1977.

Model of evapotranspiration. A model of evapotranspiration based on live aboveground biomass and saturation deficit was constructed (see Methods). Figure 17 shows the plotted values of evapotranspiration versus the biomass-saturation deficit product for the first 13 months of the study. The months that exhibited the highest rates of evapotranspiration cluster in the upper right-hand corner of the figure. Both the saturation deficit and biomass were high during June, July, August, and September of 1977, and during May 1978. In the lower left hand corner cluster those months with low live biomass and low saturation deficits. Figure 17 also presents the linear correlation ($r^2 = 0.79$) between observed evapotranspiration and the biomass-saturation deficit product for the first 13 months of the study.

A summary of measured evapotranspiration of the natural marsh area, saturation deficit, estimated aboveground live biomass of the natural marsh area, and theoretical evapotranspiration derived from the model, is shown in Table 8. As discussed in the Methods section, the model derived from the first year's data was applied to biomass and saturation deficit data over the entire two-year study period. Respective data for live biomass in Plots C and H over the entire two-year period were applied to get separate theoretical

Table 7. Empirical estimates of monthly evapotranspiration rates in the marsh. Values are derived from the combined records of the water level recorders in Plots C and H. Values expressed as cm/day.

| Month | Mean Evapotranspiration Rate (cm/day) | Range | n |
|---|---|---|---|
| May 1977 | 0.42 | 0.31-0.69 | 16 |
| June | 0.49 | 0.30-0.76 | 28 |
| July | 0.58 | 0.39-0.95 | 19 |
| August | 0.48 | 0.19-0.78 | 18 |
| September | 0.52 | 0.21-1.00 | 22 |
| October | 0.36 | 0.14-0.56 | 26 |
| November | 0.22 | 0.10-0.33 | 15 |
| December | a | --- | -- |
| January 1978 | 0.11 | 0.07-0.18 | 5 |
| February | 0.12 | 0.05-0.18 | 9 |
| March | 0.26 | 0.09-0.57 | 18 |
| April | 0.45 | 0.17-0.69 | 36 |
| May | 0.65 | 0.42-0.84 | 16 |

[a]No recorded evapotranspiration.

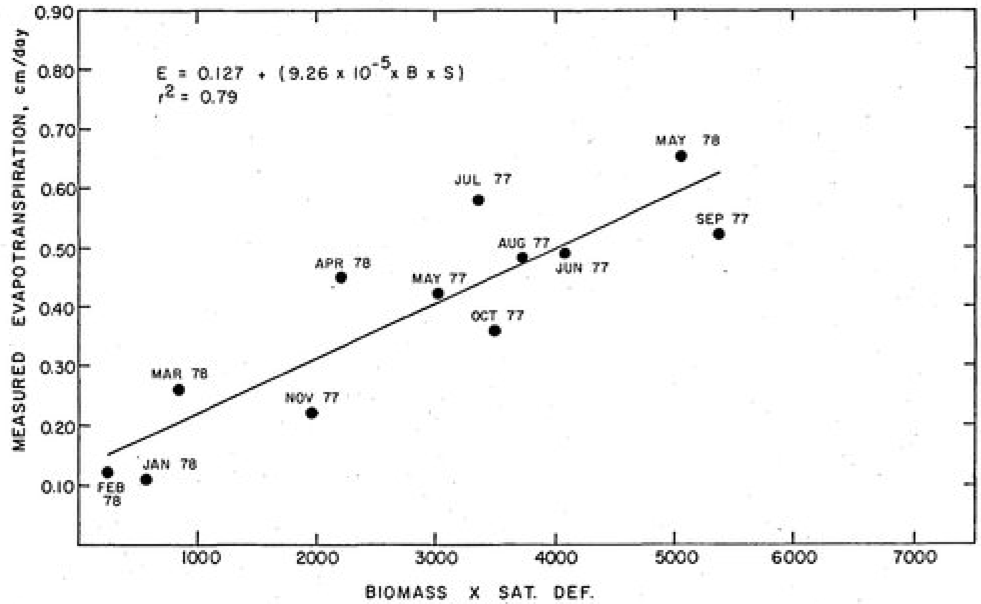



Figure 17. Average monthly evapotranspiration versus the product of average live aboveground biomass and average saturation deficit. The straight line represents the least squares linear regression equation.

Table 8. Estimates of average daily evapotranspiration. A model of the evapotranspiration process as a function of live above-ground biomass and saturation deficit was used to estimate the evapotranspiration. Values are expressed as g dry weight/$m^2$, g $H_2O/m^3$, and cm/d. Values are monthly means.

| Month | Live Above-ground Biomass ($g/m^2$) | Saturation Deficit ($g/m^3$) | Estimated Evapotranspiration[a] (cm/d) | Observed Evapotranspiration[b] (cm/d) | n |
|---|---|---|---|---|---|
| May 1977 | 277 | 10.9 | 0.41 | 0.42 | 16 |
| June | 310 | 13.1 | 0.51 | 0.49 | 28 |
| July | 346 | 10.0 | 0.44 | 0.58 | 19 |
| August | 433 | 8.5 | 0.47 | 0.48 | 18 |
| September | 443 | 11.5 | 0.62 | 0.52 | 22 |
| October | 344 | 9.9 | 0.45 | 0.36 | 26 |
| November | 241 | 8.2 | 0.31 | 0.22 | 15 |
| December | 156 | 5.8 | 0.21 | --- | --- |
| January 1978 | 144 | 5.6 | 0.18 | 0.11 | 5 |
| February | 77 | 5.1 | 0.15 | 0.12 | 9 |
| March | 100 | 8.4 | 0.20 | 0.26 | 18 |
| April | 182 | 12.1 | 0.33 | 0.45 | 36 |
| May | 400 | 12.6 | 0.59 | 0.65 | 16 |
| June | 626 | 12.2 | 0.83 | --- | -- |
| July | 728 | 9.6 | 0.77 | --- | -- |
| August | 773 | 10.1 | 0.85 | --- | -- |
| September | 819 | 10.9 | 0.95 | --- | -- |
| October | 675 | 8.9 | 0.68 | --- | -- |
| November | 505 | 9.3 | 0.56 | --- | -- |
| December | 340 | 6.5 | 0.33 | --- | -- |
| January 1979 | 256 | 5.5 | 0.26 | --- | -- |
| February | 171 | 5.8 | 0.22 | --- | -- |
| March | 240 | 8.3 | 0.31 | --- | -- |
| April | 329 | 12.1 | 0.50 | --- | -- |

[a] The following equation was used to estimate evapotranspiration (E):

$$E = 0.127 + [9.26 \times 10^{-5} \times (B \times S)]$$

(B×S) is the product of mean biomass and average saturation deficit for a given month.

[b] From Table 7.

estimates of evapotranspiration in Plots C and H for the entire two-year period. Biomass and theoretical evapotranspiration estimates for Plots C and H are shown in Table 9. The use of the same model for both years was necessary since no empirical measurement of evapotranspiration using water level records was possible during the second year, when the water table was above the peat surface. Several factors affected the accuracy of the theoretical evapotranspiration estimate for the first year: 1. The empirical rate estimates from which the theoretical model was derived were made using water level records for clear, rainless days. Lower evapotranspiration would be expected on rainy days, which experience a lower saturation deficit and less solar insolation than clear days. 2. Variables such as wind speed, solar insolation, and depth of peat above the water table probably affected evapotranspiration during the first year. These factors were not included in the theoretical model.

During the second year, water levels were higher than during the first year. Thus: 1. evaporation from a free water surface occurred; 2. transpiration by duckweed, which grew in surface water, contributed to water loss; 3. previously aerated roots were flooded, possibly altering water loss by transpiration through rooted plants; and, 4. the plots' outside region biomass, which was utilized in the model to get theoretical evapotranspiration in the natural marsh during both years, was probably influenced by applied water to a greater degree during the second year than during the first year of the study.

It is not possible to conclude whether actual evapotranspiration during the second year was higher or lower than the value predicted by the model for that year. If the actual evapotranspiration was slightly higher than the predicted values during any time period, then outflows of water with associated nitrogen and phosphorus were slightly lower during that time period.

## Water Storage and the Distribution of the Applied Treated Wastewater

Water storage. The results of the water storage calculations are presented in Table 10. A comparison of Plot H and Plot C shows

Table 9. Estimated evapotransporation in Plot C (4.4 cm/wk freshwater) and Plot H ( 9.6 cm/wk effluent). The estimates are based upon a biomass-saturation deficit-evapotranspiration correlation analysis. Values are monthly means expressed as g dry weight/$m^2$ and cm $H_2O$/d.

| Month | Plot C | | Plot H | |
|---|---|---|---|---|
| | Aboveground Live Biomass ($g/m^2$) | Evapotranspiration (cm/d) | Aboveground Live Biomass ($g/m^2$) | Evapotranspiration (cm/d) |
| May 1977 | 285 | 0.41 | 290 | 0.42 |
| June | 339 | 0.54 | 380 | 0.59 |
| July | 339 | 0.44 | 576 | 0.66 |
| August | 504 | 0.52 | 649 | 0.64 |
| September | 576 | 0.74 | 777 | 0.95 |
| October | 430 | 0.52 | 599 | 0.68 |
| November | 279 | 0.34 | 415 | 0.44 |
| December | 167 | 0.22 | 269 | 0.27 |
| January 1978 | 104 | 0.18 | 169 | 0.21 |
| February | 42 | 0.15 | 68 | 0.16 |
| March | 94 | 0.20 | 129 | 0.23 |
| April | 177 | 0.32 | 233 | 0.39 |
| May | 374 | 0.56 | 495 | 0.71 |
| June | 577 | 0.78 | 766 | 0.99 |
| July | 701 | 0.75 | 788 | 0.83 |
| August | 789 | 0.78 | 687 | 0.77 |
| September | 878 | 1.01 | 586 | 0.72 |
| October | 714 | 0.72 | 510 | 0.55 |
| November | 515 | 0.57 | 433 | 0.50 |
| December | 322 | 0.32 | 358 | 0.34 |
| January 1979 | 356 | 0.26 | 281 | 0.27 |
| February | 190 | 0.23 | 203 | 0.24 |
| March | 241 | 0.31 | 263 | 0.33 |
| April | 307 | 0.47 | 341 | 0.51 |

Table 10. Monthly changes in water storage in the peat of Plot H (9.6 cm/wk treated wastewater) and Plot C (4.4 cm/wk fresh water). Values are expressed as cm $H_2O$.

| Month | Plot H | | | Plot C | | |
|---|---|---|---|---|---|---|
| | Water Table Change[a] (cm) | Specific Yield[b] | Change in Water Storage[c] (cm) | Water Table Change[a] (cm) | Specific Yield[b] | Change in Water Storage[c] (cm) |
| May 1977 | -7.3 | 0.24 | -1.7 | -6.0 | 0.21 | -1.2 |
| June | -18.6 | 0.18 | -3.4 | -13.7 | 0.17 | -2.3 |
| July | +41.5 | 0.27 | +11.4 | +31.4 | 0.26 | +8.3 |
| August | +14.4 | 0.64 | +9.2 | +14.7 | 0.59 | +8.5 |
| September | -4.9 | 0.70 | -3.4 | -4.9 | 0.63 | -3.1 |
| October | -10.7 | 0.36 | -3.8 | -13.4 | 0.28 | -3.8 |
| November | +21.4 | 0.37 | +7.9 | +21.4 | 0.28 | +6.0 |
| December | +3.1 | 0.78 | +2.4 | +4.9 | 0.79 | +3.8 |
| January 1978 | -3.4 | 0.83 | -2.8 | -6.4 | 0.82 | -5.2 |
| February | +3.4 | 0.89 | +3.0 | +4.0 | 0.99 | +3.9 |
| March | -4.9 | 0.77 | -3.8 | -5.2 | 0.79 | -4.1 |
| April | -16.5 | 0.47 | -7.8 | -17.7 | 0.42 | -7.4 |
| May | +2.7 | 0.37 | +1.0 | +7.0 | 0.34 | +2.4 |
| June | +20.1 | 0.55[d] | +11.0 | +18.9 | 0.62[e] | +11.8 |
| July | +22.3 | 1.00 | +22.3 | +21.0 | 1.00 | +21.0 |
| August | +11.9 | 1.00 | +11.9 | +11.9 | 1.00 | +11.9 |
| September | -9.1 | 1.00 | -9.1 | -9.1 | 1.00 | -9.1 |
| October | -11.9 | 1.00 | +11.9 | -11.9 | 1.00 | -11.9 |
| November | -10.1 | 1.00 | -10.1 | -10.4 | 1.00 | -10.4 |
| December | -0.9 | 1.00 | -0.9 | -0.6 | 1.00 | -0.6 |
| January 1979 | +9.8 | 1.00 | +9.8 | +9.5 | 1.00 | +9.5 |
| February | 0.0 | 1.00 | 0.0 | 0.0 | 1.00 | 0.0 |
| March | +7.0 | 1.00 | +7.0 | +7.0 | 1.00 | +7.0 |
| April | -4.9 | 1.00 | -4.9 | -4.9 | 1.00 | -4.9 |

[a] Water table change represented the difference between water table elevation at the beginning and end of the month.

[b] Specific yield derived from the regression equations for Plots C and H, respectively, relating specific yield to depth. Values were derived for the depth midway between the depth at the beginning and end of each month.

[c] Change in water storage represents the product of specific yield and water table change.

Table 10 (continued)

[d]The regression equation for specific yield in Plot H was applied only to a height 6.13 cm above the surface of the peat. Above this height, specific yield was assumed to be 1.00. The value shown is the average specific yield for this month.

[e]The regression equation for specific yield in Plot C was applied only to a height of 2.10 cm above the surface of the peat. Above this height, specific yield was assumed to be 1.00. The value shown is the average specific yield for this month.

no major differences. Both plots undergo similar seasonal changes in water storage. The largest increases in water storage occurred during June and July, 1978. These were the two months with the largest rainfall (see Table 5). No appreciable net storage of treated wastewater or fresh water occurred in Plot H or Plot C. It appeared that the applied treated wastewater or fresh water displaced an equal volume of water out of the plot to which it was applied within the one-week period following application. If the water did not entirely flow out between applications, the water storage in the plots would have shown an overall increase with time. This was not observed. Applications of treated wastewater or fresh water only built a temporary hydrostatic head in the plots. The water table in each plot rapidly returned to equilibrium after each weekly application. An illustration of the effects of pumping when the water table was below the surface of the peat was presented in the Methods section (Fig. 7).

Distribution of treated wastewater within the plot. The extent of the distribution of the applied treated wastewater in Plot H (9.6 cm/wk treated wastewater) was determined through a chloride tracer study (see Methods). The results of this experiment are presented in Figs. 18 and 19. The chloride concentration of the treated wastewater was 48 mg/l. Six of the seven medium depth wells located within the plot (Fig. 18) exhibited chloride concentrations that were higher than the treated wastewater concentration and much higher than the concentrations in the wells located outside the plot. The chloride concentrations found in the deep wells (Fig. 19) were less than the concentrations found in the corresponding medium depth wells. Only the two deep wells in the center of the plot had concentrations close to the treated wastewater concentration.

Results of monthly chloride analyses for the applied wastewater and for sampling stations inside and outside of the experimental plots are graphed in Figs. 20-24. As shown, the average concentration of chloride in groundwater from the "natural" marsh area was significantly lower than the average concentration in the applied

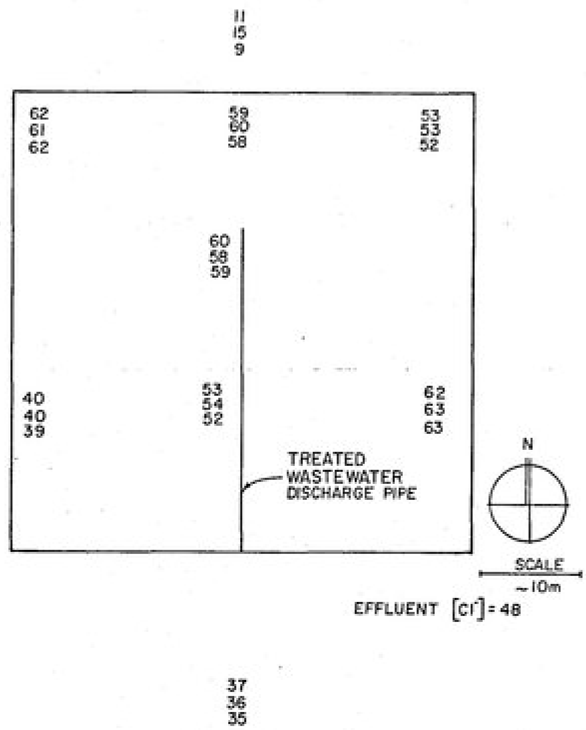



Figure 18. Results of the chloride tracer study in Plot H (9.6 cm/wk treated wastewater) from the medium depth (1.5 m) wells. Values represent mg/l $Cl^-$. The top number represents the sample collected prior to treated wastewater pumping, the middle number represents the sample collected during treated wastewater pumping, and the bottom number represents the sample collected twenty-four hours after pumping had ceased.

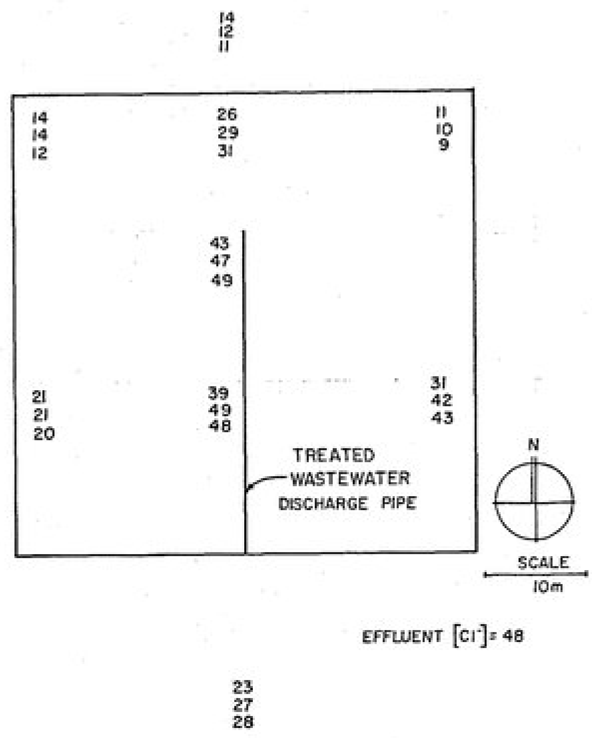



Figure 19. Results of the chloride tracer study in Plot H (9.6 cm/wk treated wastewater) from the deep (2.5 m) wells. Values listed as described for Fig. 18.

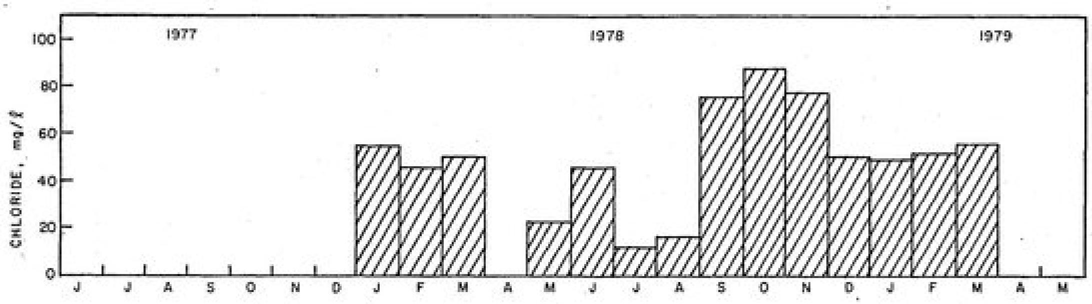



Figure 20. Chloride concentration in the secondarily treated wastewater.

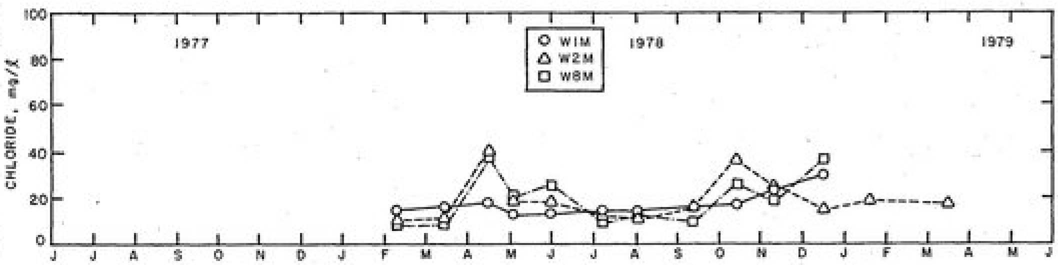



Figure 21. Chloride concentration in wells in the natural marsh. See Fig. 5 for sampling locations.

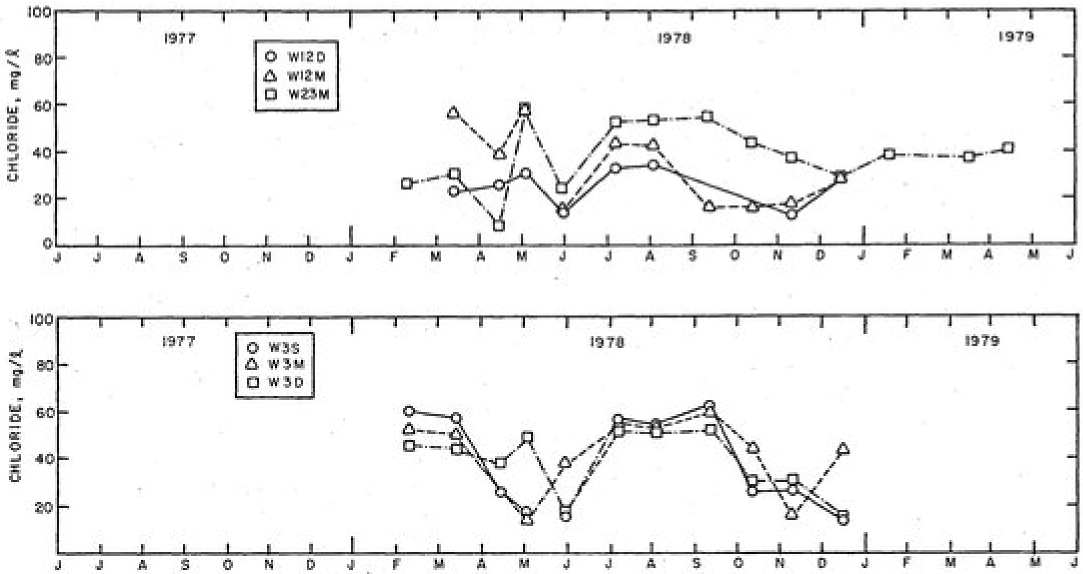



Figure 22. Chloride concentration in wells in Plot H (9.6 cm/wk of treated wastewater). See Fig. 5 for sampling locations.

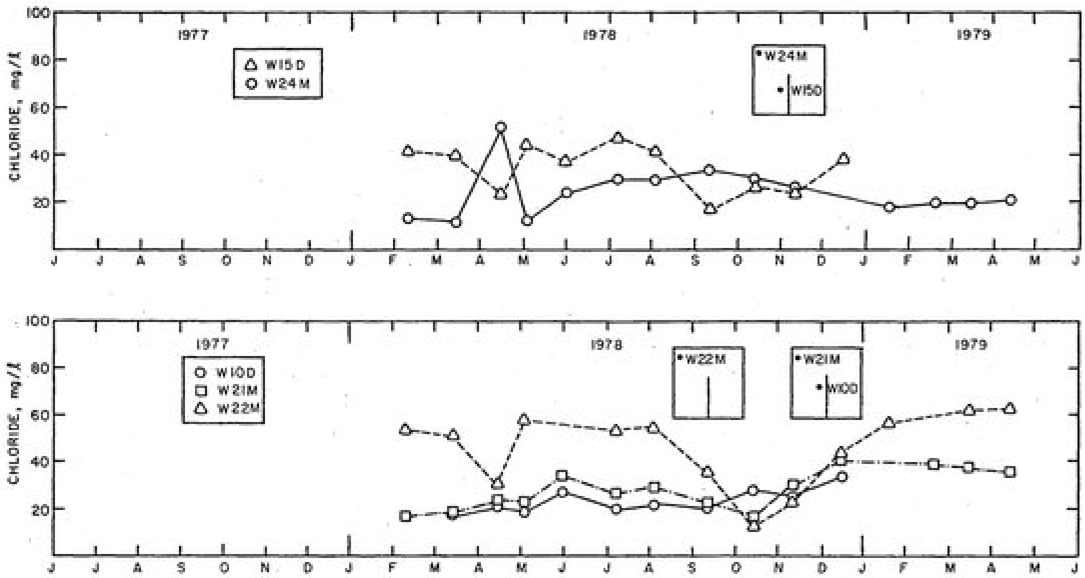



Figure 23. Chloride concentration in wells in Plot M, upper chart (3.7 cm/wk), Plot C, lower chart (W10D and W21, 4.4 cm/wk of fresh water) and Plot L (W22, 1.5 cm/wk) (see Fig. 5 for sampling locations).

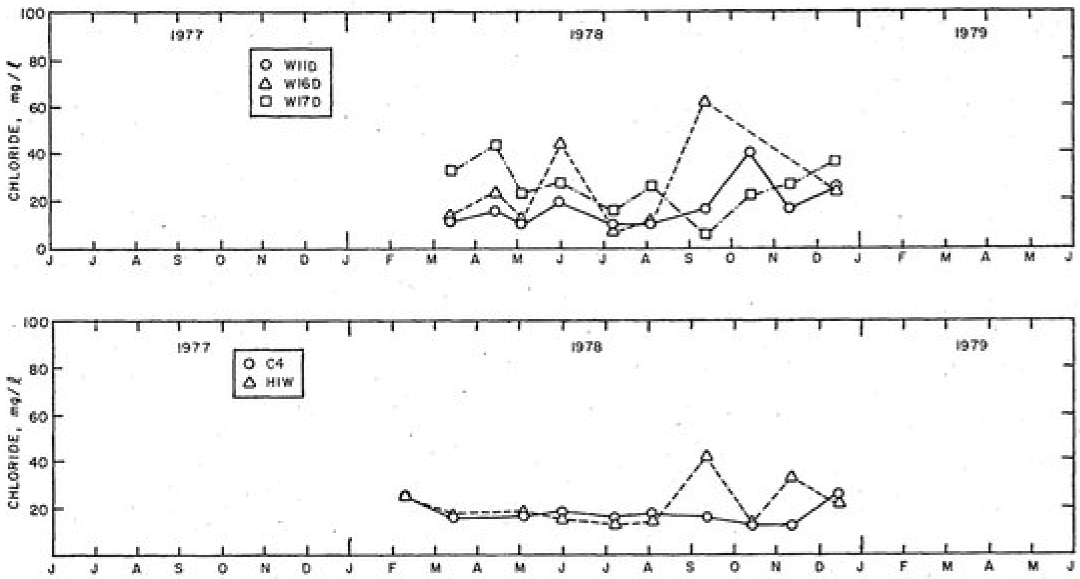



Figure 24. Chloride concentration in deep wells in the natural marsh (upper chart) and the Palatlakaha River (lower chart) (see Figs. 2 and 5 for sampling locations).

treated wastewater. Duncan's multiple range test was applied to the data for wells in the northwest corner of Plots C, L, M, and H (W21M, W22M, W24M, and W23M, respectively), and in the natural marsh (W2M). Results are given in Table 11. The concentration of chloride was significantly higher ($\alpha$ = .05) in well W23M than in the natural marsh. This suggests that chloride, and hence the treated wastewater, was distributed rather uniformly over Plot H prior to export.

Utilizing the monthly chloride concentrations and estimated water outflows for the period January - December 1978, inflow and outflow of chloride for Plots C and H were obtained. Results are shown in Table 12. It must be noted that chloride content was not a direct indicator of the rate of water flow past any particular sampling station. Although the values of Table 11 must be viewed with caution, they nonetheless provide further assurance that applied fresh water and wastewater were distributed and exported more or less evenly out through the peat layer in Plots C and H.

Duncan's multiple range test was performed on chloride concentration data for surface station N (average of N1 and N2 data), located in the natural area of the marsh near well W2M, and stations HI, HO, CI, and CO, located in the inside and outside regions of Plots H and C, respectively. Results of the analysis are given in Table 13. Since natural levels of chloride in the surface water of the marsh were fairly high, it was difficult to detect a significant increase in chloride due to the influence of treated wastewater at a particular surface site. However, a significantly higher ($\alpha$ = .05) level of chloride was found within this group of stations at the center of Plot H as compared with the natural area or Plot C.

The conclusions of the chloride tracer study and mass-balance calculations are as follows:

1. Treated wastewater was distributed throughout the bottom of the peat layer in Plot H.
2. Some leakage of applied treated wastewater occurred vertically through the peat, directly beneath the application pipe in Plot H. However, this leakage was not great enough to influence the medium or deep

Table 11. Average concentrations of chloride in medium depth wells of the experimental plots and the natural marsh (1/78 - 12/78).

| Wells | W22M | W23M | W21M | W24M | W2M |
|---|---|---|---|---|---|
| Mean Chloride Content (mg/l) | 43.55 | 37.35 | 29.35 | 25.48 | 19.23 |
| | a* | a,b | b,c | b,c | c |

* Results of the Duncan's multiple range test applied to the chloride data for the five wells shown in this table. Wells with the same letter appearing in this row were not found to be significantly different with respect to chloride content during 1/78 - 12/78 ( $\alpha = 0.05$). For example, the chloride content of W22M was not found to be significantly different from W23M, but was different from W21M.

Table 12. Estimated mass inflows and outflows of chloride in Plots C and H, January - December, 1978 ($g/m^2$-year).

| Plot | Rain | Freshwater or Wastewater | Outflow | Outflow/Input |
|---|---|---|---|---|
| Control | 0.9 | 40.2 | 32.6 | 81.09% |
| High-Rate | | | | |
| W23M [a] | 0.9 | 234.0 | 155.7 | 66.54% |
| W3M | 0.9 | 234.0 | 185.6 | 79.32% |

[a]W23M was located in the northwest corner of Plot H, and W3M was located in the center of the plot directly beneath the treated wastewater discharge pipe.

Table 13. Average concentrations of chloride ion in surface samples from Plot C, Plot H, and the natural area (August 1978 - May 1979).

| Station | Plot H Inside Region (HI) | Plot H Outside Region (HO) | Natural Marsh (N) | Plot C Inside Region (CI) | Plot C Outside Region (CO) |
|---|---|---|---|---|---|
| Mean chloride content (mg/l) | 43.54 | 39.88 | 31.09 | 29.96 | 21.19 |
| | a* | a,b | b | b,c | c |

* Results of the Duncan's multiple range test applied to the chloride data for the five locations shown in this table. Locations with the same letter appearing in this row were not found to be significantly different with respect to chloride content during August 1978 - May 1979 ($\alpha = 0.05$). For example, the chloride concentration in Plot H Inside was not found to be significantly different from Plot H Outside, but was different from Natural Marsh.

layers downgradient of the application site.

3. Applied treated wastewater flowed past the northwest corner wells of Plots L, M, and H (W22M, W24M, and W23M, respectively).

Hydrologic Budgets for the Control Plot, High-Rate Treated Wastewater Plot, and the "Average" Marsh

The monthly hydrologic inputs and outputs are presented for Plot C, Plot H, and the undisturbed, "average" marsh in Tables 14-16, respectively. The evapotranspiration totals for each month were derived by multiplying the theoretical evapotranspiration rate obtained from the model of evapotranspiration by the number of days in the month. Evapotranspiration as predicted by the model was higher in Plot H than in either Plot C or the natural marsh. This was due to the higher biomass found in Plot H. Predicted evapotranspiration was higher in all areas during the second year of the study. A summary of the hydrologic budgets is given in Table 17 for the two years studied.

Total rainfall was higher during the second year than during the first year. The effects of rainfall upon the water table in the marsh were described earlier (see Hydrologic Inputs). A slightly larger volume of fresh water was applied to Plot C during the second year than during the first year of the study.

Net outflow of water from the natural marsh, Plot C, and Plot H was calculated by the continuity equation as described in the Methods section.

The natural marsh area exhibited a net inflow of water during both years of this study. Calculated net inflow was considerably higher during the second year than during the first, due to a greater calculated evapotranspiration and a net storage of water during the second year. A net outflow of water from the natural marsh area was calculated for the winter of the first year (December 1977 - May 1978), during which time lower temperatures and lower aboveground biomass prevailed. The layer of aboveground dead biomass in the marsh possibly helped to minimize evapotranspiration during this period, at which time the water table was near the

Table 14. Hydrologic budget for Plot C (4.4 cm/wk fresh water). Values were calculated from water level records, rainfall measurements, evapotranspiration-saturation deficit-biomass regressions, and freshwater pumping records. Values are expressed as cm $H_2O$/mo.

| Month | Rain[a] (cm) | | Fresh Water[b] (cm) | | Evapotranspiration[c] (cm) | | Change in Storage[d] (cm) | | Outflow from Plot[e] (cm) | |
|---|---|---|---|---|---|---|---|---|---|---|
| May 1977 | 2.1 | | 15.3 | | 12.7 | | -1.2 | | 5.9 | |
| June | 5.5 | | 19.8 | | 16.2 | | -2.3 | | 11.4 | |
| July | 21.8 | | 15.5 | | 13.6 | | 8.3 | | 15.4 | |
| August | 16.2 | | 15.8 | | 16.1 | | 8.5 | | 7.4 | |
| September | 13.9 | | 19.1 | | 22.2 | | -3.1 | | 13.9 | |
| October | 2.8 | | 18.8 | | 16.1 | | -3.8 | | 9.3 | |
| November | 8.2 | | 14.9 | | 10.2 | | 6.0 | | 6.9 | |
| December | 10.4 | | 19.2 | | 6.8 | | 3.8 | | 19.0 | |
| January 1978 | 7.2 | | 15.2 | | 5.6 | | -5.2 | | 22.0 | |
| February | 14.9 | | 15.2 | | 4.2 | | 3.9 | | 22.0 | |
| March | 6.6 | | 15.4 | | 6.2 | | -4.1 | | 19.9 | |
| April | 1.8 | | 15.4 | | 9.6 | | -7.4 | | 15.0 | |
| May | 14.4 | 111.4[f] | 21.7 | 199.6 | 17.4 | 139.5 | 2.4 | 3.4 | 16.3 | 168.1 |
| June | 27.6 | | 16.0 | | 23.4 | | 11.8 | | 8.4 | |
| July | 32.8 | | 15.4 | | 23.3 | | 21.0 | | 3.9 | |
| August | 6.5 | | 19.3 | | 27.0 | | 11.9 | | -13.1 | |
| September | 7.9 | | 15.4 | | 30.3 | | -9.1 | | 2.1 | |
| October | 4.6 | | 15.4 | | 22.3 | | -11.9 | | 9.6 | |
| November | 0 | | 15.4 | | 17.1 | | -10.4 | | 8.7 | |
| December | 8.9 | | 15.4 | | 9.9 | | -0.6 | | 15.0 | |

Table 14 (continued).

| Month | Rain[a] (cm) | Fresh Water[b] (cm) | Evapotranspiration[c] (cm) | Change in Storage[d] (cm) | Outflow from Plot[e] (cm) |
|---|---|---|---|---|---|
| January 1979 | 17.8 | 15.4 | 8.1 | 9.5 | 15.6 |
| February | 5.0 | 34.9 | 6.4 | 0.0 | 33.5 |
| March | 10.0 | 34.9 | 9.6 | 7.0 | 28.3 |
| April | 13.3 | 34.9 | 14.1 | -4.9 | 39.0 |
| Totals | 260.2[g] 148.8[f] | 453.7 254.1 | 348.4 208.9 | 30.1 26.7 | 334.8 167.3 |

[a] Values from Table 5

[b] Values from Table 6

[c] Values from Table 9

[d] Values from Table 10

[e] Calculated by the continuity equation:

$$O = -\Delta S + F + R - E$$

where O is outflow, $\Delta S$ is change in storage, F is the fresh water, R is the rain input, and E is evapotranspiration.

[f] Yearly totals

[g] Two year totals.



Table 15. Hydrologic budget for Plot H (9.6 cm/wk). Values were calculated from water level records, rainfall measurements, evapotranspiration-saturation deficit-biomass regressions, and treated wastewater pumping records. Values are expressed as cm $H_2O$/mo.

| Month | Rain[a] (cm) | Treated Wastewater[b] (cm) | Evapotranspiration[c] (cm) | Change in Storage[d] (cm) | Outflow from Plot[e] (cm) |
|---|---|---|---|---|---|
| May 1977 | 2.1 | 41.5 | 13.0 | -1.7 | 32.3 |
| June | 5.5 | 50.9 | 17.7 | -3.4 | 42.1 |
| July | 21.8 | 40.7 | 20.5 | 11.4 | 30.6 |
| August | 16.2 | 49.6 | 19.8 | 9.2 | 36.8 |
| September | 13.9 | 51.1 | 28.5 | -3.4 | 39.9 |
| October | 2.8 | 42.2 | 21.1 | -3.8 | 27.7 |
| November | 8.2 | 41.2 | 13.2 | 7.9 | 28.3 |
| December | 10.4 | 50.9 | 8.4 | 2.4 | 50.5 |
| January 1978 | 7.2 | 40.7 | 6.5 | -2.8 | 44.2 |
| February | 14.9 | 40.7 | 4.5 | 3.0 | 48.1 |
| March | 6.6 | 21.8 | 7.1 | -3.8 | 25.1 |
| April | 1.8 | 41.4 | 11.7 | -7.8 | 39.3 |
| May | 14.4 111.4[f] | 46.2 512.7 | 22.0 172.0 | 1.0 7.2 | 37.6 444.9 |
| June | 27.6 | 45.9 | 29.7 | 11.0 | 32.8 |
| July | 32.8 | 41.1 | 25.7 | 22.3 | 25.9 |
| August | 6.5 | 51.3 | 23.9 | 11.9 | 22.0 |
| September | 7.9 | 41.1 | 21.6 | -9.1 | 36.5 |
| October | 4.6 | 41.1 | 17.1 | -11.9 | 40.5 |
| November | 0 | 41.1 | 15.0 | -10.1 | 36.2 |

Table 15 (continued).

| Month | Rain[a] (cm) | Fresh Water[b] (cm) | Evapotranspiration[c] (cm) | Change in Storage[d] (cm) | Outflow from Plot[e] (cm) |
|---|---|---|---|---|---|
| December | 8.9 | 41.1 | 10.5 | -0.9 | 40.4 |
| January 1979 | 17.8 | 41.1 | 8.4 | 9.8 | 40.7 |
| February | 5.0 | 32.7 | 6.7 | 0 | 31.0 |
| March | 10.0 | 32.7 | 10.2 | 7.0 | 25.5 |
| April | 13.3 | 32.7 | 15.3 | -4.9 | 35.6 |
| Totals | 260.2[g] 148.8[f] | 1000.8 488.1 | 378.1 206.1 | 35.6 28.4 | 849.6 404.7 |

[a] Values from Table 5

[b] Values from Table 6

[c] Values from Table 9

[d] Values from Table 10

[e] Calculated by the continuity equation:

$$O = -\Delta S + F + R - E$$

where O is outflow, $\Delta S$ is change in storage, F is the treated wastewater, R is the rain input, and E is evapotranspiration.

[f] Yearly totals.

[g] Two year totals.

Table 16. Hydrologic budget for the "average" marsh. Values were calculated from water level records and rainfall measurements. Values are expressed as cm $H_2O$/mo.

| Month | Rain[a] (cm) | | Evapotranspiration[b] (cm) | | Change in Storage[c] (cm) | | Outflow[d] (cm) | |
|---|---|---|---|---|---|---|---|---|
| May 1977 | 2.1 | | 12.7 | | -1.2 | | -9.4 | |
| June | 5.5 | | 15.3 | | -2.3 | | -7.5 | |
| July | 21.8 | | 13.6 | | 8.3 | | -0.1 | |
| August | 16.2 | | 14.6 | | 8.5 | | -6.9 | |
| September | 13.9 | | 18.6 | | -3.1 | | -1.6 | |
| October | 2.8 | | 14.0 | | -3.8 | | -7.4 | |
| November | 8.2 | | 9.3 | | 6.0 | | -7.1 | |
| December | 10.4 | | 6.5 | | 3.8 | | 0.1 | |
| January 1978 | 7.2 | | 5.6 | | -5.2 | | 6.8 | |
| February | 14.9 | | 4.2 | | 3.9 | | 6.8 | |
| March | 6.6 | | 6.2 | | -4.1 | | 4.5 | |
| April | 1.8 | | 9.9 | | -7.4 | | -0.7 | |
| May | 14.4 | 111.4[e] | 18.3 | 130.5 | 2.4 | 3.4 | -6.3 | -22.50 |
| June | 27.6 | | 24.9 | | 11.8 | | -9.1 | |
| July | 32.8 | | 23.9 | | 21.0 | | -12.1 | |
| August | 6.5 | | 26.4 | | 11.9 | | -31.8 | |
| September | 7.9 | | 28.5 | | -9.1 | | -11.5 | |
| October | 4.6 | | 21.1 | | -11.9 | | -4.6 | |
| November | 0 | | 16.8 | | -10.4 | | -6.4 | |
| December | 8.9 | | 10.2 | | -0.6 | | -0.7 | |
| January 1979 | 17.8 | | 8.1 | | 9.5 | | 0.2 | |
| February | 5.0 | | 6.2 | | 0.0 | | -1.2 | |
| March | 10.0 | | 9.6 | | 7.0 | | -6.6 | |
| April | 13.3 | | 15.0 | | -4.9 | | 3.2 | |
| Totals | 260.2 | 148.8[e] | 339.5 | 209.0 | 30.7 | 26.7 | -109.4 | -86.9 |

[a] Values from Table 5.

[b] Values from Table 8.

[c] Assumed to be the same as Plot C, values from Table 10.

[d] Calculated by the continuity equation:

$$O = -\Delta S + R - E$$

where O is outflow, $\Delta S$ is change in storage, R is the rain input, and E is evapotranspiration.

[e] Yearly totals.

Table 17. Summary of two years of hydrologic data from May 1977 through April 1979. All values in cm of water per year.

| | Freshwater Control Plot | High Rate Treated Wastewater Plot | Average Marsh |
|---|---|---|---|
| May 1, 1977 - April 30, 1978: | | | |
| Rainfall | 111.4 | 111.4 | 111.4 |
| Applied water | 199.6 | 512.7 | --- |
| Exapotranspiration | 139.5 | 172.0 | 130.5 |
| Change in storage | + 3.4 | + 7.2 | + 3.4 |
| Net outflow | 168.1 | 444.9 | -22.5 |
| May 1, 1978 - April 30, 1979: | | | |
| Rainfall | 148.8 | 148.8 | 148.8 |
| Applied water | 254.1 | 488.1 | --- |
| Evapotranspiration | 208.9 | 206.1 | 209.0 |
| Change in storage | +26.7 | +28.4 | +26.7 |
| Net outflow | 167.3 | 404.7 | -86.9 |

surface of the peat. Highest quantities of inflow in the natural marsh were calculated for the first month of the study (9.4 cm during May 1977) and for the summer of 1978 (31.8 cm during August 1978).

The freshwater control plot (Plot C) exhibited net outflow of water for both years due to the application of the fresh water. Lowest outflow values were observed for the summer of 1978, and highest outflow values were observed towards the end of the two- year study in the spring of 1978. The high rate treated wastewater application plot (Plot H) exhibited a consistent net outflow throughout the study period due to the application of the treated wastewater. Estimated outflow values for the first year were slightly higher than for the second year in Plot H. Highest outflow values were observed in Plot H during the winter months of the first year. Application of treated wastewater and fresh water thus changed Plots H and C, from net importers of adjacent channel and lake water to net exporters of applied water.

## Plant Production

### Live and Dead Aboveground Standing Crop

Analysis of variance indicated that during the first year of this study, when the water table was below the surface of the peat, aboveground live biomass was significantly greater ($\alpha = 0.01$) near the treated wastewater or freshwater discharge pipe (inside sampling region) than in the outside sampling regions (outside the influence of the distribution pipes but still inside the plots). Applied water and nutrients thus had their major impact on biomass near the site of discharge during this first year. There was no significant difference ($\alpha = 0.01$) detected in aboveground live biomass among the outside regions of the four plots during the first year.

Results for plots C, M, and H are shown together for the inside and outside regions of these plots, respectively, in Fig. 25. The

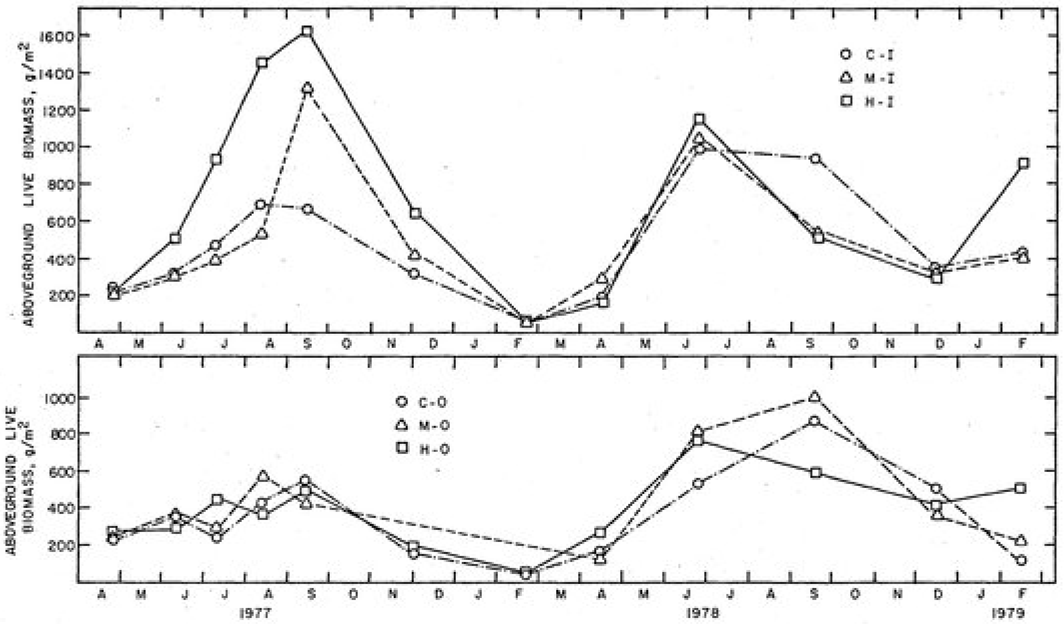



Figure 25. Aboveground live biomass for Plots C, M, and H (4.4 cm/wk of freshwater, 3.7 and 9.6 cm/wk of treated wastewater) in the inside section of the plots near the distribution pipe (upper chart), and in the outside section of the plots (outside the influence of the distribution pipe - lower chart).

stimulatory effect of applied treated wastewater is evident for the first year in this figure. The inside region of Plot H exhibited significantly higher ($\alpha$ = 0.05) values, as indicated by Duncan's multiple range test, than the inside regions of the other plots for this period. Both Plots M and H exhibited higher peak inside region values than Plot C during the growing season of the first year.

Growth patterns were much different during the second year. There was no significant difference detected ($\alpha$ = 0.01) in total aboveground live biomass among Plots C, M, and H during this period. Neither was any significant difference detected between the values for inside regions and outside regions of the plots. The peak biomass value was lower for the second year's growing season than for the first year in the inside region of Plot H. Conversely, second year values were higher than first year values for live biomass found in the outside regions of Plots C, M, and H, and in the inside region of Plot C. These results were due primarily to the higher water table and the more even distribution of applied water and nutrients during the second year. More of the nutrients applied to surface water in each plot were able to reach the outside regions of those plots during the second year. Under dry conditions, nutrient assimilation was more localized, resulting in more localized effects on plant biomass.

The presence of standing water resulted in significant physical and chemical changes in the marsh system which directly affected plant growth. Partial submersion of rooted plants, coupled with growth of algae and floating plants, limited the availabiltiy of light to shorter plants such as Panicum. Availability of oxygen may have been limited for some plants by the presence of standing water, although emergents such as Sagittaria are capable of supplying oxygen to their roots through their vascular system. Anaerobic conditions in sediments and peat result from slow diffusion of oxygen through water, coupled with the continuing oxygen demand of organic materials in the upper layers of the sediments or peat. Such conditions may result in the generation of $H_2S$, which is toxic to root metabolism for some plants (Gosselnik 1978). Micronutrient and phosphorus availability may also change with the reduced availability

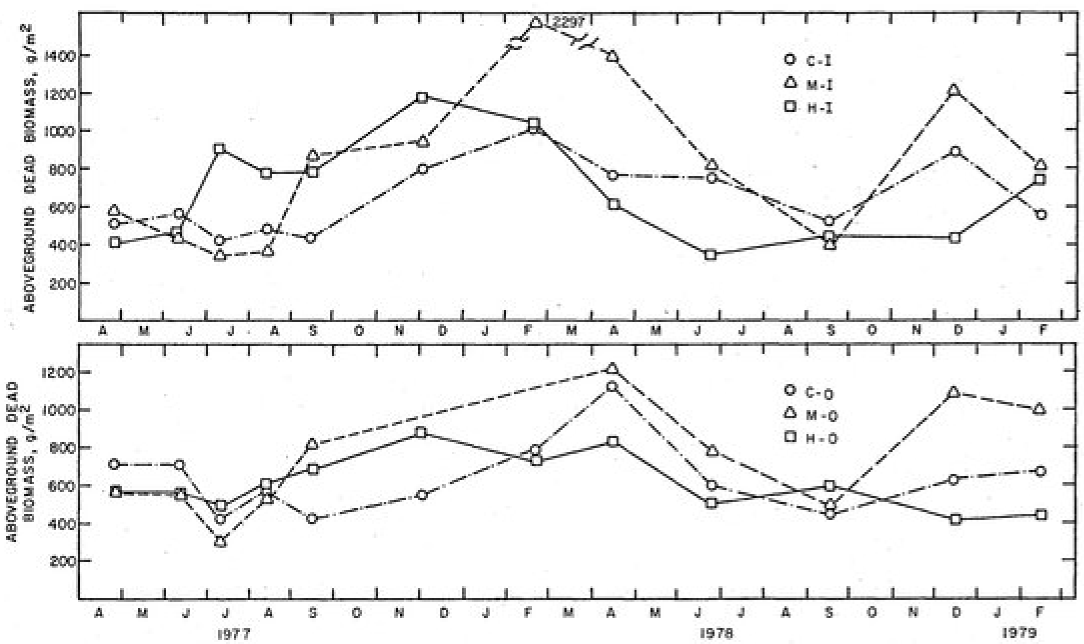



Figure 26. Aboveground dead biomass for Plots C, M, and H (4.4, 3,7, 9.6 cm/wk) in the inside section of the plot near the distribution pipe (upper chart), and in the outside section of the plot (outside the influence of the distribution pipe - lower chart).

of oxygen in the peat substrate. From the data collected in this study, it was not possible to conclude which of these effects were important deterrents or stimulants to plant growth during the second year.

A sharper dieback of aboveground live vegetation was apparent throughout the marsh during the winter of the first year relative to the second year. The lack of standing water during the first year subjected the plants to cooler ambient temperatures, leading to increased mortality at this time.

A general increase in the dead aboveground biomass contained throughout Plots C, M, and H was evident for the first (dry) year (Fig. 26). The highest aboveground dead biomass content, 2297 $g/m^2$, was exhibited by the inside region of Plot M on the February 20, 1978, sampling date. An overall decline in this component was observed for all plots between February and September of the second year as the water table rose and mean daily temperatures increased. After September, renewed accumulation of dead aboveground biomass took place in the inside and outside regions of Plot M and in the inside portion of Plot H. Application of Duncan's multiple range test to the dead aboveground biomass data showed that the dead aboveground stock in Plot M was significantly greater than the dead aboveground stock in Plot H or Plot C for both the dry and wet years ($\alpha = 0.05$). Also, the dead aboveground stock in Plot H was significantly higher than the dead aboveground stock in Plot C during the first year ($\alpha = 0.05$).

The occurrence of higher values for aboveground dead biomass in Plot M than for Plots H or C, especially during the colder periods of both years, was probably due to a lower average rate of decomposition within Plot M than within Plot H. Even though Plot H exhibited a higher aboveground net production value during the first year of the study, Plot M could have accumulated more litter during that year if decomposition there was slower than in Plot H. The rate of decomposition of plant material is governed by several factors: 1. availability of water; 2. oxygen; 3. temperature; 4. pH; 5. availability of nutrients in surrounding water; and 6. availability of nutrients in decomposing vegetation. During the first year, decomposition throughout the marsh may well have been limited by the availability of water. Deghi (1977) found decomposition of freshly harvested cypress needles proceeded at a slower rate under dry conditions than under wet conditions in a Florida cypress dome receiving treated wastewater. Dierberg and Ewel (1979) found decomposition of dead cypress needles in litter fall was significantly faster in a Florida cypress dome receiving treated wastewater than in a natural control dome. Since Plot H received the largest volume of water, maintained the highest concentration of nutrients in interstitial water, and had the highest concentrations of nitrogen and phosphorus in biomass, the rate of decomposition of newly senesced biomass (litter) would be expected to have been highest in this plot. Of Plots C, M, and H, Plot C would be expected to have had the lowest rate of decomposition during the first year, and Plot M an intermediate rate. Net accumulation of litter depends on the balance of its production and decomposition. The higher net production of live biomass and hence litter in Plot M relative to Plot C, coupled with a lower rate of decomposition in Plot M relative to Plot H, may have led to the greater litter accumulation in Plot M.

Belowground Standing Crop

Belowground biomass results are illustrated in Figs. 27-29 for the inside region of Plots C, M, and H, respectively. The results for aboveground live biomass in the specified areas are plotted for comparison on the same figures. Since the belowground component includes both live and dead roots, the seasonal trend observed for any particular year may be affected by root growth and decay that occurred in previous years.

The inside region of Plot C exhibited lower belowground stock during the summer of the first and second years than during the winter of those years (Fig. 27), although no significant difference was detected at the 0.05 level. The lower values in the summer could reflect the loss of tissue produced during the previous year,

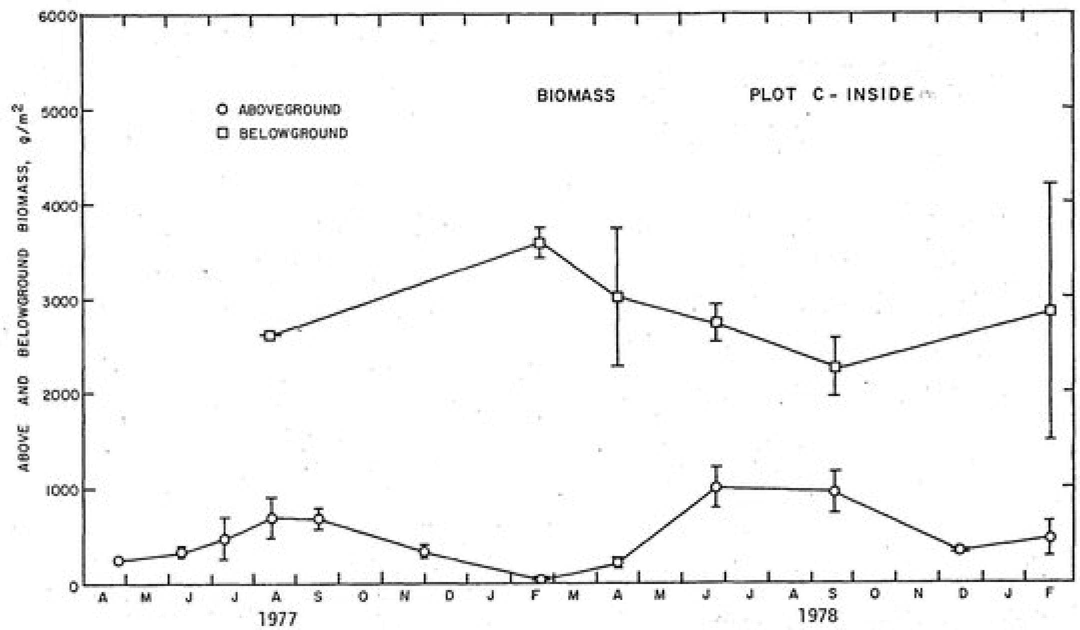



Figure 27. Aboveground live and belowground live and dead biomass for the inside region (near the distribution pipe) of Plot C (4.4 cm/wk of fresh water). Values ±1 S.E.

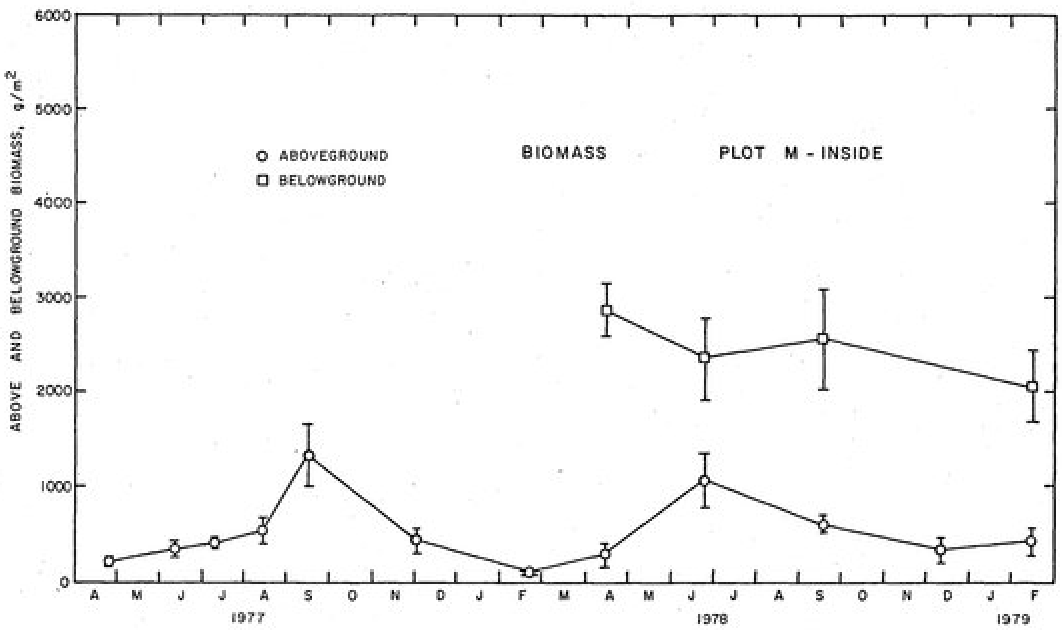



Figure 28. Aboveground live and belowground live and dead biomass for the inside region (near the distribution pipe) of Plot M (3.7 cm/wk). Valves ± 1 S.E.

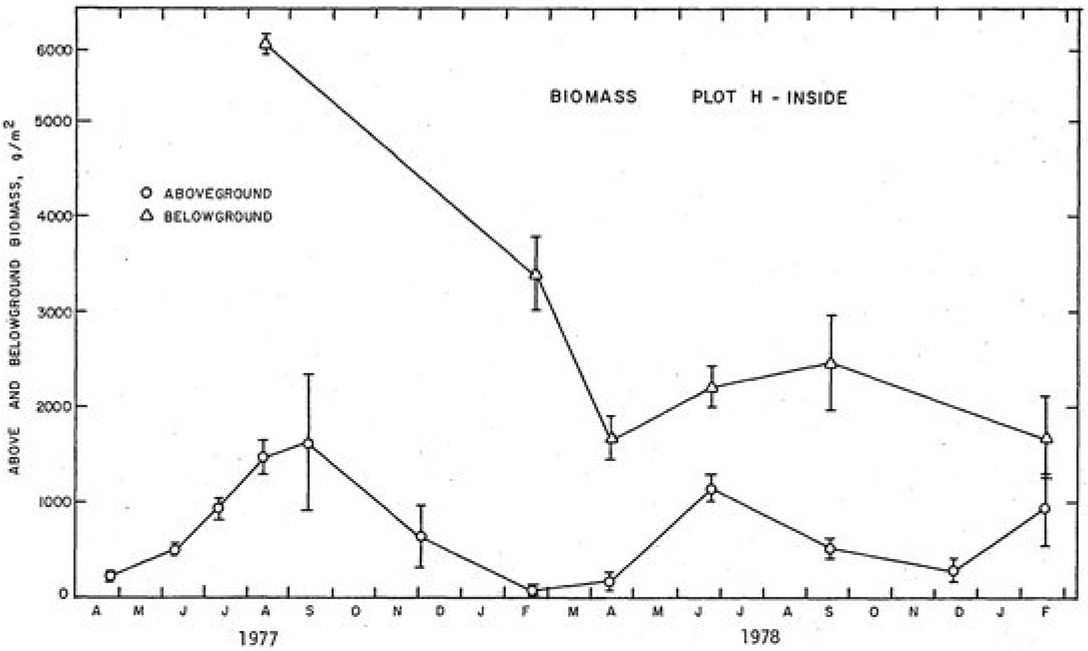



Figure 29. Aboveground live and belowground live and dead biomass for the inside region (near the distribution pipe) of Plot H (9.6 cm/wk). Values ± 1 S.E.

which decomposed throughout the spring and early summer following its production. Mobilization of stored energy reserves in the spring could also have depleted belowground stocks (Whigham et al. 1978). If the decompostion and mobilization of compounds in live and dead roots proceeded at a faster rate than new root production during the spring and early summer, a net decline in belowground live plus dead stock would be expected. After most of the dead tissue had been converted to $CO_2$ and peat, the continuing net production of new root tissue would raise the total belowground live plus dead stock.

The inside region of Plot H exhibited significantly ($\alpha$ = 0.05) higher belowground stock during the summer than during the winter of the dry year (Fig. 29). The belowground stock exhibited by the inside region of Plot H during August of the first year was 6071 g dry weight/$m^2$. The roots were well aerated during the growing season of the first year, since the water table was below the surface of the peat throughout most of this period (see Figs. 14 and 15). As with the aboveground component, rapid and localized growth of roots occurred in the vicinity of the treated wastewater application pipe (inside region) in Plot H during the dry growing season. The large root stock accumulated here during the first year was subsequently translocated, decomposed, and converted to new peat. Conditions were apparently less favorable for root growth near the discharge pipe in Plot H during the second (wet) growing season, than during the first (dry) growing season.

Belowground biomass data for the inside, outside, and total regions of Plots C, M, and H are summarized in Table 18. Plots M and H exhibited an overall decrease in belowground stock between April and February of the second (wet) year, both for their outside regions and for the total region of these plots. This decrease could represent the utilization, decomposition, and conversion to peat of root stock produced during the first (dry) year. Analysis of variance of the belowground biomass data for the period April 1978 - February 1979 indicated no significant differences in storage among the plots ($\alpha$ = 0.01) during that period.

Table 18. Below ground live plus dead biomass (g dry weight/m$^2$ $\pm$ 1 S.E.).

| Date | Plot C | Plot M | Plot H |
|---|---|---|---|
| | | Inside Regions | |
| 8/11/77 | 2607.0±1.1 | --- | 6071.1±85.6 |
| 2/20/78 | 3581.6±160.2 | --- | 3409.1±280.8 |
| 4/15/78 | 3006.7±730.3 | 2869.9±291.3 | 1675.9±238.6 |
| 6/25/78 | 2731.9±190.0 | 2364.8±437.7 | 2205.7±210.4 |
| 9/18/78 | 2265.3±304.5 | 2570.9±528.8 | 2476.0±500.0 |
| 2/17/79 | 2840.9±1345.4 | 2302.3±370.4 | 1669.2±426.8 |
| | | Outside Regions | |
| 4/15/78 | 2959.5±212.2 | 2905.5±448.1 | 4292.0±706.4 |
| 6/25/78 | 2638.0±266.7 | 3055.6±211.5 | 2805.3±549.5 |
| 9/18/78 | 1726.3±204.1 | 3152.0±38.4 | 2323.3±251.6 |
| 2/17/79 | 2929.2±673.3 | 2376.1±332.1 | 2322.9±246.7 |
| | | Total Regions | |
| 4/15/78 | 2971.3±341.7 | 2896.6±408.9 | 3638.0±589.4 |
| 6/25/78 | 2661.5±247.5 | 2882.9±268.1 | 2655.4±464.8 |
| 9/18/78 | 1861.0±229.2 | 3006.7±161.0 | 2361.5±313.7 |
| 2/17/79 | 2907.1±841.3 | 2357.7±341.7 | 2159.5±292.9 |

Net Production

Peak aboveground live biomass attained during the growing season of each year was used as an estimate of net annual aboveground production during each year (see Methods chapter for a discussion of this technique). Table 19 shows the production values for the experimental plots. The production value for the low-loading plot (Plot L) was not measured during 1978 due to a manpower shortage. The total region value for each plot was obtained by using a 25-75 area-weighted average of the values for the inside and outside regions of the respective plots (see Methods).

Net annual aboveground production was greatest near the discharge pipe (inside region) of Plot H during both the first (dry; 1977) and second (wet; 1978) years. Several factors were responsible for the apparent drop in aboveground production between years for the inside regions of Plots M and H. Some of these factors were discussed in the live and dead aboveground standing crop section. One probable cause for the lower values is the wider distribution of applied nutrients and water which occurred when standing water was present in the marsh. Also, different species present near the distribution pipes probably attained their respective maximum biomass at different times throughout the second year's growing season. This occurred because drier conditions were present during the first year, and not all species that were established near the application pipes during the first year were equally well adapted to the higher water table, which was established by the end of the second year's growing season. Such differential peaking of different species' biomass results in lower net production estimates than would be obtained if all species attained peak biomass simultaneously (Whigham et al. 1978).

Production of aboveground biomass in the outside regions of Plots C, M, and H was greater during the second (wet) year than during the first (dry) year. Greater access to applied nutrients and water during the second year was in part responsible for the observed increase in these regions.

Table 19. Net annual above ground production of plots. All values are given in g dry matter/$m^2$, $\pm$ 1 S.E.

| | | Inside Region (n=3) | Outside Region (n=3) | Total Region (n=6) |
|---|---|---|---|---|
| Plot C | 1977 | 689.6±195.0 | 546.3±25.4 | 582.1±67.8 |
| | 1978 | 986.5±221.7 | 872.3±419.1 | 900.9±369.8 |
| Plot L | 1977 | 699.7±202.9 | 396.2±30.7 | 472.1±73.8 |
| | 1978 | --- | --- | --- |
| Plot M | 1977 | 1326.3±336.5 | 577.7±115.3 | 773.9±170.6 |
| | 1978 | 1054.2±285.0 | 1000.8±304.4 | 1014.2±299.6 |
| Plot H | 1977 | 1629.2±720.9 | 493.1±166.2 | 777.1±304.9 |
| | 1978 | 1150.8±138.0 | 753.9±59.3 | 853.1±79.0 |

The computed net annual aboveground biomass production for the total region of Plot M or H was higher than the production for the total region of Plot C during the first year of the study. The apparent difference was not statistically significant at the 0.05 level, perhaps due to the small (n = 6) sample size used in this experiment. During the second year, higher net production was observed for the aboveground component of the total region of Plot M relative to Plots C and H. Once again no significant differences were detected at the 0.05 level, presumably due to the small sample size used. Higher net annual aboveground production of vegetation (aquatic macrophytes and semiwoody species) was calculated for the total region of Plots C, M, and H during the second (wet) year than during the first (dry) year. Apparently, flooded conditions were not a deterrent to production in the plots during the second year.

## Phosphorus Considerations

### Phosphorus Water Values

Figure 30 shows the concentration of orthophosphate and total phosphorus in the secondarily treated wastewater applied to Plots H, M, and L (9.6, 3.7, and 1.5 cm/wk of treated wastewater, respectively). There do not appear to be any discernible seasonal trends with respect to phosphorus concentration in the applied treated wastewater. The orthophosphate fraction made up 61.5% of the average phosphorus applied.

Figure 31 shows the total phosphorus concentration of samples collected from selected wells representing the four experimental Plots H, M, L and C, the sand aquifer at various points throughout the natural marsh (W16D, W17D, W11D), and medium depth wells located in the natural marsh (W1M, W2M, W8M). The phosphorus concentrations in these wells were compared with the total phosphorus concentration representing 97% removal in the applied secondarily treated wastewater. The experimental plots receiving the treated wastewater (H, M, and L) achieved 97% or greater removal 84% of the time. The natural marsh exceeded the concentration representing 97% removal

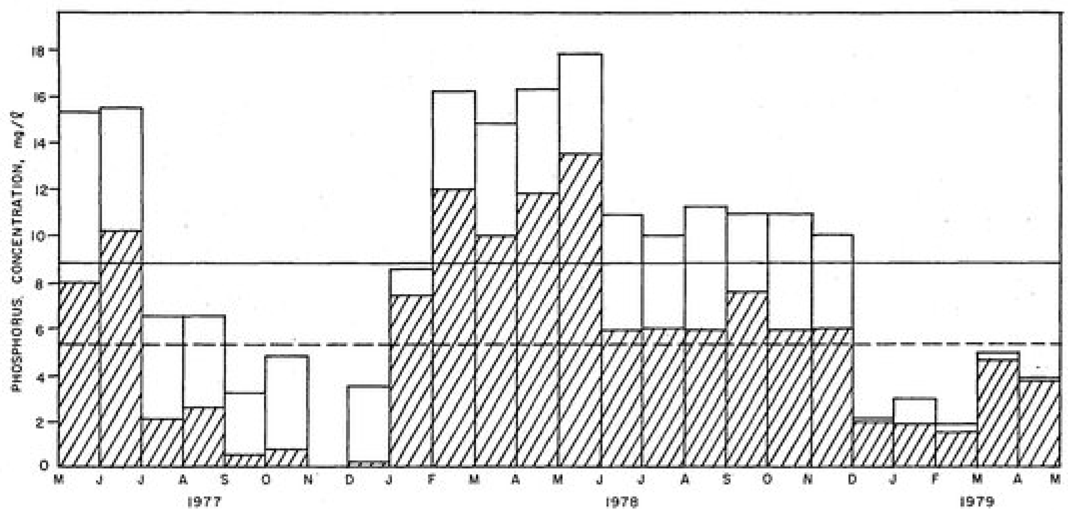



Figure 30. Total phosphorus in applied secondarily treated wastewater represented by the sum of the shaded and unshaded areas. The solid horizontal line represents the average total phosphorus concentration of 8.72 mg/l, and the dashed line represents the average orthophosphate concentration (shaded area) of 5.37 mg/l.

| WELL LOCATION | WELL NUMBER | MONTH J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PLOT C | W10D | / | / | / | / | / | / | / | — | — | — | — | — | — | — | — | — | — | — | — | 1.76 | .40 | .17 | — | — |
| | W21M | — | — | — | .35 | 0 | 0 | / | — | — | — | — | — | — | — | — | — | — | — | 0 | 0 | — | — | — | — |
| PLOT L | W22M | — | .50 | .22 | .26 | .15 | .16 | / | — | — | — | — | — | — | — | — | — | / | / | / | / | / | / | / | / |
| PLOT H | W3M | / | — | .36 | .45 | .36 | .40 | / | — | — | — | / | — | — | — | — | — | — | — | — | — | 76 | .08 | — | — |
| | W3D | / | / | / | / | / | / | / | .24 | 0 | — | — | — | — | — | — | — | — | — | — | / | / | / | — | — |
| | W12M | / | / | / | / | / | / | / | / | / | .75 | — | — | — | — | — | — | — | — | — | — | / | — | — | — |
| | W12D | / | / | / | / | / | / | / | / | / | — | — | — | — | — | — | — | — | — | / | / | / | / | — | — |
| | W23M | .63 | .65 | 0 | .23 | .13 | 0 | / | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| PLOT M | W15D | / | / | / | / | / | / | / | — | — | — | — | — | — | — | — | — | / | / | / | / | / | / | / | / |
| | W24M | — | — | — | — | .22 | .20 | / | — | — | — | — | — | — | — | — | — | / | / | / | / | / | / | / | / |
| NATURAL MARSH (DEEP) | W16D | / | / | / | / | / | / | / | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| | W17D | / | / | / | / | / | / | / | — | — | — | — | — | — | — | — | — | — | — | / | / | / | / | / | / |
| | W11D | / | / | / | / | / | / | / | 0 | — | — | — | — | .76 | — | — | — | — | — | — | / | / | / | — | — |
| NATURAL MARSH | W1M | — | — | — | — | 0 | / | / | — | — | — | — | — | — | — | — | — | — | — | 0 | — | — | — | — | — |
| | W2M | — | — | .23 | | .13 | .15 | / | — | — | — | — | — | — | — | — | — | — | — | — | / | / | — | — | — |
| | W8M | / | — | .29 | .22 | .18 | / | / | — | — | — | — | — | — | — | — | — | — | — | — | / | — | — | — | — |
| TREATED WASTEWATER | EFF x .03 | .46 | .47 | .20 | .20 | .10 | .14 | | .11 | .26 | .49 | 44 | 49 | .53 | .33 | .30 | .34 | .33 | .33 | .30 | .06 | .09 | .05 | .15 | .14 |
| | EFF | 153 | 155 | 6.5 | 6.5 | 3.2 | 4.8 | | 3.5 | 8.5 | 102 | 148 | 16.3 | 178 | 109 | 100 | 11.2 | 109 | 109 | 100 | 2.1 | 2.9 | 1.8 | 4.9 | 4.8 |

Figure 31. Comparison of total phosphorus levels between selected wells and applied secondarily treated wastewater (EFF). An "0" indicates EFF x .03 (ie., 97% reduction). A "—" indicates a reduction greater than 97%. When "EFF x .03" was exceeded, the actual concentration is given. A "/" indicates no sample was available.

13% of the time. Weighting the values in Fig. 31 to eliminate sampling days on which natural marsh concentrations exceeded the 97% removal value (i.e., August 1977, September 1977, October 1977, November 1977, etc.) provides for 97% removal of total phosphorus being achieved 94% of the time.

Table 20 shows the removal efficiencies for the medium depth and deep wells located in Plots H, M, and L. The efficiencies were based on all samples collected. The average removal for medium depth wells was 97.6%, with well W3M providing the least treatment at 94.1% removal. This well was located directly beneath the wastewater application pipe in the high loading plot (Plot H). The average removal of total phosphorus, based on deep well values, was 99.2%. This includes well W3D (98.8% removal), which was located adjacent to well W3M directly beneath the application pipe.

Figure 32 shows the phosphorus concentration of samples collected from the northwest corner wells of Plots H (W23M), M (W24M), and C (W21M). Computer analysis of variance techniques (ANOVA) and Duncan's Multiple Range Comparisons indicated that the concentrations of these three wells and the corner well in Plot L were not significantly different ($\alpha = 0.05$) from each other or from the concentrations found in the natural marsh as represented by well W2M. All of the wells depicted in Fig. 32 follow similar monthly trends. The relatively high phosphorus concentrations reported for wells W23M (Plot H) and W21M (Plot C) during the winter of 1978 appear to have been related to natural decomposition throughout the marsh.

Figures 33 and 34 represent the total and orthophosphate concentrations found in wells located in Plot H. Wells W12D, W12M, and W23M (located in the outside region of the plot) had relatively uniform concentrations of both total phosphorus and orthophosphate (0.05 to 0.3 mg/l) throughout the study period. There appeared to be an increase in concentrations found in these wells after the May 1978 sampling period. This phenomena may be attributed to a rise in the water table above the peat surface. The well data for W3M, W3D, and W3S showed great variability. These wells were located directly beneath the application pipe and phosphorus values may reflect the

Table 20. Total phosphorus removal efficiencies for wells located in Plots H, M and L (9.6, 3.7, and 1.5 cm/wk of treated wastewater, respectively). Removal efficiencies were based on a total phosphorus concentration of 8.72 mg/l in the applied secondarily treated wastewater.

| Well Number | Average Concentration (mg/l) | Average % Removal | Number of Observations |
|---|---|---|---|
| Treated wastewater | 8.722 | --- | 23 |
| W22M | 0.121 | 98.6 | 19 |
| W3M | 0.514 | 94.1 | 21 |
| W3D | 0.103 | 98.8 | 14 |
| W12M | 0.147 | 98.3 | 14 |
| W12D | 0.069 | 99.2 | 11 |
| W23M | 0.122 | 98.6 | 21 |
| W15D | 0.045 | 99.5 | 13 |
| W24M | 0.117 | 98.7 | 18 |

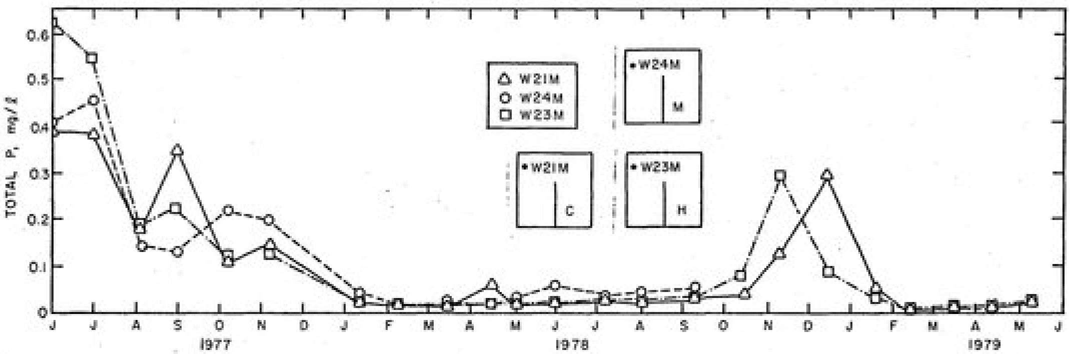



Figure 32. Total phosphorus for northwest corner medium-depth wells.



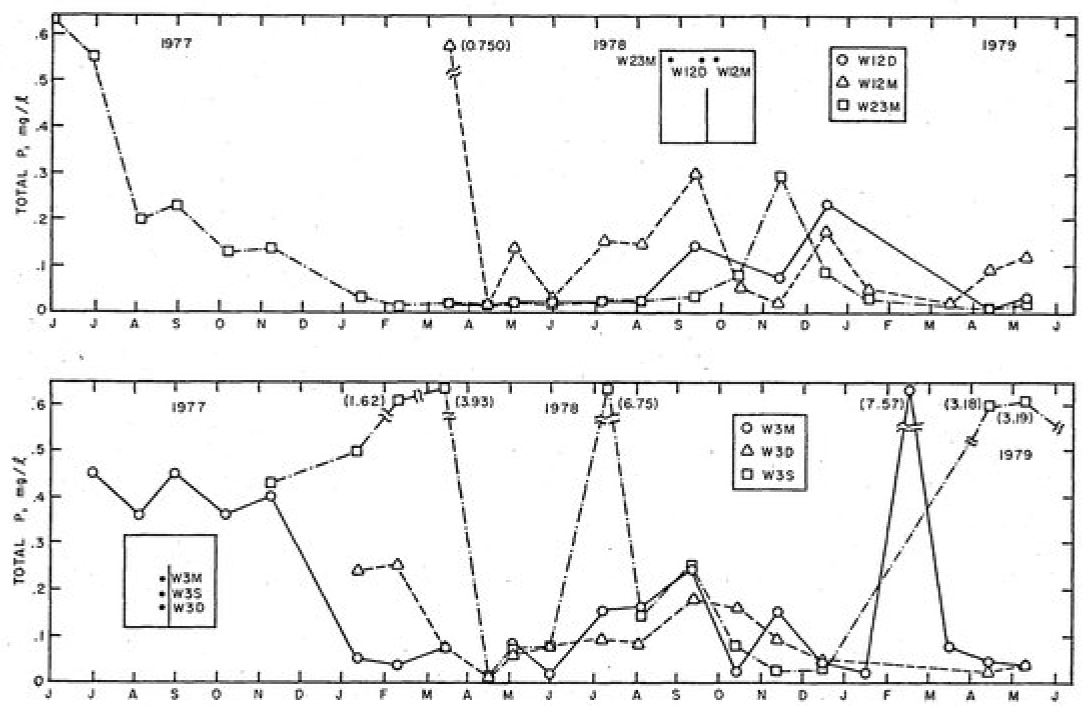



Figure 33. Total phosphorus for Plot H wells (9.6 cm/wk of treated wastewater).

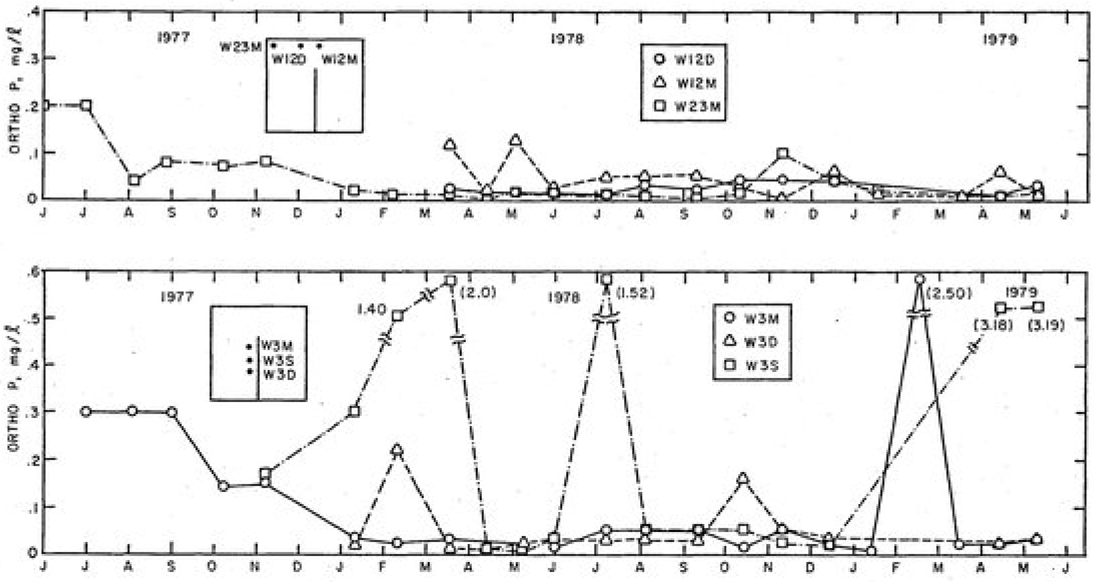



Figure 34. Orthophosphate for Plot H wells (9.6 cm/wk of treated wastewater).

great variability of the phosphorus in applied treated wastewater. Well W3S was a shallow well and for this reason maintaining a seal to isolate the well from surface water contamination was very difficult. This may have contributed to the relatively high values reported. Figure 35 represents the total phosphorus and orthophosphate concentrations found in wells W10D and W21M located in the freshwater control plot. These wells maintained low concentrations of total phosphorus until the winter of 1978 (October through February), when high water conditions and natural decomposition may have released high concentrations of organic phosphorus into the groundwater.

The total and orthophosphate concentrations in the natural marsh medium depth wells are shown in Figs. 36 and 37. The total phosphorus levels for W1M, W2M, and W8M show a decreasing trend from June 1977 to January 1978; a stable concentration of approximately 0.05 mg/l until October 1978; and finally an organic phosphorus peak from November to February 1979 followed by decreased concentrations. The peak in organic phosphorus mirrors the peak observed in the control plot wells and the high loading plot wells W12M, W12D, and W23M. As previously mentioned, this may have been the result of a high water table and decomposition. The minor peak located from March 1978 to May 1978 was also seen in the above mentioned wells. This peak might represent the initial release of phosphorus due to the anaerobic conditions being created by a rising water table.

The phosphorus concentrations for the deep natural wells (W16D, W17D, and W11D) are shown in Fig. 38. These values, which represent the sand aquifer below the marsh, had greater variability than anticipated. The fluctuations could have been caused by influences from the percolation pond at the sewage treatment plant or natural fluxes of phosphorus through the aquifer to and from the Palatlakaha River. Wells W16D and W17D are located between the percolation pond of the Clermont Sewage Treatment Plant and the experimental plots. Well W11D is located within 60 yards of the Palatlakaha River (see Fig. 5).

Surface water phosphorus concentrations for Plots C and H are shown in Figs. 39 and 40. The marsh water table exceeded the peat

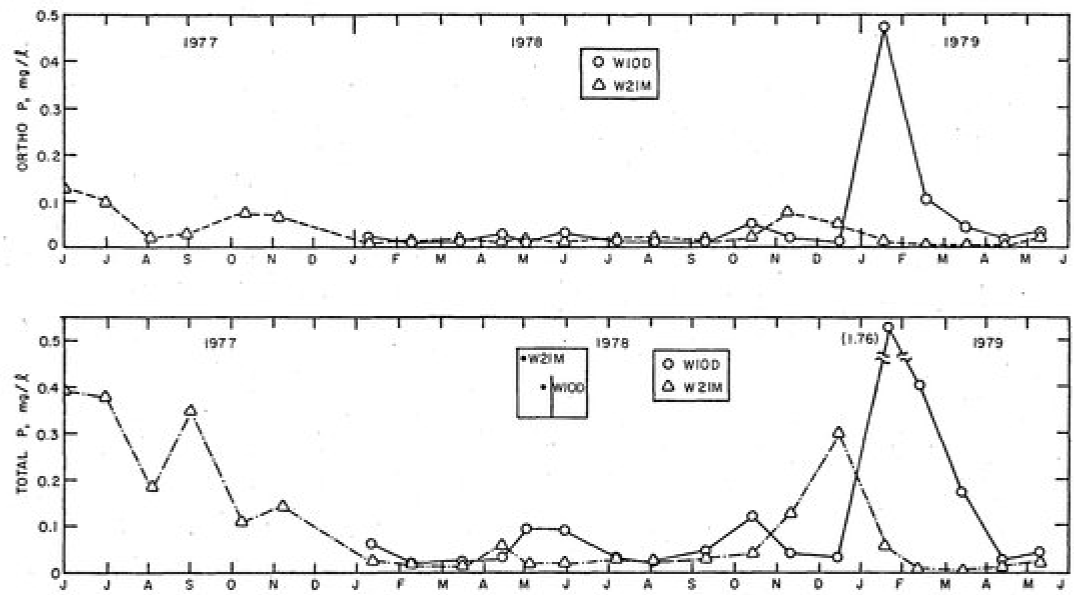



Figure 35. Phosphorus concentrations for wells in Plot C (4.4 cm/wk of fresh water).



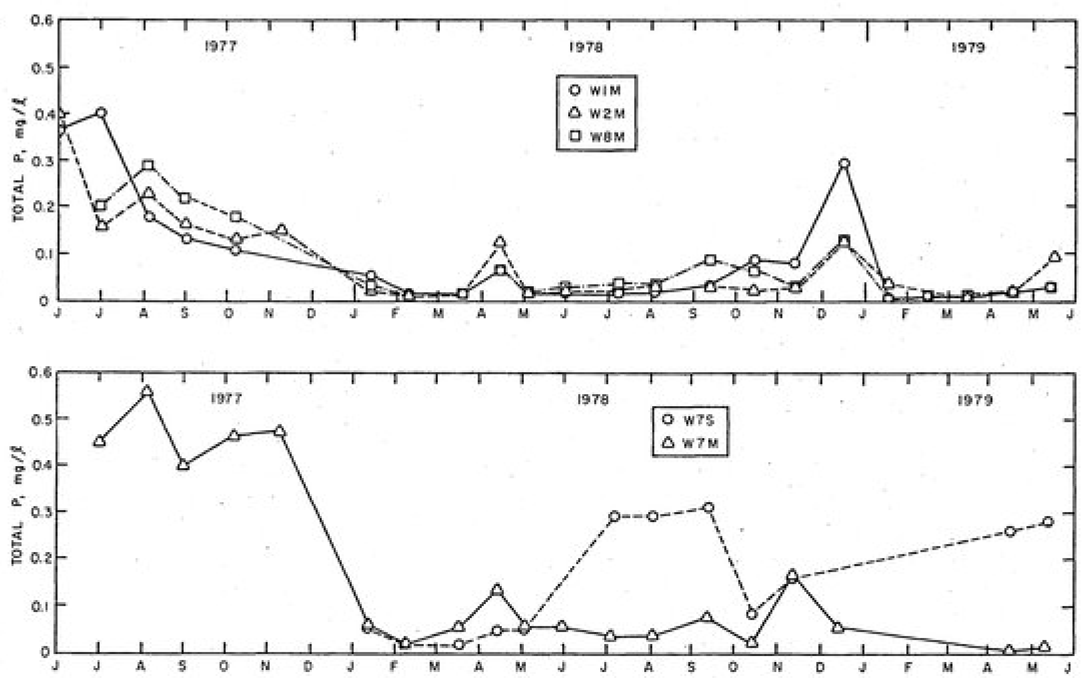



Figure 36. Total phosphorus concentrations for the natural marsh wells. See Fig. 5 for sampling locations.

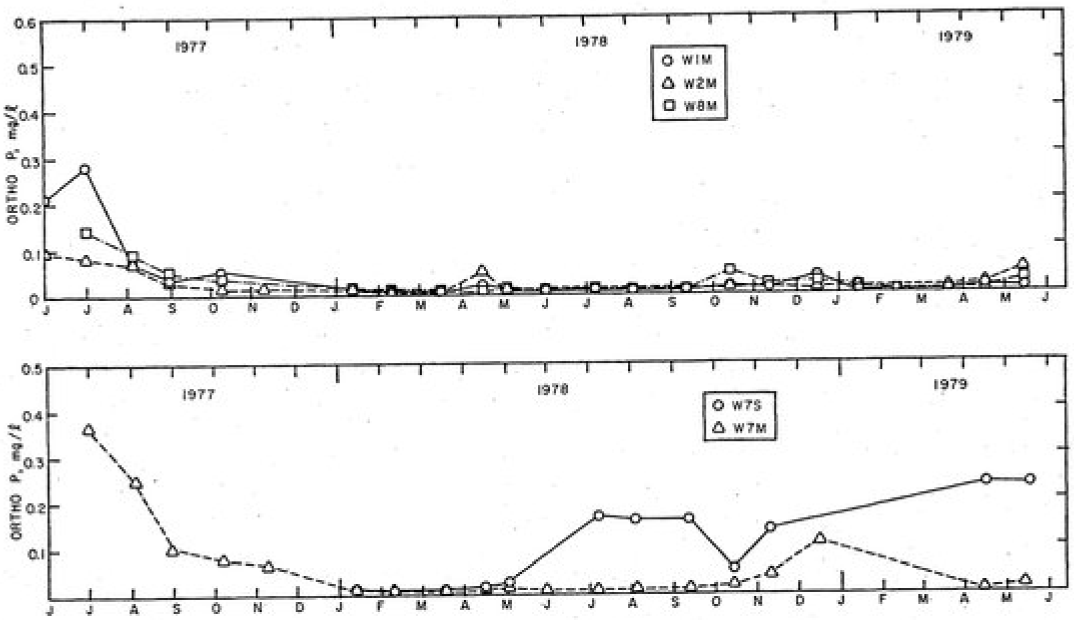



Figure 37. Orthophosphate concentrations for the natural marsh wells (see Fig. 5 for sampling locations).



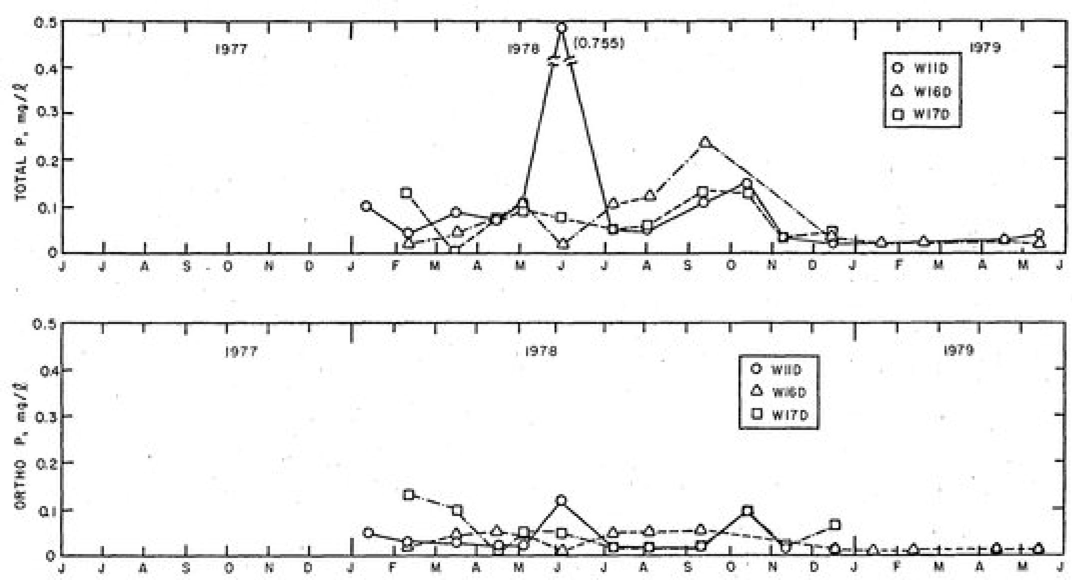



Figure 38. Phosphorus concentrations for the natural marsh deep wells (see Fig. 5 for sampling locations).

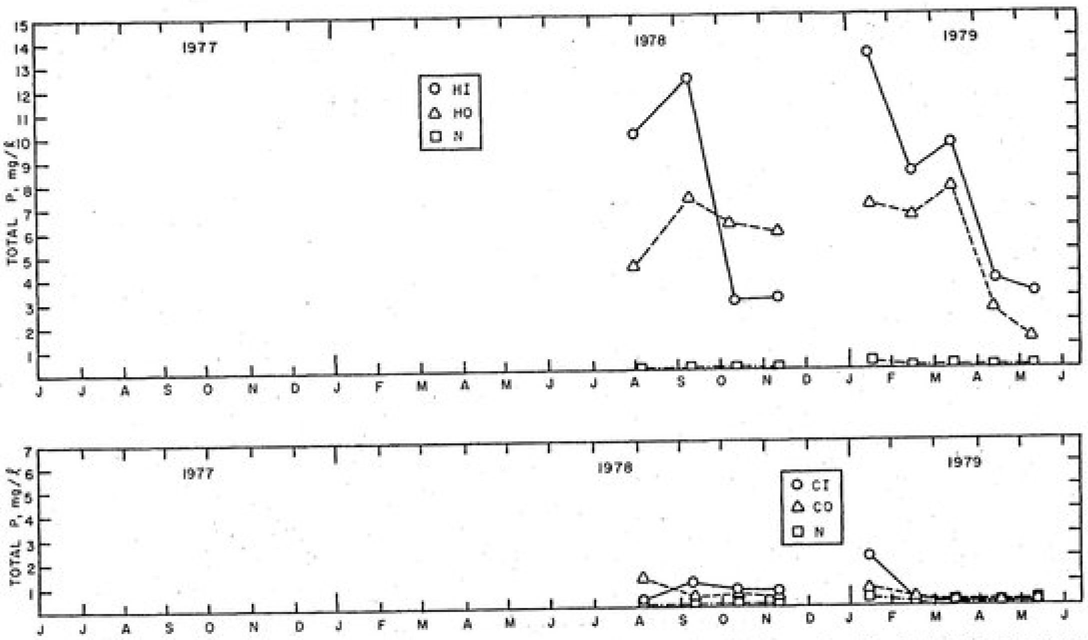



Figure 39. Surface water total phosphorus concentrations for Plot H (upper chart), Plot C (lower chart), and the undisturbed natural marsh ( N). The inside values (near the distribution pipe) are denoted by "I", with "O" representing values outside the influence of the distribution pipe but still within the plot. No data means no surface water was present.

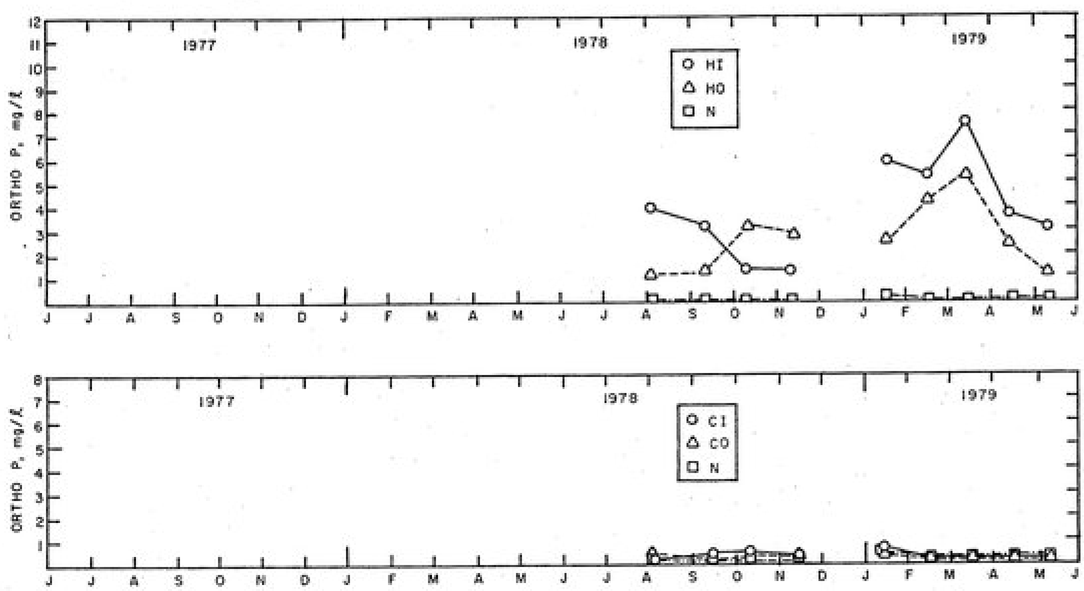



Figure 40. Surface water orthophosphate concentrations for Plot H (upper chart), Plot C (lower chart), and the undisturbed natural marsh ( N). The inside values (near the distribution pipe) are denoted by "I", with "O" representing values outside the influence of the distribution pipe but still within the plot. No data means no surface water was present.

surface between May and June of 1978. Surface water samples were collected during August 1978. Figure 39 compares the total phosphorus concentrations of the inside (near the application pipe) and outside region of Plot H and Plot C with the natural marsh surface concentrations. The high values presented (generally greater than 4.0 mg/l) for Plot H reflect the treated wastewater loading, release of phosphorus from sediments, and decomposition. During October and November 1978, the inside concentrations of phosphorus in Plot H were lower than the concentrations exhibited in the outside region of the plot. This phenomena may be attributed to increased algal activity toward the inside of the plot during this time. Clorophyll-a concentrations of composite samples collected from the inside and outside portions of Plots H, M, and C are shown in Table 21. These values indicated greater algal productivity and therefore greater phosphorus uptake toward the inside of Plot H. It should be noted that only two monthly samples were taken, and that clorophyll-a determinations were not a part of the regular analysis schedule. The higher algal productivity near the distribution pipes of all sampled plots would result in more phosphorus being tied up in algal cells and therefore not measured in the water samples when they were filtered.

Figure 39 also compares the total phosphorus concentration of Plot C surface water with the natural marsh surface water. The mean concentration of total phosphorus in the outside region surface water of Plot C was not significantly different from the surface water concentration in the natural marsh. Figure 40 shows orthophosphate concentrations for the surface waters in Plots C and H. Figure 41 represents the surface water total phosphorus and orthophosphate concentrations present in the Palatlakaha River and Lake Hiawatha.

In summary the trends in phosphorus concentration observed for wells in Plots H, M, L and C parallel the trends observed in natural marsh wells over the course of this study. All wells reported relatively high concentrations of phosphorus from the time treated wastewater was first applied (June 1977) through December 1977. These high values were followed by a period of low, stable phosphorus

Table 21. Chlorophyll-a results for Plots H, M, L, and C (9.6, 3.7, and 1.5 cm/wk of treated wastewater and 4.4 cm/wk of fresh water, respectively), and the undisturbed natural marsh (N).

| Location | Chlorophyll-a 2/17/79 | ($mg/m^3$) 3/16/79 |
|---|---|---|
| Plot H | | |
| Inside | 4247 | 7144 |
| Outside | 226 | 826 |
| Plot M | | |
| Inside | 1402 | 3095 |
| Outside | 97 | -- |
| Plot C | | |
| Inside | 3868 | 495 |
| Outside | 357 | 66 |
| Natural Marsh | 255 | 111 |

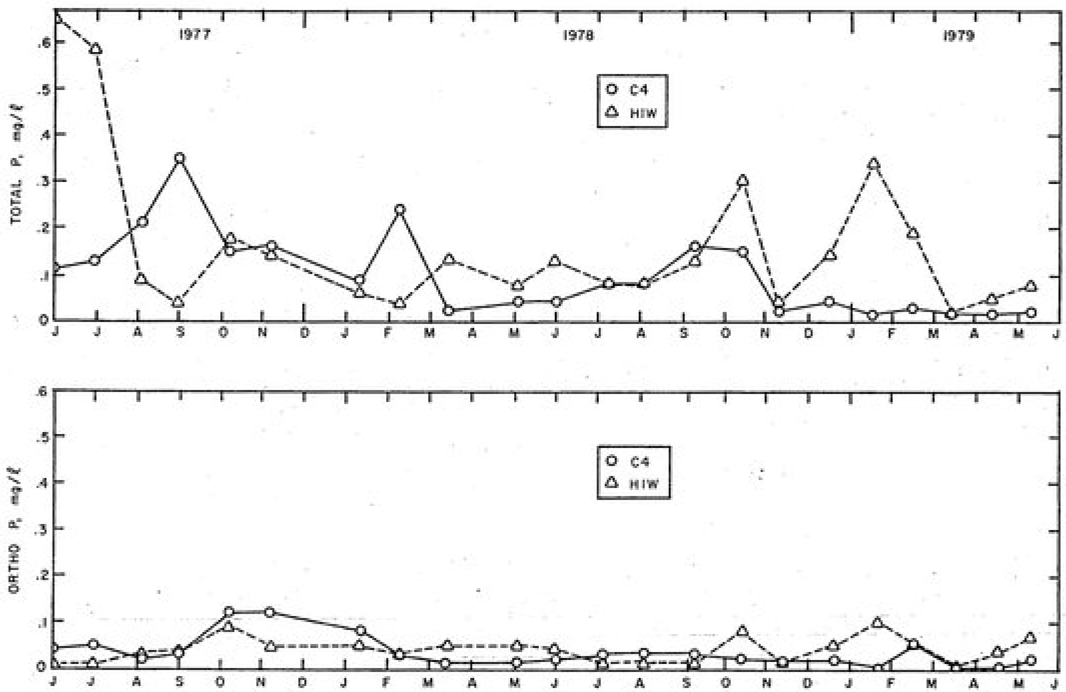



Figure 41. River phosphorus concentrations (see Fig. 2 for sampling locations).

concentrations with the exception of the Plot H wells W3M, W3D, W3S, W12M and W12D. During the winter of 1978 all wells showed high phosphorus concentrations, which were probably caused by decomposition of dead marsh vegetation.

Surface water concentrations of phosphorus generally reflected the phosphorus concentrations found in the applied treated wastewater as well as decomposition and peat soil desorption phenomena. The data reported for surface water phosphorus concentrations (Figs. 39 and 40) indicate the necessity for treated wastewater to be confined and forced to exit the confinement area via groundwater discharge.

Phosphorus Aboveground Vegetation Values

Tables 22 and 23 present the concentration of phosphorus in the major plant species of Plots H and C during the dry period of the study. Table 24 presents the concentration of phosphorus in three major plant categories: live aboveground vegetation, semiwoody vegetation, and aboveground dead material in Plots H and C during the wet period of the study. During the dry period in the freshwater plot (Plot C), there were no large differences in phosphorus levels over time or between species. Panicum, a grass, generally exhibited lower phosphorus concentrations than Sagittaria or Pontederia. The phosphorus level in the aboveground dead material remained nearly constant. There were no apparent differences between the concentrations found in the inside region samples of the plot versus the outside region samples.

The vegetation in Plot H exhibited marked differences in phosphorus levels depending on the location of the sample. All the aboveground plants collected from the inside of Plot H after April 1977 exhibited a large increase in phosphorus levels as compared to the outside samples for Plot H. The concentration in the Sagittaria stem samples collected from the inside underwent more than four-fold increase in phosphorus content betweeen April and June 1977. The levels in Panicum increased three-fold. A continual increase in the phosphorus concentration of the aboveground dead vegetation was seen for the inside region samples of Plot H.

Table 22. Phosphorus content of marsh vegetation in Plot H (9.6 cm/wk of of treated wastewater). Values are expressed as parts per hundred of phosphorus (%P).

| Sampling Date | Sagittaria Leaf | Sagittaria Stem | Pontederia Leaf | Pontederia Stem | Panicum | Hibiscus | Aboveground Dead |
|---|---|---|---|---|---|---|---|
| | | | | Outside Region | | | |
| 4/25/77 | 0.15 | 0.17 | 0.12 | 0.10 | 0.06 | --- | 0.04 |
| 6/10/77 | 0.17 | 0.15 | 0.10 | 0.08 | 0.10 | --- | 0.05 |
| 7/8/77 | 0.28 | 0.37 | 0.24 | 0.15 | 0.15 | --- | 0.07 |
| 8/11/77 | 0.22 | 0.35 | --- | 0.16 | 0.15 | --- | 0.06 |
| 9/15/77 | 0.23 | 0.22 | --- | 0.28 | 0.14 | 0.10 | 0.08 |
| 12/3/77 | --- | --- | --- | --- | 0.16 | --- | 0.08 |
| 2/20/78 | --- | 0.52 | --- | --- | 0.31 | --- | 0.08 |
| | | | | Inside Region | | | |
| 4/25/77 | 0.22 | 0.17 | 0.11 | 0.09 | 0.09 | --- | 0.04 |
| 6/10/77 | 0.47 | 0.75 | 0.41 | 0.59 | 0.29 | --- | 0.20 |
| 7/8/77 | 0.41 | 0.65 | 0.46 | 0.46 | 0.25 | 0.33 | 0.12 |
| 8/11/77 | 0.38 | 0.66 | 0.29 | 0.57 | 0.26 | 0.46 | 0.23 |
| 9/15/77 | 0.28 | 0.45 | --- | --- | 0.16 | 0.49 | 0.32 |
| 12/3/77 | --- | 0.56 | --- | --- | 0.18 | 0.34 | 0.32 |
| 2/20/78 | --- | 0.73 | --- | --- | 0.24 | --- | 0.36 |

[a]Outside values represent samples collected from the outer region of the plot; inside values represent samples collected from the interior region (near the distribution pipe).

Table 23. Phosphorus content of marsh vegetation in Plot C (4.4 cm/wk) of fresh water. Values are expressed as parts per hundred of phosphorus (%P).

| Sampling Date | Sagittaria Leaf | Sagittaria Stem | Pontederia Leaf | Pontederia Stem | Panicum | Hibiscus | Aboveground Dead |
|---|---|---|---|---|---|---|---|
| | | | Outside Region | | | | |
| 4/25/77 | 0.18 | 0.17 | 0.13 | 0.11 | 0.08 | --- | 0.06 |
| 6/1 | 0.18 | 0.14 | 0.09 | 0.06 | 0.07 | 0.15 | 0.06 |
| 7/8/77 | 0.17 | 0.20 | 0.09 | 0.06 | 0.08 | --- | 0.06 |
| 8/11/77 | 0.14 | 0.13 | --- | --- | 0.07 | --- | 0.05 |
| 9/1 | 0.20 | 0.22 | 0.20 | 0.06 | 0.09 | --- | 0.07 |
| 12/3/77 | --- | 0.13 | --- | --- | 0.05 | --- | 0.06 |
| 2/20/78 | --- | 0.63 | --- | --- | 0.17 | --- | 0.07 |
| | | | Inside Region | | | | |
| 4/25/77 | 0.15 | 0.17 | 0.14 | 0.10 | 0.07 | --- | 0.06 |
| 6/10/77 | 0.17 | 0.15 | 0.09 | 0.08 | 0.10 | --- | 0.06 |
| 7/8/77 | 0.16 | 0.09 | --- | 0.05 | 0.07 | 0.11 | 0.05 |
| 8/11/77 | 0.14 | 0.16 | --- | 0.06 | 0.05 | 0.15 | 0.06 |
| 9/15/77 | 0.16 | 0.12 | --- | --- | 0.08 | --- | 0.07 |
| 12/3/77 | --- | 0.13 | --- | --- | 0.06 | 0.03 | 0.07 |
| 2/20/78 | --- | 0.75 | --- | --- | 0.16 | --- | 0.09 |

[a]Outside values represent samples collected from the outer region of the plot; inside values represent samples collected from the interior region (near the distribution pipe).

Table 24. Phosphorus content of marsh vegetation in Plots H and C (9.6 cm/wk of treated wastewater and 4.4 cm/wk of freshwater, respectively). Values are expressed as % phosphorus and represent weighted averages.[a]

| Sampling Date | Plot H | | | Plot C | | |
|---|---|---|---|---|---|---|
| | Above ground Live[b] | Woody Tissue | Above ground Dead | Above ground Live[b] | Woody Tissue | Above ground Dead |
| | | | Outside Region | | | |
| 4/14/78 | 0.454 | 0.140 | 0.150 | 0.491 | --- | 0.131 |
| 6/24/78 | 0.381 | --- | 0.170 | 0.268 | 0.054 | 0.117 |
| 9/11/78 | 0.454 | 0.169 | 0.179 | 0.237 | 0.098 | 0.133 |
| 2/17/79 | 0.112 | 0.056 | 0.064 | 0.161 | --- | 0.002 |
| | | | Inside Region | | | |
| 4/14/78 | 0.548 | --- | 0.179 | 0.606 | --- | 0.096 |
| 6/24/78 | 0.474 | 0.289 | 0.198 | 0.324 | 0.206 | 0.056 |
| 9/11/78 | 0.517 | 0.071 | 0.266 | 0.400 | 0.196 | 0.141 |
| 2/17/79 | 0.199 | 0.084 | 0.053 | 0.084 | 0.014 | 0.036 |

[a]Values calculated by weighting averages based on sample size.

[b]Excluding live woody and dead woody tissue.

During the wet period, aboveground live vegetation in the freshwater plot (Plot C) showed a general decreasing trend in phosphorus, levels for both inside and outside regions of the plot. Semiwoody species exhibited lower phosphorus concentrations than nonwoody vegetation, and those semiwoody species located toward the inside of the plot had higher concentrations that those semiwoody species located toward the plots's outside. Aboveground dead concentration remained constant over time and location with the exception of the February 17, 1979 sampling period, which showed very low phosphorus concentrations for both inside and outside regions of the plot.

During the wet year, the phosphorus content of the aboveground live vegetation in Plot H remained constant in both the inside and outside regions of the plot until the February 17, 1979 sampling period. Both inside and outside regions of the plot showed reduced phosphorus levels during this period.

Figure 42 shows the average phosphorus content of live aboveground vegetation (including semiwoody species) for Plots H and C. The inside vegetation found in Plot H showed a rapid increase in phosphorus content after treated wastewater application began on May 1, 1977. The phosphorus content of the outside vegetation in Plot H showed an increase as the water level in the plot became higher. This trend may reflect redistribution of phosphorus from the peat complex and the more uniform distribution of applied treated wastewater. The phosphorus concentration of the control plot aboveground live vegetation (both inside and outside) also increased during the wet period. The vegetation in both Plots H and C showed reduced phosphorus concentrations during the February 17, 1979 sampling period.

Tables 25 to 28 present uptake and changes in phosphorus storage for aboveground live and aboveground dead components for Plots H and C. These values were calculated from area-weighted standing crop data and the average phosphorus concentrations shown in Fig. 42. In comparison to Plot C, Plot H exhibited higher rates of phosphorus uptake during the dry growing season (April 15 - August 8, 1977). The aboveground dead vegetative fraction showed a slight

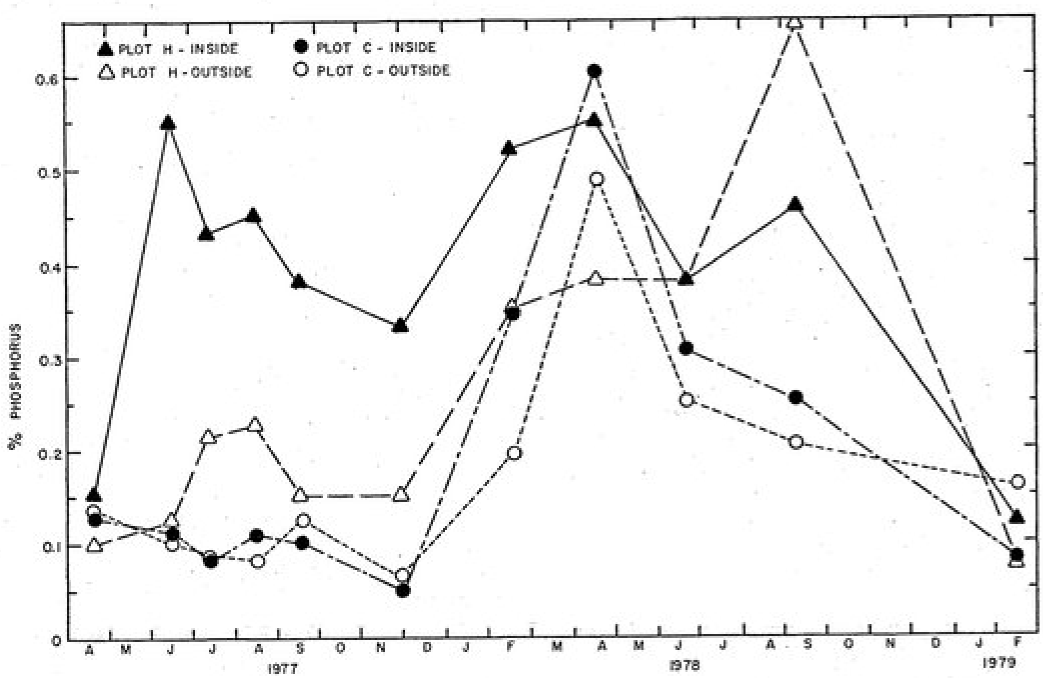



Figure 42. Average phosphorus concentrations in live aboveground biomass in Plot C (4.4 cm/wk of fresh water) and Plot H (9.6 cm/wk of treated wastewater).

Table 25. Uptake of phosphorus by above ground live vegetation in Plot H (9.6 cm/wk of treated wastewater).

| Sampling Date | t (days) | Total Live Aboveground[a] $g\ P/m^2$ | Uptake[b] $g\ P/m^2 \cdot d$ | Seasonal Uptake[c] $g\ P/m^2 \cdot season$ | Yearly Uptake[d] $g\ P/m^2 \cdot yr$ |
|---|---|---|---|---|---|
| 4/25/77 | | 0.281 | | | |
| | 46 | | +0.015 | | |
| 6/10/77 | | 0.979 | | | |
| | 28 | | +0.028 | +2.049 | |
| 7/8/77 | | 1.757 | | | |
| | 34 | | +0.017 | | |
| 8/11/77 | | 2.330 | | | +1.109 |
| | 35 | | -0.004 | | |
| 9/15/77 | | 2.178 | | | |
| | 79 | | -0.018 | -2.112 | |
| 12/3/77 | | 0.748 | | | |
| | 79 | | -0.007 | | |
| 2/20/78 | | 0.218 | | | |
| | 53 | | +0.022 | | |
| 4/14/78 | | 1.390 | | | |
| | 71 | | +0.027 | +2.668 | |
| 6/24/78 | | 3.327 | | | |
| | 79 | | +0.009 | | -0.828 |
| 9/11/78 | | 4.058 | | | |
| | 159 | | -0.022 | -3.496 | |
| 2/17/79 | | 0.562 | | | |

[a]Values calculated from mean standing crop data (inside and outside) and the average phosphorus concentrations.

[b]Values represent the difference between two sampling dates divided by the number of days in the interval.

[c]Seasons represented by the dates4/25/77 to 8/11/77 (growth); 8/11/77 to 2/20/78 (dieback); 4/14/78 to 9/11/78 (growth); 9/11/78 to 2/17/79 (dieback).

[d]Assumed no change from 2/17/79 to 4/14/79.

Table 26. Changes in phosphorus storage in above ground dead vegetation in Plot H (9.6 cm/wk of treated wastewater).

| Sampling Date | t (days) | Total Dead[a] g P/m$^2$ | Change in Storage[b] g P/m$^2$·d | Seasonal Change[c] g P/m$^2$·season | Yearly Change[d] g P/m$^2$·yr |
|---|---|---|---|---|---|
| 4/25/77 | | 0.207 | | | |
| | 46 | | +0.005 | | |
| 6/10/77 | | 0.440 | | | |
| | 28 | | +0.003 | +0.511 | |
| 7/8/77 | | 0.525 | | | |
| | 34 | | +0.006 | | |
| 8/11/77 | | 0.718 | | | +1.186 |
| | 35 | | +0.009 | | |
| 9/15/77 | | 1.029 | | | |
| | 79 | | +0.006 | +0.649 | |
| 12/3/77 | | 1.464 | | | |
| | 79 | | -0.001 | | |
| 2/20/78 | | 1.367 | | | |
| | 53 | | +0.001 | | |
| 4/14/78 | | 1.393 | | | |
| | 71 | | -0.013 | | |
| 6/24/78 | | 0.509 | | -0.371 | |
| | 79 | | +0.007 | | -1.064 |
| 9/11/78 | | 1.022 | | | |
| | 159 | | -0.004 | -0.693 | |
| 2/17/79 | | 0.329 | | | |

[a] Values calculated from mean standing crop data (inside and outside) and the average phosphorus concentration.

[b] Values represent difference between two sampling dates divided by the number of days in the interval.

[c] Seasons represented by the dates 4/25/77 to 8/11/77 (growth); 8/11/77 to 2/20/78 (dieback); 4/14/78 to 9/11/78 (growth); 9/11/78 to 2/17/79 (dieback).

[d] Assumed no change from 2/17/79 to 4/14/79.

Table 27. Uptake of phosphorus in above ground live vegetation in Plot C (4.4 cm/wk of fresh water).

| Sampling Date | t (days) | Total Live Aboveground[a] g P/m$^2$ | Uptake[b] g P/m$^2$·d | Seasonal Uptake[c] g P/n$^2$·season | Yearly Uptake[d] g P/m$^2$·yr |
|---|---|---|---|---|---|
| 4/25/77 | | 0.312 | | | |
| | 46 | | -0.004 | | |
| 6/10/77 | | 0.119 | | | |
| | 28 | | +-.005 | +0.164 | |
| 7/8/77 | | 0.261 | | | |
| | 34 | | +0.006 | | |
| 8/11/77 | | 0.476 | | | |
| | 35 | | +0.004 | | +0.610 |
| 9/15/77 | | 0.625 | | | |
| | 79 | | -0.007 | | |
| 12/3/77 | | 0.099 | | -0.399 | |
| | 79 | | 0.000 | | |
| 2/20/78 | | 0.077 | | | |
| | 53 | | +0.016 | | |
| 4/14/78 | | 0.922 | | | |
| | 71 | | +0.011 | +1.727 | |
| 6/25/78 | | 1.707 | | | |
| | 79 | | +0.012 | | -0.697 |
| 9/11/78 | | 2.649 | | | |
| | 159 | | -0.015 | -2.424 | |
| 2/17/79 | | 0.225 | | | |

[a]Values calculated from mean standing crop data (inside and outside) and the average phosphorus concentrations.

[b]Values represent the difference between two sampling dates divided by the number of days in the intervals.

[c]Seasons represented by the dated 4/25/77 to 8/11/77(growth); 8/11/77 to 2/20/78 (dieback); 4/14/78 to 9/11/78 (growth); 9/11/78 to 2/17/79 (dieback).

[d]Assumed no change from 2/17/79 to 4/14/79.

Table 28. Changes in phosphorus storage in above ground dead vegetation in Plot C (4.4 cm/wk of freshwater).

| Sampling Date | t (days) | Total Dead[a] g P/m$^2$ | Change in Storage[b] g P/m$^2$·d | Seasonal Change[c] g P/m$^2$·season | Yearly Change[d] g P/m$^2$·yr |
|---|---|---|---|---|---|
| 4/25/77 | | 0.396 | | | |
| | 46 | | 0.000 | | |
| 6/10/77 | | 0.404 | | | |
| | 28 | | -0.006 | -0.113 | |
| 7/8/77 | | 0.241 | | | |
| | 34 | | +0.001 | | |
| 8/11/77 | | 0.283 | | | +1.000 |
| | 35 | | 0.000 | | |
| 9/15/77 | | 0.293 | | | |
| | 79 | | +0.001 | +0.357 | |
| 12/3/77 | | 0.386 | | | |
| | 79 | | +0.003 | | |
| 2/20/78 | | 0.640 | | | |
| | 53 | | +0.016 | | |
| 4/14/78 | | 1.396 | | | |
| | 71 | | -0.014 | | |
| 6/24/78 | | 0.435 | | -0.158 | |
| | 79 | | +0.010 | | -1.336 |
| 9/11/78 | | 1.238 | | | |
| | 159 | | -0.007 | -1.178 | |
| 2/20/79 | | 0.060 | | | |

[a]Values calculated from mean standing crop data (inside and outside) and the average phosphorus concentration.

[b]Values represent difference between two sampling dates divided by the number of days in the interval.

[c]Seasons represented by the dated 4/25/77 to 8/11/77 (growth); 8/11/77 to 2/20/78 (dieback); 4/14/78 to 9/11/78 (growth); 9/11/78 to 2/17/79 (dieback).

[d]Assumed no change from 2/17/79 to 4/14/79.

uptake in Plot H and a slight decrease in Plot C for the dry growing season.

Both Plots H and C exhibited phosphorus reductions in the aboveground live vegetation during the dry dieback season (August 8, 1977 to February 20, 1978) due to lower standing stocks. The magnitude of this reduction was approximately the same as the uptakes noted during the growing season. Increased uptake of phosphorus was noted for the dead vegetation during this dieback season for both plots.

The uptake of phosphorus in Plot C by aboveground live vegetation during the wet growing season (April 14, 1978 - September 11, 1978) was significantly greater ($\alpha = 0.05$) than the uptake exhibited during the dry growing season. The uptake of phosphorus exhibited by the vegetation in Plot H during the wet season was also greater than the uptake shown during the dry growing season. The aboveground dead fraction exhibited releases during this period in both Plots H and C.

Both aboveground live and dead vegetation for Plots H and C exhibited releases during the wet dieback season (September 11, 1978 - February 17, 1979).

On a yearly basis, the live vegetation in Plots H and C exhibited phosphorus uptake during the dry year (April 14, 1978 - February 17, 1979). The releases observed for both aboveground live and dead vegetation during the wet year were approximately equivalent to the uptaked observed during the dry year for both plots.

## Phosphorus Belowground Vegetation Values

The concentrations of phosphorus in the belowground standing crop showed seasonal fluctuations as well as a response to dry and wet conditions. Figure 43 shows root phosphorus concentrations as they appeared in the high loading plot and the control plot. Lower concentrations were found during the marsh growth period (April - June 1978) and higher concentrations were found during the peak standing crop concentration period (August - September 1977 and 1978). The seasonal trends in root storage of phosphorus may

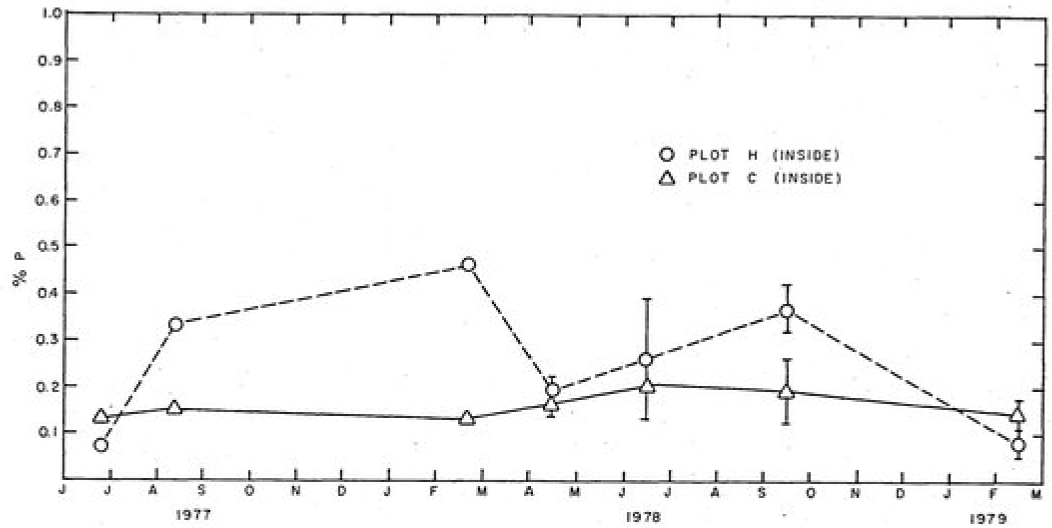



Figure 43. Inside (near the distribution pipe) root phosphorus concentrations for Plot H (9.6 cm/wk). Valves after Feb. 1978 ± 1 S.E.

correspond to nutrient translocations in response to aboveground growth.

The evaluation of storage capacity and uptake of phosphorus by roots is presented in Tables 29 and 30. During the dry growing season (April - August 1977), extremely high uptake rates were observed (121 mg P/$m^2$·day) in Plot H. A small release of phosphorus (25 mg P/$m^2$·day) was observed during the dry dieback season (August 1977 - February 1978). During the wet growing season (April - September 1978), roots had less phosphorus uptake (29 mg P/$m^2$·day) than during the dry growing season. A large reduction was observed for the wet dieback season (50 mg P/$m^2$·day).

On a yearly basis, the dry year (April 1977 - April 1978) had an overall uptake of approximately 3.5 g P/$m^2$, and the wet year (April 1978 - February 1979) had an overall loss of approximately 3.7 g P/$m^2$. Over a two-year period, there was no net uptake by the root system in the high loading plot.

The control plot showed negligible fluctuations in root phosphorus concentrations (Fig. 43). Uptake of phosphorus by roots in the control plot is shown in Table 30. The yearly trends observed for Plot H were seen in Plot C. The dry year had an overall uptake while the wet year had an overall reduction.

Phosphorus in Peat Soil

Table 31 presents peat soil phosphorus concentrations measured in Plots H, M, and C, together with the phosphorus levels measured in an undisturbed, "natural" area of the research marsh (N). The phosphorus concentrations shown for the first sampling period (March 16, 1978) represent samples taken from the inside portions of Plots H and C. The September 22, 1978 and February 17, 1979 sampling periods included inside and outside samples.

The data show a general decrease in peat soil phosphorus concentrations for each sampling period. However, there was no significant difference ($\alpha$ = 0.05) in the peat soil phosphorus concentrations between plots for a specific sampling period. There was also no significant difference between the inside and outside region samples

Table 29. Phosphorus uptake by roots in Plot H (9.6 cm/wk treated wastewater).

| Sampling Date | Total Phosphorus ($g\ P/m^2$) | t (days) | Uptake of Phosphorus[b] ($g\ P/m^2 \cdot d$) | Seasonal Uptake ($g\ P/m^2 \cdot season$) | Yearly Uptake ($g\ P/m^2 \cdot yr$) |
|---|---|---|---|---|---|
| 4/25/77 | 2.061[a] | | | | |
| | | 108 | +0.121 | +13.053 | |
| 8/11/77 | 15.114 | | | | +3.547 |
| | | 193 | -0.025 | - 4.718 | |
| 2/20/78 | 10.396 | | | | |
| | | 53 | -0.090 | | |
| 4/14/78 | 5.608 | | | | |
| | | 71 | -0.006 | | |
| 6/24/78 | 5.220 | | | + 4.300 | |
| | | 79 | +0.059 | | -3.705 |
| 9/11/78 | 9.908 | | | | |
| | | 159 | -0.050 | - 8.005 | |
| 2/17/79 | 1.903 | | | | |

[a]Value calculated using 4/14/78 biomass data.

[b]Calculated by dividing the change in total phosphorus between sampling periods by length of the interval.

Table 30. Phosphorus uptake by roots in Plot C (4.4 cm/wk freshwater).

| Sampling Date | Total Phosphorus ($g\ P/m^2$) | t (days) | Uptake of Phosphorus[b] ($g\ P/m^2 \cdot d$) | Seasonal Uptake ($g\ P/m^2 \cdot season$) | Yearly Uptake ($g\ P/m^2 \cdot yr$) |
|---|---|---|---|---|---|
| 4/25/77 | 3.731[a] | | | | |
| | | 108 | -0.014 | -1.541 | |
| 8/11/77 | 2.190 | | | | +1.216 |
| | | 193 | +0.005 | +0.982 | |
| 2/20/78 | 3.172 | | | | |
| | | 53 | +0.034 | | |
| 4/14/78 | 4.947 | | | | |
| | | 71 | -0.019 | +0.864 | |
| 6/24/78 | 3.597 | | | | |
| | | 79 | +0.028 | | -1.477 |
| 9/11/78 | 5.811 | | | | |
| | | 159 | -0.015 | -2.341 | |
| 2/17/79 | 3.470 | | | | |

[a]Value calculated using 4/14/78 biomass data.

[b]Calculated by dividing the change in total phosphorus between sampling periods by length of the interval.

Table 31. Overall (inside and outside) phosphorus content of soil samples collected in March 1978, September 178, and February from Plot C (4.4 cm/wk fresh water), Plot H (9.6 cm/wk treated wastewater Plot M (3.7 cm/wk treated wastewater), and an undisturbed natural area (N). Values are in %P, mean ± standard error, sample size series.

| Date | Depth (cm) | H | M | C | N |
|---|---|---|---|---|---|
| 3/16/78 | 0-25 | 0.110±.005 | --- | 0.090±.003 | 0.090±.001 |
| | 25-50 | 0.080±.007 | --- | 0.090±.002 | 0.070±.003 |
| | 50-75 | 0.060±.002 | --- | 0.080±.004 | 0.050±.003 |
| | Total | 0.083±.005 | --- | 0.087±.003 | 0.070±.002 |
| 9/11/78 | 0-25 | 0.089±.008 | 0.090±.003 | 0.096±.008 | 0.087±.001 |
| | 25-50 | 0.068±.002 | 0.070±.002 | 0.087±.003 | 0.072±.003 |
| | 50-75 | 0.064±.002 | 0.067±.004 | 0.075±.004 | 0.073±.005 |
| | Total | 0.074±.004 | 0.075±.003 | 0.086±.004 | 0.077±.003 |
| 2/17/79 | 0-25 | 0.074±.005 | 0.081±.004 | 0.073±.003 | 0.085±.007 |
| | 25-50 | 0.066±.004 | 0.071±.005 | 0.066±.005 | 0.063±.013 |
| | 50-75 | 0.063±.006 | 0.059±.002 | 0.058±.002 | 0.063±.010 |
| | Total | 0.068±.003 | 0.070±.003 | 0.066±.002 | 0.070±.006 |

[a]Pipe-influenced area only (inside).

for September 11, 1978 and February 17, 1979. This information provided the criteria for comparing March 16, 1978 (inside only) with the other two sampling periods (inside and outside).

The data presented for the March 16, 1978 sampling period indicated that the peat soil phosphorus concentrations found in Plot H tended to be greater than those found in the natural marsh. The Plot H concentrations for the 0-25 cm and 50-75 cm levels were significantly higher than the natural marsh values ($\alpha = 0.10$). The control plot (C) also showed significantly higher peat soil phosphorus concentrations at the 25-50 cm and 50-75 cm levels ($\alpha = 0.10$) than the natural marsh.

The control plot peat soil phosphorus concentrations for the Semptember 11, 1978 sampling period were significantly higher than those concentrations found in Plots H and M. However, these values were not significantly different from the peat soil phosphorus concentrations found in the natural marsh ($\alpha = 0.05$). The overall concentrations as well as the depth interval concentrations (0-25 cm, 25-50 cm, and 50-75 cm) for Plots H, M, and the natural marsh were not significantly different ($\alpha = 0.05$). The peat soil phosphorus concentrations for the February 17, 1979 sampling period showed no significant difference between any of the plots, including the natural marsh.

Summarizing the data presented in Table 31, it appears that over approximately a one-year period (March 16, 1978 - February 17, 1979), peat soil phosphorus concentrations have decreased throughout the plots and the natural marsh regardless of treated wastewater loadings.

Table 32 shows peat soil phosphorus uptake values for the natural marsh and the experimental plots. The data indicate a phosphorus uptake of 0.072 g $P/m^2 \cdot day$ in the natural marsh during the interval between the March 16, 1978 sampling and the September 11, 1978 sampling. Both the control plot and the high loading plot show phosphorus losses during this period (0.021 g $P/m^2 \cdot day$ and 0.011 g $P/m^2 \cdot day$, respectively). The experimental plots and the natural marsh appear to release phosphorus during the September 11,

Table 32. Uptake of phosphorus by the peat soil in the natural marsh and Plots (9.6 cm/wk of treated wastewater) and C (4.4 cm/wk of freshwater).

| Plot | Depth (cm) | Phosphorus Concentration (g P/m$^2$) | Phosphorus Uptake ( P/m$^2$·d) | Phosphorus Concentration (g P/m$^2$) | Phosphorus Uptake (g P/m$^2$·d) | Phosphorus Concentration (g P/m$^2$) | Overall Uptake (g P/m$^2$·d) |
|---|---|---|---|---|---|---|---|
| | | 3/16/78 | | 9/11/78 | | 2/17/79 | |
| Natural marsh | 0-25 | 13.50 | -0.003 | 13.05 | -0.002 | 12.75 | -0.002 |
| | 25-50 | 12.60 | +0.002 | 12.96 | -0.010 | 11.34 | -0.003 |
| | 50-75 | 10.50 | +0.027 | 15.33 | -0.013 | 13.23 | +0.008 |
| | 75-150 | 37.20 | +0.045 | 45.26 | -0.039 | 39.06 | +0.006 |
| | Total | 73.80 | +0.072 | 86.60 | -0.064 | 76.38 | +0.008 |
| H | 0-25 | 16.50 | -0.018 | 13.35 | -0.014 | 11.10 | -0.016 |
| | 25-50 | 14.40 | -0.012 | 12.24 | -0.002 | 11.88 | -0.007 |
| | 50-75 | 12.60 | +0.005 | 13.44 | -0.001 | 13.23 | +0.002 |
| | 75-150 | 37.20 | +0.014 | 39.68 | -0.004 | 39.06 | +0.006 |
| | Total | 80.70 | -0.011 | 78.71 | -0.022 | 75.27 | -0.016 |
| C | 0-25 | 13.50 | +0.005 | 14.40 | -0.022 | 10.95 | -0.008 |
| | 25.50 | 16.20 | -0.003 | 15.66 | -0.024 | 11.88 | -0.013 |
| | 50-75 | 16.80 | -0.006 | 15.75 | -0.023 | 12.18 | -0.014 |
| | 75-150 | 49.60 | -0.017 | 46.50 | -0.066 | 35.96 | -0.040 |
| | Total | 96.10 | -0.021 | 92.31 | -0.134 | 70.97 | -0.074 |

1978 - February 17, 1979 sampling interval. The release observed in the control plot for this period was significantly greater ($\alpha = 0.05$) than the releases observed in the natural marsh and the high loading plot.

The losses of phosphorus from the peat soil complex may be at least in part explained by the flooded condition of the marsh during the sampling periods referred to in the preceding paragraph (March 16, 1978, September 11, 1978 and February 17, 1979). Flooding created anaerobic conditions in the peat, which may have allowed phosphorus bound as an iron-phosphorus complex to become mobile and therefore released (Stumm and Morgan 1970). The iron-phosphorus complex may have formed during the dry year of this study under aerobic conditions when phosphorus, in the presence of iron (III), was precipitated.

Unfortunately, the location of the phosphorus released from the peat soil complex was not known. Iron was not a parameter measured regularly during this study. There were no increases of phosphorus observed in well data or in the vegetative fractions measured during this period.

Peat Soil Adsorption Studies

Laboratory investigations were conducted to determine the possible capacity of the peat soil complex to adsorb phosphorus. The results of this study are summarized in Table 33. There was no significant difference between the means in each 25 cm interval ($\alpha = 0.05$). The data from Table 33 are plotted in Fig. 44.

To estimate adsorption as a function of the phosphorus content of the interstitial solution, the data were plotted as Freundlich adsorption isotherms. These plots are shown in Figs. 45-47. A Freundlich isotherm is an empirical model that assumes infinite adsorption is possible. The equation may take the form:

$$\log(x/m) = \log K + (1/n)\log C$$

where: $x/m$ = the quantity of phosphorus adsorbed per unit weight of dry soil

Table 33. Phosphorus adsorption study. Isotherms were conducted under the following conditions: pH 7.0, temperature 25°C, conductivity 670 μ mho/cm, time 48 hrs.

| Depth of Sample (cm) | Initial P Concentration (mg/l) | Average Equil. Concentration[a] (mg/l) | Average P Adsorbed (μg/g) |
|---|---|---|---|
| 0-25 | 0.00 | 0.32 | --- |
| | 6.32 | 5.05 | 127.0 |
| | 12.64 | 9.34 | 330.0 |
| | 57.25 | 43.13 | 1412.5 |
| | 87.34 | 61.50 | 2584.0 |
| | 110.73 | 88.04 | 2269.5 |
| 25-50 | 0.00 | 1.75 | --- |
| | 6.32 | 5.55 | 77.5 |
| | 12.64 | 9.96 | 268.0 |
| | 57.25 | 40.45 | 1680.5 |
| | 87.34 | 66.16 | 2118.0 |
| | 110.73 | 89.83 | 2090.5 |
| 50-75 | 0.00 | 1.35 | --- |
| | 6.32 | 4.66 | 166.5 |
| | 12.64 | 9.16 | 348.0 |
| | 57.25 | 46.25 | 1100.0 |
| | 87.34 | 73.31 | 1403.5 |
| | 110.73 | 94.74 | 1599.5 |

[a]Average of 2 replicate samples.

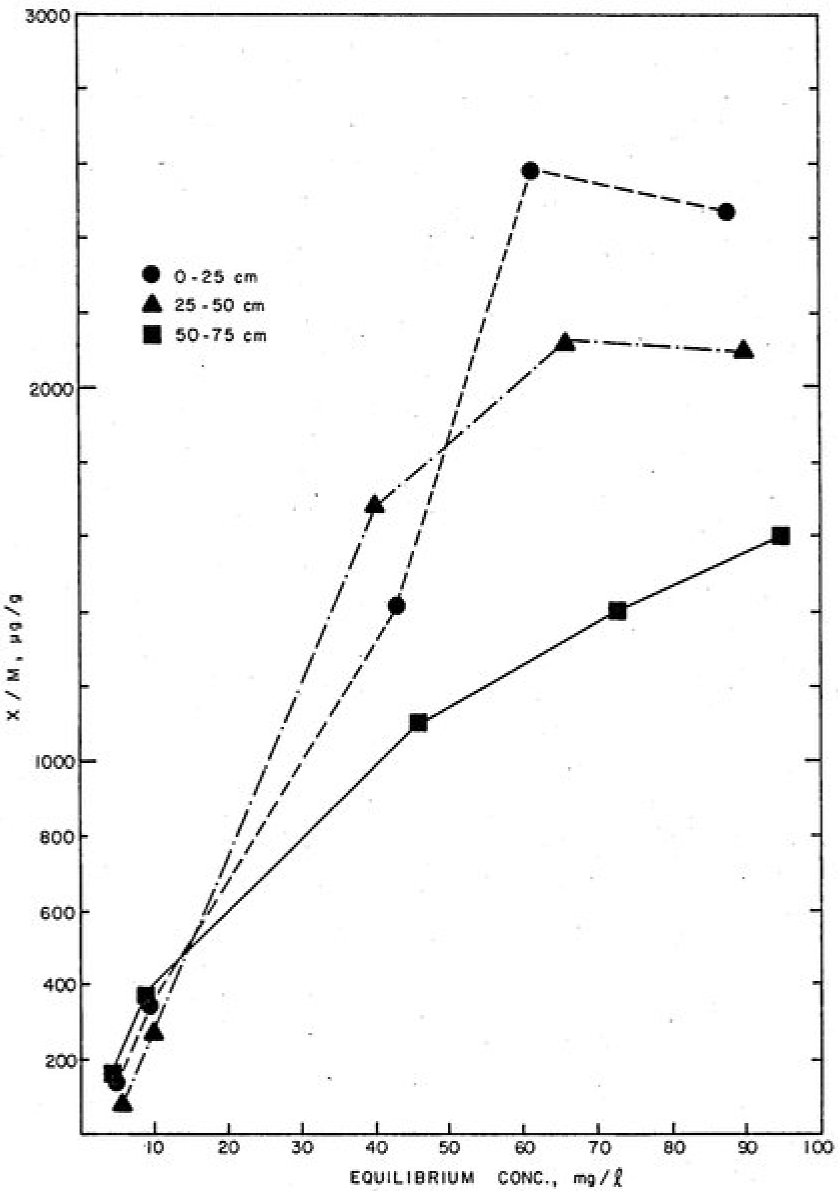



Figure 44. Adsorption isotherms for peat taken from the natural marsh.

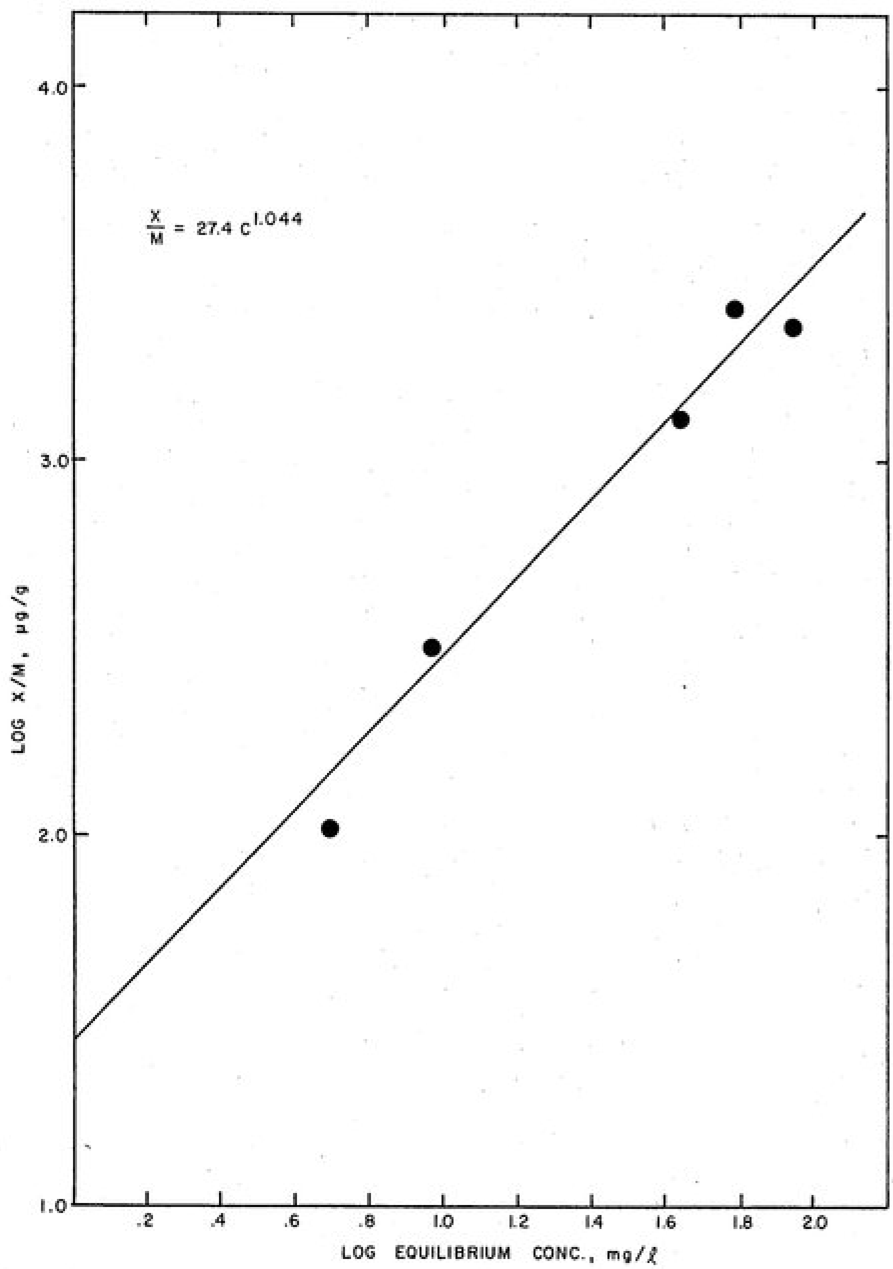



Figure 45. Freundlich isotherm for peat depth 0-25 cm for the natural marsh.

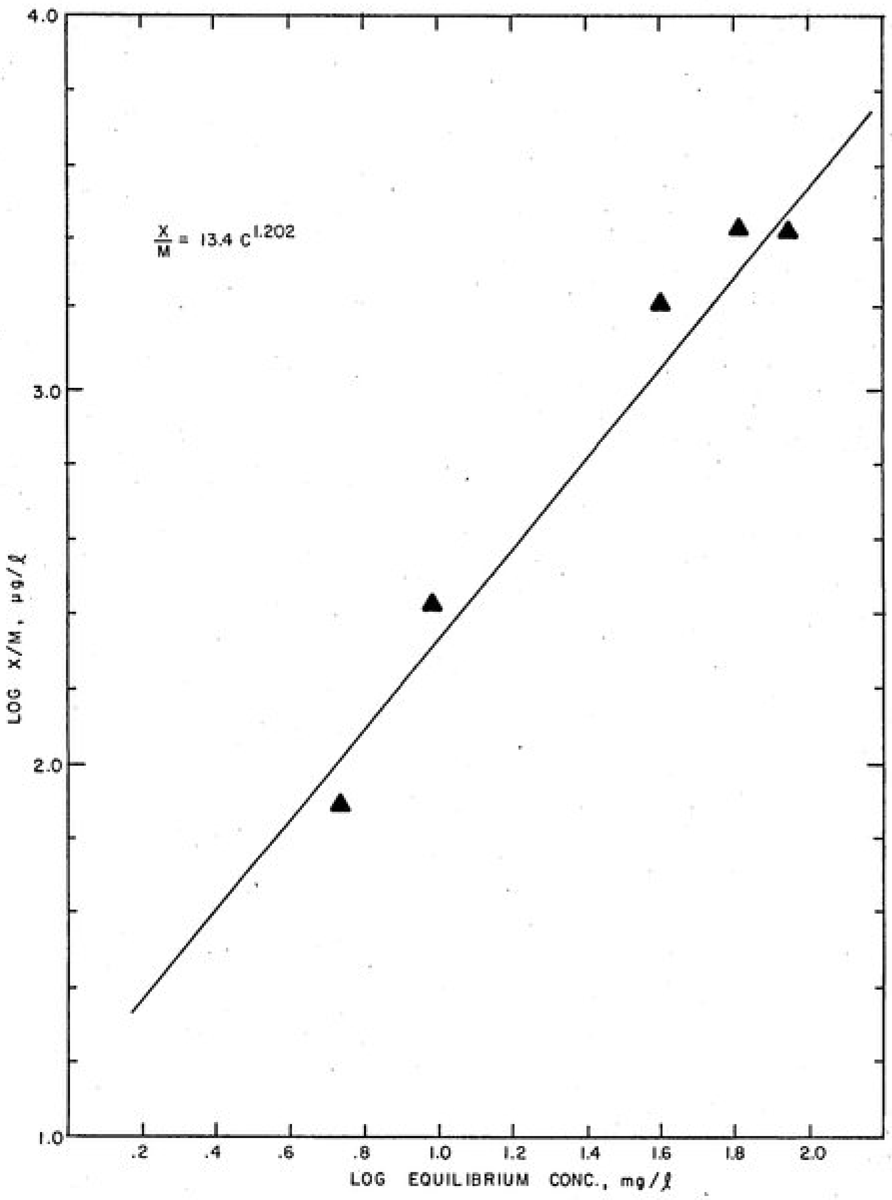



Figure 46. Freundlich isotherm for peat depth 25-50 cm for the natural marsh.

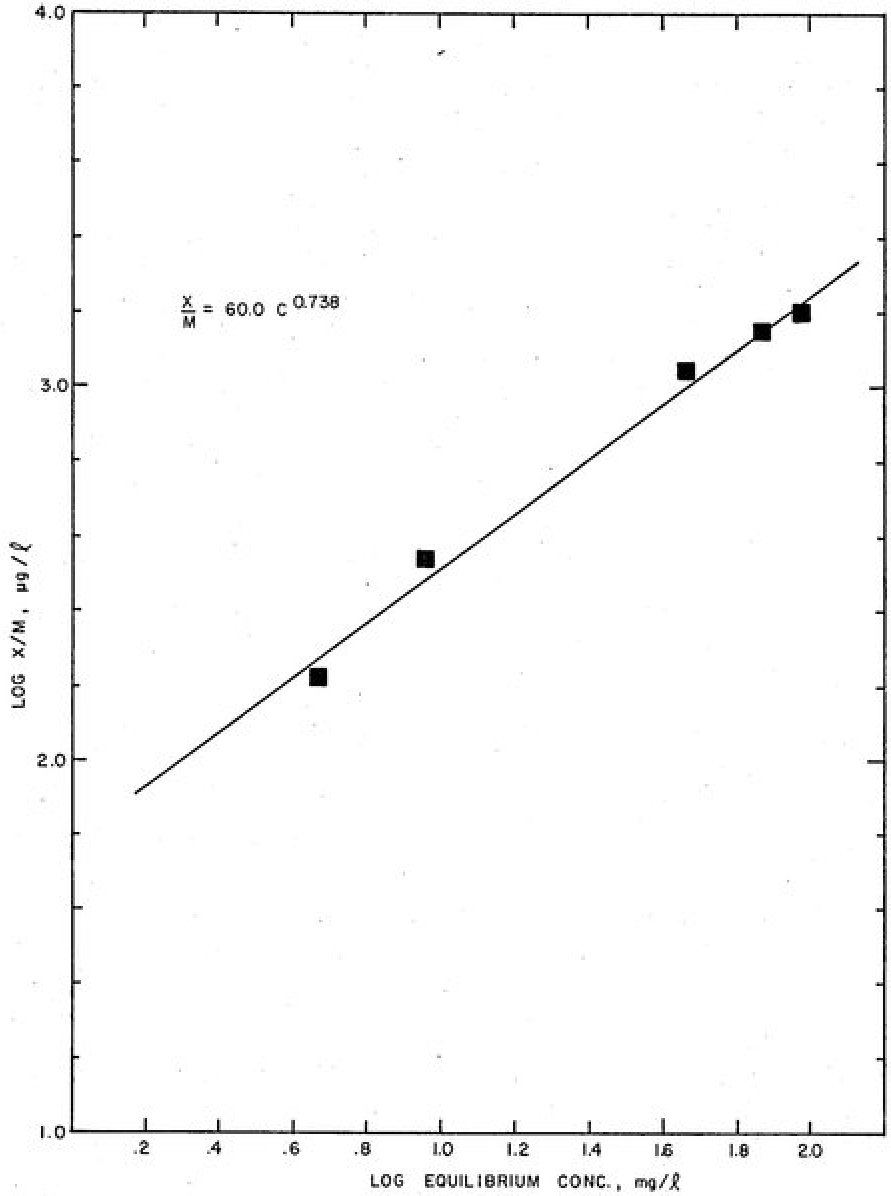



Figure 47. Freundlich isotherm for peat depth 50-75 cm for the natural marsh.

C = the equilibrium concentration of the phosphorus

K = the y-intercept of the straight line isotherm (constant)

1/n = slope of the straight line isotherm (constant).

As seen from the information presented in Figs. 45-47, all peat depths (0-25 cm, 25-50 cm, and 50-75 cm) evaluated yielded excellent conformation to the Freundlich model.

In order to relate the information provided by the isotherms to conditions in the experimental plot the mean phosphorus concentrations found in wells W3S (1.36 mg/l inside of Plot H, adjacent to discharge pipe, 0.75 m depth), W3M (0.8 mg/l inside of Plot H, adjacent to discharge pipe, 1.5 m depth), and the Plot H inside surface water samples (7.6 mg/l) were used to represent equilibrium concentrations. An exponential line of best fit was passed through these values ($r^2$ = 0.9975), and the average phosphorus concentration values were evaluated at depths of 0-25 cm, 25-50 cm, 50-75 cm, and 75-150 cm (see Fig. 48). Table 34 shows the estimated adsorption capacity as determined from the concentrations of phosphorus generated above. The value representing the total capacity of the peat soil to adsorb phosphorus (7.66 $g/m^2$) is strictly related to a specific set of conditions for pH, ionic strength, and temperature. However, it does provide an indication that a small portion of the applied phosphorus (approximately 40 g $P/m^2 \cdot yr$ applied) was being chemically bound by the peat soil. The adsorption thought to have occurred during the first (dry) year of this study could not be solely attributed to chemical binding, but may have been the result of microbial uptake and chemical binding in the peat. Subsequently, phosphorus releases from the peat soil during the wet year may have been caused by reduced microbial populations as well as chemically induced releases.

Dry Year Plant Decomposition and Phosphorus

The results of the decomposition bag-experiment involving Panicum and Sagittaria are presented in Fig. 49. Panicum lost over

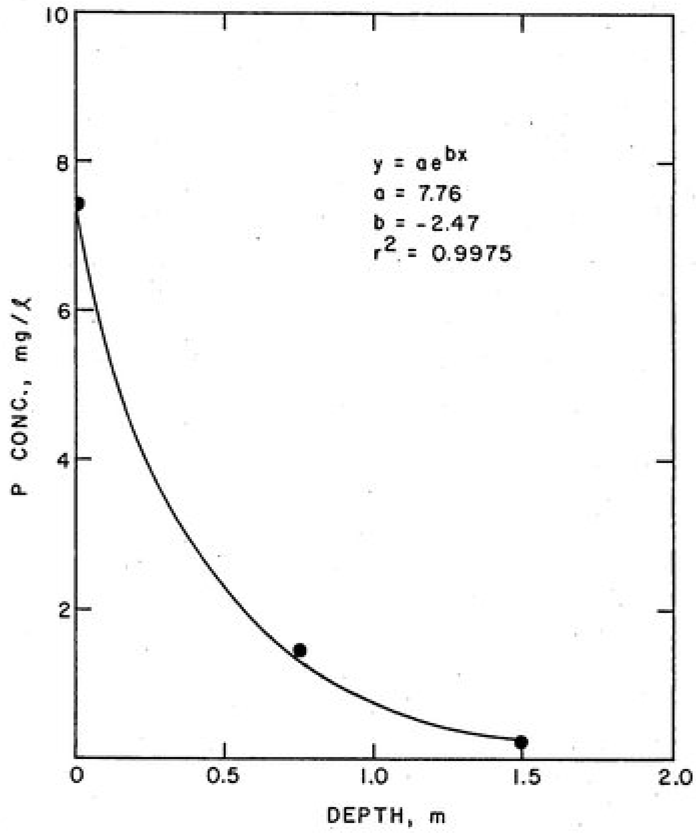



Figure 48. Plot of observed phosphorus concentration with peat depth.

Table 34. Estimated adsorption capacity as determined by the Freundlich model.

| Depth (cm) | Weight of Soil[a] (g/m²) | Equilibrium Concentration (mg/l) | Adsorption | |
|---|---|---|---|---|
| | | | (μg/g)[b] | (g/m²)[c] |
| 0-25 | $1.5x10^4$ | 5.79 | 171.39 | 2.57 |
| 25-50 | $1.75x10^4$ | 3.12 | 52.61 | 0.92 |
| 50-75 | $2.05x10^4$ | 1.68 | 87.99 | 1.80 |
| 75-150 | $6.15x10^4$ | 0.55 | 38.60 | 2.37 |
| Totals | $11.45x10^4$ | --- | --- | 7.66 |

[a]Calculated from depth of interval and bulk density of the peat.

[b]Calculated from $\frac{x}{m} = kC^n$.

[c]Calculated from adsorption and weight of soil.

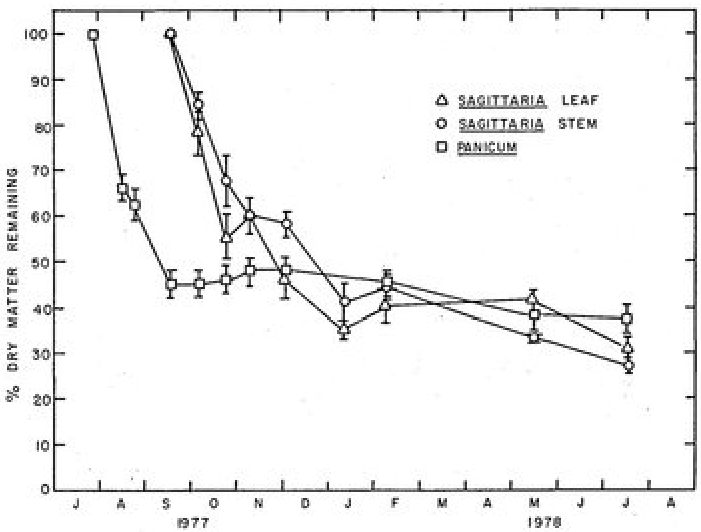



Figure 49. Dry year decomposition bag experiment. The litter bags were in the natural marsh for 300 days. Valves ± 1 S.E.

60% of its dry weight during the first 60 days. Sagittaria stem and leaf lost approximately 40% of their dry matter during the first 60 days. After this initial rapid loss of dry matter, the loss rates slowed. By the middle of February, all three plant materials had lost approximately 60% of their initial dry weight.

The phosphorus concentrations in the plant tissues did not show any overall trends (Fig. 50). The phosphorus concentration in Panicum and Sagittaria stems remained relatively constant for the first six months of the experiment while the concentration of Sagittaria leaf increased sharply after 30 days. By the end of the dry year decomposition experiment (300 days), both Panicum and and Sagittaria stems had increased slightly while Sagittaria leaf had returned to its initial concentration.

Figure 51 combines the dry matter results with the phosphorus concentrations to show the loss of total phosphorus over the course of the experiment. Phosphorus was lost at a relatively constant rate over the course of the experiment. By the end of the experiment all three plant materials had lost approximately 60% of their initial phosphorus. Dry matter loss was approximately equal to the loss of total phosphorus concentrations of the three plant materials.

No decomposition experiments were conducted with respect to phosphorus during the wet year of this study.

## Phosphorus Budget for Plots H and C

### Treated Wastewater Phosphorus Loading

The wastewater and freshwater loadings of phosphorus to the high loading plot and the control plot are shown in Tables 35 and 36. In Plot H the phosphorus loading rates ranged from 0.05 g $P/m^2 \cdot day$ to 0.27 g $P/m^2 \cdot day$. The annual totals for Plot H were 49.35 g $P/m^2$ during the first year and 42.03 g $P/m^2$ during the second year. This provided a two-year total of 91.38 g $P/m^2$.

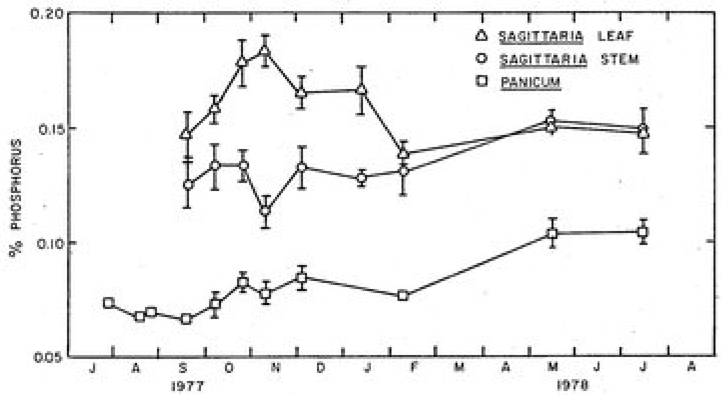



Figure 50. Phosphorus concentration in decomposing marsh vegetation during the dry year. Valves ± 1 S.E.

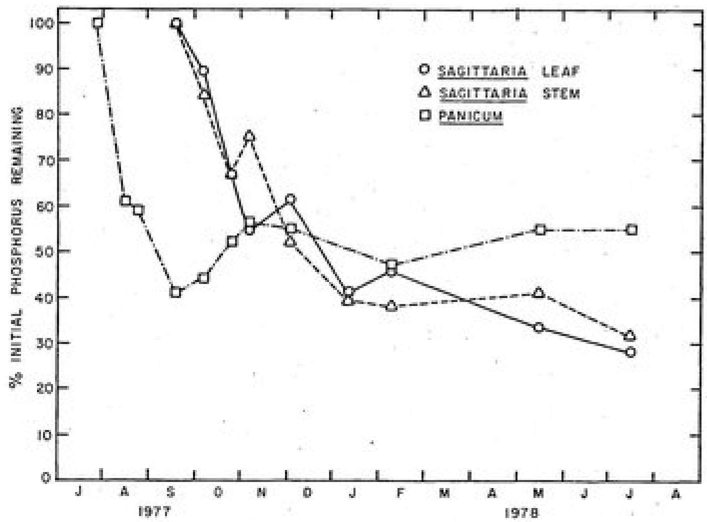



Figure 51. Percent phosphorus remaining in the decomposition bags during the dry year.

Table 35. Phosphorus loading rates for Plot H (9.6 cm/wk). Note that loadings are g P/m$^2$·day and g P/m$^2$·mo.

| | Wastewater concentration mg/l | | Loadings g P/m$^2$·mo | | Loadings g P/m$^2$·day | |
|---|---|---|---|---|---|---|
| | Ortho P | Total P | Ortho P | Total P | Ortho P | Total P |
| May 1977 | 7.95 | 15.30 | 3.30 | 6.35 | 0.11 | 0.21 |
| June | 10.20 | 15.50 | 5.19 | 7.89 | 0.17 | 0.26 |
| July | 2.10 | 6.49 | 0.86 | 2.64 | 0.03 | 0.09 |
| August | 2.60 | 6.48 | 1.29 | 3.21 | 0.05 | 0.12 |
| September | 0.51 | 3.20 | 0.26 | 1.64 | 0.01 | 0.05 |
| October | 0.66 | 4.80 | 0.28 | 2.03 | 0.01 | 0.07 |
| November | 0.42[a] | 4.15[a] | 0.17 | 1.71 | 0.01 | 0.06 |
| December | 0.17 | 3.50 | 0.09 | 1.78 | 0.00 | 0.05 |
| January 1978 | 7.42 | 8.48 | 3.02 | 3.45 | 0.11 | 0.12 |
| February | 9.71[a] | 12.34[a] | 3.95 | 5.02 | 0.14 | 0.18 |
| March | 12.00 | 16.20 | 4.93 | 6.65 | 0.16 | 0.22 |
| April | 12.80[a] | 17.00[a] | 5.26 | 6.98 | 0.18 | 0.23 |
| First year totals | --- | --- | 28.60 | 49.35 | --- | --- |
| May 1978 | 13.50 | 17.80 | 6.23 | 8.22 | 0.20 | 0.27 |
| June | 5.90 | 10.90 | 2.71 | 5.00 | 0.09 | 0.17 |
| July | 6.20 | 11.10 | 2.55 | 4.56 | 0.08 | 0.15 |
| August | 5.90 | 11.20 | 3.03 | 5.70 | 0.10 | 0.18 |
| September | 7.60 | 10.90 | 3.12 | 4.48 | 0.10 | 0.15 |
| October | 5.90 | 10.90 | 2.42 | 4.48 | 0.08 | 0.15 |
| November | 6.00 | 10.00 | 2.46 | 4.11 | 0.08 | 0.14 |
| December | 2.00 | 2.10 | 0.82 | 0.86 | 0.03 | 0.03 |
| January 1979 | 1.80 | 2.90 | 0.74 | 1.19 | 0.02 | 0.04 |
| February | 1.60 | 1.80 | 0.52 | 0.59 | 0.02 | 0.02 |
| March | 4.60 | 4.90 | 1.50 | 1.60 | 0.05 | 0.05 |
| April | 3.80 | 3.80 | 1.24 | 1.24 | 0.04 | 0.04 |
| Second year totals | --- | --- | 27.34 | 42.03 | --- | --- |
| Two year totals | | | 55.94 | 91.38 | | |

[a]Value represents average of preceding and succeeding months.

Table 36. Phosphorus loading rates for Plot C (4.4cm/wk freshwater)[a]. Note that loadings are mg $P/m^2 \cdot d$ and mg $P/m^2 \cdot mo$.

| | mg $P/m^2 \cdot mo$ | | mg $P/m^2 \cdot d$ | |
|---|---|---|---|---|
| | Ortho P | Total P | Ortho P | Total P |
| May 1977 | 15 | 29 | 0.5 | 1.0 |
| June | 20 | 38 | 0.7 | 1.3 |
| July | 16 | 29 | 0.5 | 0.9 |
| August | 16 | 30 | 0.5 | 1.0 |
| September | 19 | 36 | 0.6 | 1.2 |
| October | 19 | 36 | 0.6 | 1.2 |
| November | 15 | 28 | 0.5 | 0.9 |
| December | 19 | 37 | 0.6 | 1.2 |
| January 1978 | 15 | 29 | 0.5 | 0.9 |
| February | 15 | 29 | 0.5 | 1.0 |
| March | 15 | 29 | 0.5 | 0.9 |
| April | 11 | 25 | 0.4 | 0.8 |
| First year total[a] | 195 | 375 | --- | --- |
| May 1978 | 15 | 35 | 0.5 | 1.1 |
| June | 11 | 26 | 0.4 | 0.9 |
| July | 11 | 25 | 0.4 | 0.8 |
| August | 14 | 31 | 0.4 | 1.0 |
| September | 11 | 25 | 0.4 | 0.8 |
| October | 11 | 25 | 0.4 | 0.8 |
| November | 11 | 25 | 0.4 | 0.8 |
| December | 11 | 25 | 0.4 | 0.8 |
| January 1978 | 11 | 25 | 0.4 | 0.8 |
| February | 24 | 56 | 0.9 | 2.0 |
| March | 24 | 56 | 0.8 | 1.8 |
| April | 24 | 56 | 0.8 | 1.9 |
| Second year total[b] | 178 | 410 | --- | --- |
| Two year totals | 373 | 785 | --- | --- |

[a]Average phosphorus concentration for the first year was 0.10 mg/l ortho-P and 0.19 mg/l total-P.

[b]Average phosphorus concentration for the second year was 0.07 mg/l ortho-P and 0.16 mg/l total-P.

The control plot loadings were only 0.86% of that applied to Plot H. Values for both ortho-P and total-P were generally less than 1 mg P/m$^2$·day throughout the study. The annual totals for Plot C were 0.38 g P/m$^2$ during the first year and 0.41 g P/m$^2$ during the second year. The two year-total was 0.79 g P/m$^2$.

Rainfall Phosphorus Loading

The phosphorus loading from rainfall and dryfall (Table 37) was not significant when compared to the treated wastewater loading in Plot H. Bulk precipitation accounted for less than 0.15% of the total phosphorus loading to Plot H. However, the phosphorus loading due to bulk precipitation accounted for 13.4% of the phosphorus loading to Plot C (freshwater control). Dry fallout accounted for approximately four times as much phosphorus loading as did wet fallout.

Outflow of Phosphorus from Plots H and C

The outflow of phosphorus through the peat layer was determined using the calculated water outflow rates from the hydrologic budget and the phosphorus concentrations measured in the medium depth wells. The monthly phosphorus outflows for Plots H and C are presented in Tables 38 and 39, respectively.

Phosphorus outflow in Plot H was calculated from concentrations reported from wells W3M, W23M, and W3D. Well W3M was located immediately adjacent to the discharge pipe at the bottom of the peat layer. Well W3D was located the same distance from the discharge pipe as W3M and penetrated the sand layer beneath the peat. Well W23M was located in the northwest corner of the plot and was felt to represent flow moving laterally through the peat from the discharge pipe. The results of the analyses for W3M indicated that 1.003 g P/m$^2$·yr was exported during the dry year, and results of the analyses for W3D indicated that 2.668 g P/m$^2$·yr was exported during the wet year. If the water moved laterally through the peat (as represented by W23M), 0.733 g P/m$^2$·yr (dry year) and 0.251 g P/m$^2$·yr (wet year) would have been discharged over the course of this study.

Table 37. Phosphorus loading from rainfall[a]. Values are expressed as mg P/$m^2$·mo.

| Month | Wet Fall[a] Ortho-P | Wet Fall[a] Total-P | Bulk Precipitation[a] Ortho-P | Bulk Precipitation[a] Total-P | Seasonal[b] Total-P | Yearly Total |
|---|---|---|---|---|---|---|
| 5/77 | --- | --- | 0.6 | 0.8 | | |
| 6/77 | --- | --- | 1.7 | 2.2 | 18.2 | |
| 7/77 | --- | --- | 6.5 | 8.7 | | |
| 8/77 | --- | --- | 4.9 | 6.5 | | |
| 9/77 | --- | --- | 4.2 | 5.6 | | |
| 10/77 | --- | --- | 0.8 | 1.1 | | 50.0 |
| 11/77 | --- | --- | 2.5 | 3.3 | 23.1 | |
| 12/77 | --- | --- | 3.1 | 4.2 | | |
| 1/78 | --- | --- | 2.2 | 2.9 | | |
| 2/78 | --- | --- | 4.5 | 6.0 | | |
| 3/78 | 0.5 | 0.9 | 2.5 | 4.9 | | |
| 4/78 | 0.1 | 0.3 | 2.1 | 4.3 | | |
| 5/78 | 1.2 | 2.0 | 3.2 | 6.0 | 41.7 | |
| 6/78 | 2.2 | 3.9 | 4.2 | 7.9 | | |
| 7/78 | 2.6 | 4.6 | 4.6 | 8.6 | | |
| 8/78 | 0.5 | 0.9 | 2.5 | 4.9 | | |
| 9/78 | 0.6 | 1.1 | 2.6 | 5.1 | | |
| | | | | | | 57.5* |
| 10/78 | 0.4 | 0.6 | 2.4 | 4.6 | | |
| 11/78 | 0.0 | 0.0 | 2.0 | 4.0 | | 72.8** |
| 12/78 | 0.7 | 1.2 | 2.7 | 5.2 | 25.0 | |
| 1/79 | 1.4 | 2.5 | 3.4 | 6.5 | | |
| 2/79 | 0.4 | 0.7 | 2.4 | 4.7 | | |
| | | | | | * | |
| 3/79 | 0.8 | 1.4 | 2.8 | 5.4 | | |
| 4.79 | 1.1 | 1.9 | 3.1 | 5.9 | | |
| 5/79 | 0.0 | 0.0 | 2.0 | 4.0 | ** | |

[a]The total phosphorus and orthophosphate concentrations were assumed to be 0.04 mg/l and 0.03 mg/l, respectively, for the period 5/77 to 2/78. These were averages from Winter Garden, Fla., 20 km west of Clermont. Only bulk precipitation was collected during this time (C. Hendry, pers. comm.). The total phosphorus and orthophosphate concentrations for the period 3/78

Table 37. (Continued)

to 5/79 were assumed to be 0.014 mg/l and 0.008 mg/l, respectively. Dry fall was measured to be 2 mg $P/m^2 \cdot mo$ for orthophosphate and 4 mg $P/m^2 \cdot mo$ for total phosphorus. These samples were collected from a wet and dry collector at Lake Apopka, Fla., approximately 20 km west of Clermont (C. Hendry, pers. comm.).

[b]Seasons 4/77 to 8/77 (growing season, dry); 9/77 to 2/78 (dieback, dry); 3/78 to 9/78 (growing, wet); 10/78 to 2/79 (dieback, wet).

Table 38. Outflow of phosphorus from Plot H. Values are expressed as mg/l and mg P/m$^2$·mo.

| | W3M | | | | W23M | | | | W3D | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TP | OP | TP | OP | TP | OP | TP | OP | TP | OP | TP | OP |
| Month | (mg/l) | | (mg P/m$^2$·mo) | | (mg/l) | | (mg P/m$^2$·mo) | | (mg/l) | | (mg P/m$^2$·mo) | |
| 5/77 | 0.45 | 0.30 | 145 | 97 | 0.63 | 0.19 | 204 | 61 | ---- | ---- | ---- | ---- |
| 6/77 | 0.45 | 0.30 | 190 | 126 | 0.55 | 0.20 | 232 | 84 | ---- | ---- | ---- | ---- |
| 7/77 | 0.36 | 0.32 | 110 | 98 | 0.20 | 0.03 | 61 | 9 | ---- | ---- | ---- | ---- |
| 8/77 | 0.45 | 0.26 | 166 | 96 | 0.23 | 0.08 | 85 | 29 | ---- | ---- | ---- | ---- |
| 9/77 | 0.36 | 0.14 | 144 | 56 | 0.13 | 0.06 | 52 | 24 | ---- | ---- | ---- | ---- |
| 10/77 | 0.40 | 0.15 | 111 | 42 | 0.14 | 0.07 | 39 | 19 | ---- | ---- | ---- | ---- |
| 11/77 | 0.23 | 0.09 | 65 | 26 | 0.08 | 0.04 | 23 | 11 | ---- | ---- | ---- | ---- |
| 12/77 | 0.05 | 0.03 | 25 | 15 | 0.03 | 0.01 | 15 | 5 | ---- | ---- | ---- | ---- |
| 1/78 | 0.04 | 0.02 | 18 | 9 | 0.01 | 0.01 | 4 | 4 | ---- | ---- | ---- | ---- |
| 2/78 | 0.06 | 0.02 | 29 | 10 | 0.01 | ---- | 5 | ---- | ---- | ---- | ---- | ---- |
| 3/78 | 0.08 | 0.02 | 14 | 4 | 0.01 | ---- | 5 | ---- | ---- | ---- | ---- | ---- |
| 4/78 | 0.01 | 0.00 | 3 | 1 | 0.10 | 0.07 | 39 | 29 | 0.01 | 0.00 | 4 | 4 |
| Total first year | | | 1,003 | 580 | | | 712 | 275 | | | | |
| 5/78 | 0:08 | 0:01 | 31 | 5 | 0.02 | 0.01 | 6 | 2 | 0.07 | 0.02 | 24 | 6 |
| 6/78 | 0.02 | 0.01 | 6 | 2 | 0.01 | 0.01 | 4 | 2 | 0.08 | 0.03 | 24 | 8 |
| 7/78 | 0.15 | 0.05 | 40 | 12 | 0.06 | 0.00 | 14 | 1 | 0.10 | 0.03 | 25 | 8 |
| 8/78 | 0.16 | 0.05 | 36 | 11 | 0.03 | 0.01 | 6 | 1 | 0.09 | 0.04 | 19 | 8 |
| 9/78 | 0.25 | 0.05 | 89 | 18 | 0.04 | 0.01 | 13 | 2 | 0.18 | 0.03 | 66 | 12 |
| 10/78 | 0.02 | 0.01 | 9 | 3 | 0.08 | 0.01 | 32 | 2 | 0.16 | 0.16 | 66 | 63 |

Table 38 (continued).

| Month | W3M TP (mg/l) | W3M OP (mg/l) | W3M TP (mg P/m²·mo) | W3M OP (mg P/m²·mo) | W23M TP (mg/l) | W23M OP (mg/l) | W23M TP (mg P/m²·mo) | W23M OP (mg P/m²·mo) | W3D TP (mg/l) | W3D OP (mg/l) | W3D TP (mg P/m²·mo) | W3D OP (mg P/m²·mo) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/78 | 0.15 | 0.02 | 55 | 19 | 0.29 | 0.10 | 105 | 37 | 0.10 | 0.05 | 34 | 17 |
| 12/78 | 0.03 | 0.16 | 13 | 7 | 0.08 | 0.04 | 34 | 18 | 0.05 | 0.02 | 20 | 9 |
| 1/79 | 0.02 | 0.00 | 6 | 2 | 0.03 | 0.02 | 11 | 9 | 0.02 | 0.01 | 9 | 3 |
| 2/79 | 7.57 | 2.50 | 2,347 | 775 | 0.06 | 0.02 | 19 | 7 | ---- | ---- | ---- | ---- |
| 3/79 | 0.08 | 0.02 | 20 | 5 | 0.01 | 0.01 | 3 | 2 | 0.12 | 0.03 | 31 | 8 |
| 4/79 | 0.04 | 0.02 | 16 | 7 | 0.01 | 0.00 | 4 | 0 | 0.02 | 0.01 | 6 | 5 |
| Total second year | | | 2,668 | 866 | | | 251 | 85 | | | 324 | 147 |

Table 39. Outflow of phosphorus from Plot C.

| Month | TP (mg/l) | OP (mg/l) | TP (mg P/m$^2$·mo) | OP (mg P/m$^2$·mo) |
|---|---|---|---|---|
| 5/77 | .39 | .13 | 23 | 8 |
| 6/77 | .38 | .10 | 43 | 11 |
| 7/77 | .18 | .02 | 28 | 3 |
| 8/77 | .35 | .03 | 26 | 2 |
| 9/77 | .11 | .07 | 15 | 10 |
| 10/77 | .15 | .07 | 14 | 7 |
| 1/77 | .09 | .04 | 6 | 3 |
| 12/77 | .02 | .01 | 4 | 2 |
| 1/78 | .01 | .01 | 2 | 2 |
| 2/78 | .01 | .01 | 2 | 2 |
| 3/78 | .01 | .01 | 2 | 2 |
| 4/78 | .06 | .01 | 9 | 2 |
| Totals first year | | | 174 | 54 |
| 5/78 | .02 | .01 | 3 | 2 |
| 6/78 | .02 | .01 | 2 | 1 |
| 7/78 | .02 | .01 | 1 | 0 |
| 8/78 | .02 | .01 | -- | -- |
| 9/78 | .03 | .01 | 1 | 0 |
| 10/78 | .04 | .02 | 4 | 2 |
| 11/78 | .13 | .08 | 11 | 7 |
| 12/78 | .30 | .05 | 45 | 8 |
| 1/79 | .06 | .02 | 9 | 3 |
| 2/79 | .01 | .00 | 3 | 0 |
| 3/79 | .00 | .00 | 0 | 0 |
| 4/79 | .01 | .01 | 4 | 0 |
| Totals second year | | | 84 | 23 |

The chloride tracer study described previously indicated that flow within the plots was fairly uniform, and outflow probably occurred past W3M as well as W23M. The outflow of phosphorus from Plot C was 0.174 g P/m$^2$·yr during the dry year and 0.083 g P/m$^2$·yr during the wet year. These values represented 41% of the applied phosphorus during the dry year and 17% during the wet year.

Dry Year Budget

The dry year budgets for Plots H and C are presented in Tables 40 and 41, respectively. These budgets were further reduced to dry year seasonal budgets (growing season and dieback). The total phosphorus input to Plot H in the treated wastewater and bulk precipitation was 49.40 g P/m$^2$. The export of phosphorus in groundwater was 1.00 g P/m$^2$ when values for well W3M (assuming completely vertical flow) were used and 0.7 g P/m$^2$ when values for net storage of 1.20 g P/m$^2$ and 1.11 g P/m$^2$ in litter and aboveground live biomass, respectively. The root compartment stored 3.54 g P/m$^2$. The sum of these values represented 13.8% of the treated wastewater applied. The remainder of the applied phosphorus was believed to have been stored in the peat complex.

The litter fraction in Plot H stored phosphorus during both the growing season and dieback while the aboveground and belowground (roots) standing stock lost significant portions of phosphorus that had been stored during the growing season during dieback. The complete growing season budget accounted for 90% of the applied phosphorus loading for Plot H while the dieback budget indicated a release of previously stored phosphorus. This phosphorus was assumed to have been incorporated into the peat complex.

The total phosphorus input to Plot C was 0.43 g P/m$^2$ for the dry year. Freshwater loading accounted for 88.4%, and bulk precipitation accounted for 11.6% of the input. The export of phosphorus in groundwater was 0.17 g P/m$^2$. Storages were 1.00 g P/m$^2$ and 0.61 g P/m$^2$ in litter and aboveground live biomass, respectively. A net storage of 1.22 g P/m$^2$ was observed in the root compartment. The total for all storages and exports represents 719% of the applied phosphorus and therefore indicated that input of phosphorus to Plot C from sources other than bulk precipitation and freshwater loading was

Table 40. Phosphorus budget for the "dry year" for Plot H.

| Source | Seasonal Budgets: Growing Season[a] g P/m²·season | Seasonal Budgets: Dieback[a] g P/m²·season | Yearly Budget[b] g P/m²·yr | % of Inputs % |
|---|---|---|---|---|
| Inputs | | | | |
| Treated Wastewater[c] | 20.09 | 15.63 | 49.35 | 99.9 |
| Rainfall[d] | 0.02 | 0.02 | 0.05 | 0.1 |
| Totals | 20.11 | 15.65 | 49.40 | 100.0 |
| Outputs | | | | |
| Export[e] W3M | 0.61 | 0.39 | 1.00 | 2.0 |
| W23M | (0.58) | (0.09) | (0.71) | (1.4) |
| Litter[f] | 0.51 | 0.65 | 1.19 | 2.4 |
| Aboveground Live[g] | 2.05 | -2.11 | 1.11 | 2.3 |
| Roots[h] | 13.05 | -4.72 | 3.54 | 7.2 |
| Soil | --- | --- | --- | (86.2)[i] |
| Totals | 16.19 | -5.83 | 6.80 | 13.8 |

[a]Growing season 4/25/77 through 8/11/77. Dieback season 8/11/77 through 2/20/78

[b]Dry year of the study 4/25/77 to 4/14/78.

[c]Values from Table 35.

[d]Values from Table 37.

[e]Values from Table 38. The highest value assumed to represent outflow.

[f]Values from Table 26.

[g]Values from Table 25.

[h]Values from Table 29.

[i]No representative soil data available. It is assumed that a large portion of the applied phosphorus was stored in the soil complex during the dry year.

Table 41. Phosphorus budget for the "dry year" for Plot C.

| Source | Seasonal Budgets: Growing[a] g P/m$^2$·season | Seasonal Budgets: Dieback[a] g P/m$^2$·season | Yearly Budget[b] g P/m$^2$·yr | % of Input % |
|---|---|---|---|---|
| Inputs | | | | |
| Freshwater[c] | 0.13 | 0.20 | 0.38 | 88.4 |
| Rainfall[d] | 0.02 | 0.02 | 0.05 | 11.6 |
| Totals | 0.15 | 0.22 | 0.43 | 100.0 |
| Outputs | | | | |
| Export[e] W21M | 0.12 | 0.04 | 0.17 | 40.5 |
| Litter[f] | -0.11 | 0.36 | 1.00 | 232.6 |
| Aboveground[g] Live | 0.16 | -0.40 | 0.61 | 141.8 |
| Roots[h] | -1.54 | 0.98 | 1.22 | 283.7 |
| Soil | --- | --- | --- | --- |
| Totals | -1.37 | 0.98 | 3.00 | 719.0 |

[a]Growing season 4/25/77 through 8/11/77. Dieback season 8/11/77 through 2/20/78.

[b]Dry year of the study 4/25/77 to 4/14/78.

[c]Values from Table 36.

[d]Values from Table 37.

[e]Values from Table 39.

[f]Values from Table 28.

[g]Values from Table 27.

[h]Values from Table 30.

likely. These sources could have been released from the peat complex and/or periodic influxes from the Palatlakaha River, which was located less that 25 meters from Plot C.

The seasonal budgets for Plot C indicated a net loss of phosphorus during the growing season and a net uptake of phosphorus during dieback. The magnitude of these fluxes was relatively small and may represent influences other than freshwater application.

Wet Year Budget

The wet year budgets for Plots H and C are presented in Tables 42 and 43, respectively. The budgets were further reduced to wet year seasonal budgets. The total phosphorus input to Plot H in the treated wastewater and bulk precipitation was 42.10 g P/m$^2$. The export of phosphorus in groundwater was 2.67 g P/m$^2$ when values for well W3M (assuming vertical outflow) were used and 0.29 g P/m$^2$ when values for well W23M (assuming lateral outflow) were used. The extremely high value for well W3M can be attributed to a single sampling period (February 17, 1979), without which an export value of 0.32 g P/m$^2$ would have been realized (see Table 38). Even when this anomalous value was used, 93.7% removal was achieved. There was a net loss of phosphorus from litter (1.06 g P/m$^2$), aboveground and belowground standing stock (0.83 g P/m$^2$ and 3.71 g P/m$^2$, respectively), and the peat complex (5.43 g P/m$^2$). The sum of these losses created a net loss of phosphorus from the plot. This loss was not observed as increased phosphorus concentrations in the wells monitoring outflow from the plot. Storage of phosphorus in surface water accounted for only 1.76 g P/m$^2$, which was 4.2% of the applied phosphorus.

The total phosphorus input to Plot C was 0.48 g P/m$^2$. Freshwater loading accounted for 85.4% of this input. As in the case of Plot H, there was a net loss of phosphorus in all measured compartments: litter (1.48 g P/m$^2$), aboveground live (0.70 g P/m$^2$), roots (1.48 g P/m$^2$), and peat (25.13 g P/m$^2$).

The losses of phosphorus exhibited in both Plots H and C during the wet year were not the result of seasonal variations but may represent a combination of decompositional losses and release of

Table 42. Phosphorus budget for Plot H (9.6 cm/wk of treated wastewater) for the wet year.

| Source | Seasonal Budgets: Growing (g P/m²·season)[a] | Seasonal Budgets: Dieback (g P/m²·season)[a] | Yearly Budget[b] (g P/m²·yr)[b] | % of Input (%) |
|---|---|---|---|---|
| Inputs | | | | |
| Treated[c] wastewater | 27.96 | 11.23 | 42.03 | 99.8 |
| Rainfall[d] | 0.04 | 0.03 | 0.07 | 0.2 |
| Totals | 28.00 | 11.26 | 42.10 | 100.0 |
| Outputs | | | | |
| Export[e] W3M | 0.21 | 2.43 | 2.67 | 6.3 |
| W23M | (0.08) | (0.20) | (0.29) | (0.7) |
| Litter[f] | -0.37 | -0.69 | -1.06 | --- |
| Aboveground live[g] | 2.67 | -3.50 | -0.83 | --- |
| Roots[h] | 4.30 | -8.01 | -3.71 | --- |
| Soil[i] | -1.99 | -3.44 | -5.43 | --- |
| Storage[j] in surface water | 1.76 | 0.00 | 1.76 | 4.2 |
| Totals | 6.58 | -13.21 | 6.63 | --- |

[a]Growing season 4/14/78 through 9/11/78. Dieback 9/11/78 to 2/17/79.

[b]Wet year of the study 4/14/78 to 2/17/79.

[c]Values from Table 35.

[d]Values from Table 37.

[e]Values from Table 38.

[f]Values from Table 26.

[g]Values from Table 25.

[h]Values from Table 29.

[i]Values from Table 32.

[j]Value calculated from surface water concentration and water depth above peat surface.

Table 43. Phosphorus budget for Plot C for the wet year.

| | Seasonal Budgets | | | |
|---|---|---|---|---|
| | Growing | Dieback | Yearly budget[b] | % of Inputs |
| | (g P/m$^2$·season) | | (g P/m$^2$·yr) | (%) |
| Inputs | | | | |
| Freshwater[c] | 0.14 | 0.16 | 0.41 | 85.4 |
| Rainfall[d] | 0.04 | 0.03 | 0.07 | 14.6 |
| Totals | 0.18 | 0.19 | 0.48 | 100.0 |
| Outputs | | | | |
| Export[e] W21M | 0.01 | 0.07 | 0.08 | 16.7 |
| Litter[f] | -0.16 | -1.18 | -1.34 | --- |
| Aboveground Live[g] | 1.73 | -2.42 | -.070 | --- |
| Roots[h] | 0.86 | -2.34 | -1.48 | --- |
| Soil[i] | -3.79 | -21.34 | -25.13 | --- |
| Storage in surface water[j] | 0.13 | -0.11 | 0.02 | 4.2 |
| Totals | -1.22 | -27.32 | -28.55 | --- |

[a]Growing season 4/14/78 through 9/11/78. Dieback 9/11/78 through 2/17/79.

[b]Wet year of study 4/14/78 through 2/17/79.

[c]Values from Table 36.

[d]Values from Table 37.

[e]Values from Table 39.

[f]Values from Table 28.

[g]Values from Table 27.

[h]Values from Table 30.

[i]Values from Table 32.

[j]Values calculated from surface water concentration and depth.

previously bound phosphorus from the peat complex due to flooded conditions in the experimental marsh. The magnitude of these losses would have required large export values of phosphorus to be observed in the well systems. However, increased concentrations were not observed over this time period, and a budget based strictly on inflow and export estimates would indicate removal efficiencies of 94% (assuming vertical outflow, W3M) to 98% (assuming lateral outflow, W23M).

The large reduction of phosphorus observed in the well system and the relatively high concentrations of phosphorus observed in surface water (average for Plot H during the wet year: 6.4 mg/l) indicate the necessity to confine the applied phosphorus load and force outflow to occur through the peat. Hypothetical export of phosphorus (assuming no containment) would be approximately 19 g $P/m^2 \cdot yr$ for the wet year. This hypothetical value assumes all outflow to occur as overland flow and no passage of treated wastewater throught the peat.

Summarizing the phosphorus budgets for Plot H, it appears that phosphorus that had entered the plots was removed prior to export in groundwater. A two-year total of 91.4 g $P/m^2$ was loaded on Plot H with an uptake of 0.13 g $P/m^2$ and 0.28 g $P/m^2$ being observed in the litter and aboveground live vegetation. Losses were incurred in the root compartment (0.16 g $P/m^2$) and the soil compartment (5.43 g $P/m^2$; wet year only). Storage in surface water (wet year only) accounted for 1.76 g $P/m^2$. Noting that the fiberglass panels forced the applied treated wastewater to flow through the peat, export of phosphorus through groundwater indicated an overall removal 96.2% (assuming only vertical outflow through 1.5 m of peat; W3M) and 98.9% (assuming vertical and lateral outflow to the inside edge of the plots; W23M) for the two years the study took place.

## Nitrogen Considerations

### Model of Microbial Transformations of Nitrogen

Nitrogen is an extremely mobile element in wetland systems; it is readily converted from one oxidation state to another under appropriate conditions in those systems. The most important microbial transformations of nitrogen in waters of the marsh, plus sources and sinks for nitrogen in waters of the marsh, are illustrated in Fig. 52 (see the Appendix for a description of symbols). The four major species of dissolved nitrogen considered in this study were nitrate ($NO_3^-$), nitrite ($NO_2^-$), ammonia ($NH_3$ or $NH_4^+$), and dissolved organic nitrogen. As shown in Fig. 52, all of these forms have several different sources and sinks, both within the marsh system and outside of it. The major nitrogen sources in the experimental plots were treated wastewater, rainfall plus dry fallout (together called bulk precipitation), and nitrogen fixation. Nitrogen fixation is carried out by certain algae and bacteria, which incorporate free $N_2$ gas directly into their cell biomass to produce $NH_3$. The fixed $N_2$ is obtained either directly from the atmosphere or from the $N_2$ gas dissolved in water.

Through the process of ammonification, organic nitrogen (primarily in the form of proteins and amino acids) is broken down to $NH_3$. $NH_3$ may subsequently be converted to $NO_2^-$ and then to $NO_3^-$ in the process known as nitrification. Nitrification is usually carried out by autotrophic bacteria, although heterotrophic nitrifiers also exist. Both types require oxygen for nitrification to occur. The bacteria Nitrosomonas convert $NH_3$ to $NO_3^-$, and the bacteria Nitrobacter convert $NO_2^-$ to $NO_3^-$. Some species of microbes may reduce $NO_3^-$ back to $NO_2^-$ or $NH^3$, or convert $NO_2^-$ back to $NH_3$. This is known as assimilatory nitrate and nitrite reduction. Nitrogen in nitrate can be released to the atmosphere as $N_2O$ and $N_2$ through the microbial process of dentrification. Denitrification is heterotrophic, requiring a carbon source for energy. It occurs only under relatively anoxic conditions.

Utilization of dissolved nitrogen by plants also results in the interconversion of nitrogen species in the marsh water. Nitrate and ammonium assimilated by rooted plants, floating plants, and algae are reduced to organic form in the production of proteins within cells. Subsequent release of organic nitrogen and ammonia occurs especially when cells lyse during senescence. Further release of organic and

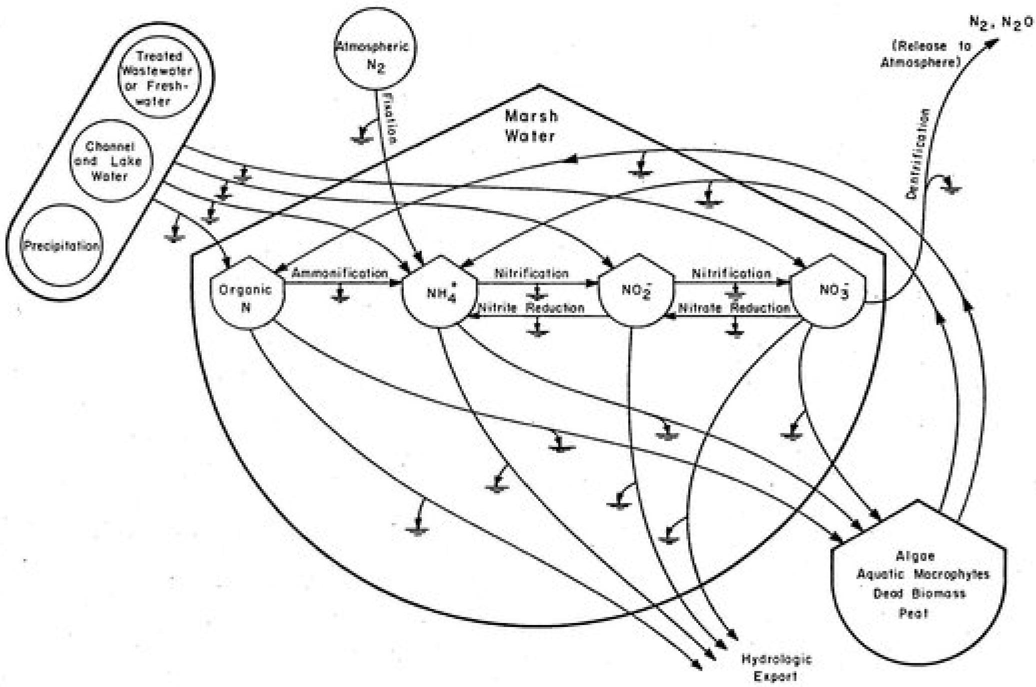



Figure 52. Microbial transformations and sources of nitrogen in the marsh. See Appendix for a description of symbols.

ammoniacal nitrogen occurs as plant materials continue to decompose. Released compounds are then subject to the microbial transformations described above.

Oxidation of aerated peat soil will release significant quantities of organic and inorganic nitrogen. Since large quantities of peat soil are present in the marsh, such oxidation is an important dissolved nitrogen source to marsh waters when the water table is below the peat surface. Nitrogen released by oxidizing peat is then subject to plant and microbial transformations. Some, perhaps most, of the nitrogen liberated from the peat will ultimately be lost to the atmosphere through denitrification. Hence, oxidation of peat does not necessarily result in much higher concentrations of dissolved nitrogen in the marsh waters.

The two most significant microbial transformations of nitrogen from the standpoint of treated wastewater renovation by marshes are nitrification and denitrification. Together they can remove ammonium, nitrite, and nitrate from applied treated wastewater. The occurrence of these two processes in the Clermont marsh will be discussed in detail in the following sections of this chapter.

## Nitrification

Laboratory Experiments. Initial studies were designed to determine if nitrification would occur in the marsh water without any sediment. Air was bubbled through one half of the samples while the other half was not aerated. Ammonium was then added to all samples except the control, and the ammonium, nitrate, dissolved oxygen, and pH values were followed over a 30-day period. These data, reported in Table 44, indicate that nitrification does not occur in the water alone, since there was essentially no change in ammonium or nitrate concentrations over the 30-day period. Since aeration had no effect on ammonium concentration, dissolved oxygen was not a limiting factor. The pH was also within acceptable limits for nitrification to occur.

Additional potentially limiting factors were investigated. Previous work (Rice and Pancholy 1973) suggested that yellow-colored, dissolved organic compounds (tannins) present in the water may

Table 44. Ammonium, nitrate, dissolved oxygen, and pH values measured in nonaerated and aerated marsh water incubated in the laboratory without soil.

| Treatment | Days | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 2 | 4 | 8 | 18 | 30 |
| | $NH_4$-N, ppm | | | | | |
| $NH_4$ added, nonaerated | 25.0 | 26.7 | 26.3 | 26.2 | 27.1 | 27.9 |
| $NH_4$ added, aerated | 25.0 | 27.5 | 27.9 | 28.9 | 33.8 | 33.1 |
| Control, nonaerated | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 1.0 |
| Control, aerated | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | 1.0 |
| | $NO_3$-N, ppm | | | | | |
| $NH_4$ added, nonaerated | 1.12 | <0.5 | <0.5 | 1.37 | <0.5 | 0.56 |
| $NH_4$ added, aerated | 1.12 | <0.5 | <0.5 | 1.04 | 0.62 | 0.61 |
| Control, nonaerated | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Control, aerated | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| | Dissolved oxygen, ppm | | | | | |
| $NH_4$ added, nonaerated | 7.9 | 7.9 | 7.9 | 7.9 | 7.8 | 7.9 |
| $NH_4$ added, aerated | 7.9 | 8.0 | 8.1 | 8.1 | 7.9 | 8.1 |
| Control, nonaerated | 7.9 | 7.8 | 8.0 | 7.8 | 7.8 | 7.9 |
| Control, aerated | 7.9 | 7.8 | 8.1 | 8.0 | 7.9 | 8.1 |
| | pH | | | | | |
| $NH_4$ added, nonaerated | ---- | 6.2 | 6.4 | 6.6 | 6.3 | 6.5 |
| $NH_4$ added, aerated | ---- | 6.3 | 6.4 | 6.4 | 6.0 | 6.1 |
| Control, nonaerated | ---- | 6.3 | 6.6 | 6.8 | 6.8 | 7.1 |
| Control, aerated | ---- | 6.3 | 6.5 | 6.8 | 6.7 | 7.0 |

inhibit nitrification. An attempt was made to remove tannins with charcoal filtration. Another possibility was that nitrifying organisms were not present in the water, and a water extract from a soil containing nitrifiers was added as an inoculant to the samples. Water from Lake Alice on the University of Florida campus was included for comparative reasons. Results are shown in Table 45. Initial observation of the ammonium concentrations in the marsh water suggested that either no change occurred, or that ammonium actually increased. However, increases in nitrate concentrations indicated that nitrification may have been occurring. This appparent discrepancy was resolved by considering that evaporation was occurring in this study, resulting in higher concentrations.

Effects of the two treatments, filtration and inoculation, are best explained using the nitrate data. With the marsh water, there was only a small increase in nitrate concentration in the samples not receiving inoculant, while the inoculated samples showed considerable nitrification. Charcoal filtration had no effect on the nitrification rate. Since Lake Alice water was not highly colored, it was not subjected to charcoal filtration. Some nitrification occurred in natural Lake Alice water but the rate was considerably faster in inoculated water. Lake Alice receives sewage effluent and consequently appeared to have some nitrifiers already present. This was the likely reason for nitrification occurring in uninoculated Lake Alice water and also why nitrification started sooner in Lake Alice water.

Nitrification results in the release of hydrogen ions into solution, and thus during the course of the experiment, the pH dropped approximately two units. Because of the low buffering capacity of the water, the pH went below that level normally acceptable for nitrification and at 25 days was artificially adjusted upward. Dissolved oxygen did not appear to be limiting throughout the study period.

From the above experiments, it became apparent that nitrifiers were not normally present in the marsh water. Previous experience with agricultural soils suggested that nitrifiers would be present

Table 45 . Effect of charcoal filtration and inoculation with soil water extract on nitrification in marsh and lake waters without soil.

| Water Source | Treatments: Charcoal filtration | Treatments: Inoculated | Days: 0 | 2 | 7 | 11 | 18 | 25 | 25 [a] | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $NH_4$-N, ppm | | | | | | | |
| Marsh | yes | yes | 52.4 | 49.0 | 51.5 | 51.3 | 52.2 | 59.7 | --- | 54.7 |
| Marsh | no | yes | 50.1 | 46.5 | 49.6 | 47.1 | 50.8 | 50.1 | --- | 52.9 |
| Marsh | yes | no | 52.4 | 51.9 | 52.1 | 54.1 | 57.6 | 61.6 | --- | 65.6 |
| Marsh | no | no | 50.1 | 51.1 | 48.7 | 52.2 | 54.0 | 60.1 | --- | 63.8 |
| Lake Alice | no | yes | 52.3 | 45.9 | 38.6 | 33.0 | 32.3 | 33.0 | --- | 27.0 |
| Lake Alice | no | no | 52.3 | 46.5 | 40.6 | 35.5 | 36.8 | 39.1 | --- | 40.8 |
| | | | $NO_3$-N, ppm | | | | | | | |
| Marsh | yes | yes | 0 | 0.58 | 1.0 | 3.6 | 4.9 | 7.9 | --- | 17.0 |
| Marsh | no | yes | 0 | 0.70 | 1.0 | 2.7 | 4.9 | 11.9 | --- | 13.4 |
| Marsh | yes | no | 0 | 0.10 | 1.0 | 0.18 | 0.46 | 0.10 | --- | 0.81 |
| Marsh | no | no | 0 | 0 | 1.0 | 0.50 | 0.28 | 1.2 | --- | 0.84 |
| Lake Alice | no | yes | 0.35 | 0 | 6.2 | 12.3 | 12.8 | --- | --- | 23.2 |
| Lake Alice | no | no | 0.35 | 1.1 | 3.4 | 9.5 | 10.3 | 11.5 | --- | 11.5 |
| | | | Dissolved oxygen, ppm | | | | | | | |
| Marsh | yes | yes | 8.0 | 8.0 | 8.1 | 8.1 | 8.2 | 7.4 | --- | 7.3 |
| Marsh | no | yes | 7.8 | 8.1 | 8.1 | 8.2 | 8.0 | 7.3 | --- | 7.2 |
| Marsh | yes | no | 8.0 | 8.2 | 8.2 | 8.2 | 8.2 | 7.2 | --- | 7.2 |
| Marsh | no | no | 7.8 | 7.8 | 8.1 | 8.0 | 8.3 | 7.5 | --- | 7.3 |
| Lake Alice | no | yes | 8.3 | 7.7 | 7.3 | 8.0 | 8.0 | 7.2 | --- | 7.2 |
| Lake Alice | no | no | 8.3 | 7.9 | 7.4 | 8.1 | 8.1 | 7.2 | --- | 7.0 |

Table 45 . (Continued)

| Water Source | Treatments: Charcoal filtration | Treatments: Inoculated | Days: 0 | 2 | 7 | 11 | 18 | 25 | 25'[a] | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | pH | | | | | | | |
| Marsh | yes | yes | 6.6 | 6.6 | 6.2 | 5.1 | 4.2 | 4.1 | 7.2 | 4.4 |
| Marsh | no | yes | 6.5 | 6.6 | 6.1 | 4.9 | 4.0 | 3.9 | 7.1 | 4.2 |
| Marsh | yes | no | 6.6 | 6.7 | 6.6 | 6.5 | 5.9 | 5.6 | 7.2 | 6.0 |
| Marsh | no | no | 6.5 | 6.5 | 6.5 | 6.1 | 5.8 | 4.5 | 7.2 | 5.5 |
| Lake Alice | no | yes | 7.9 | 7.9 | 7.4 | 5.0 | 4.4 | 4.3 | 7.1 | 4.2 |
| Lake Alice | no | no | 7.9 | 8.0 | 7.7 | 5.4 | 5.6 | 5.3 | 7.1 | 5.2 |

[a]pH adjusted to 7.2 ($\pm$0.1) with 0.5 N NaOH after 25-day samples taken.

in the soil. The next experiment was designed using soil:water columns to simulate various marsh conditions. Plants play an important role in controlling nitrogen concentrations in marsh systems and were, therefore, included in this study. Water depth and pH were also included as variables.

Ammonium and nitrate concentrations observed over a 52-day period are shown in Figs. 53-60. Overlying water in the columns was not aerated initially and oxygen diffusion in these still systems was not sufficient to provide adequate aeration. Consequently, oxygen became depleted during the first days of the study. This resulted in a leveling-off of the ammonium concentrations in the columns without plants. This effect was not observed in columns with plants because the plants continued to assimilate ammonium. Subsequently (day 9) all columns were artificially aerated.

Ammonium removal and subsequent nitrate appearance in columns with 15 cm of overlying water are shown in Figs. 53-54. Initial ammonium concentrations were higher than are typically found in secondarily treated wastewater but were used for ease of measuring the various nitrogen transformations. In the columns with plants, this amount of ammonium was gone in approximately 15 days despite the aeration problems. At 18 days, additional ammonium was added to both the columns with and without plants. Ammonium removal continued to be rapid with plants, and, in contrast to the earlier days of the study, ammonium removal was also relatively rapid in the columns without plants. Only small amounts of nitrate were detected in either column (Fig. 53). This can be explained by the fact that some nitrate was removed by the plants. More importantly, as will be shown later, nitrate diffusion into the anaerobic sediment and subsequent denitrification was probably responsible for the low nitrate concentrations. Ammonium removal rates (Table 46) were about twice as fast in the columns with plants as in the columns without plants (3.8 vs 1.8 mg N/day).

Increasing the water depth to 30 cm did not significantly affect the ammonium removal rate (Table 46), but because the total amount of ammonium was greater, the removal time was somewhat longer (Fig. 55). As was the case with the 15-cm water depths, the ammonium removal rate was greater with plants (4.4 mg N/day) than without plants (2.8 mg N/day). Nitrate concentrations were low throughout the study

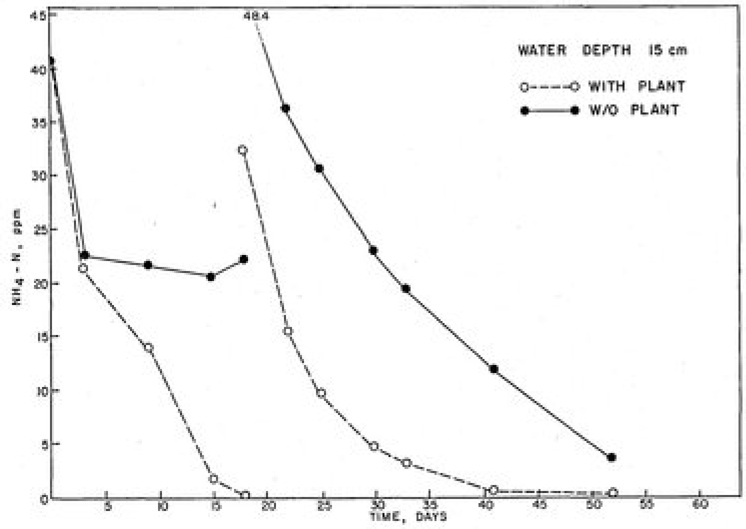



Figure 53. Ammoniacal nitrogen remaining in flooded soil core inoculated with ammonium at day 0 and day 18.

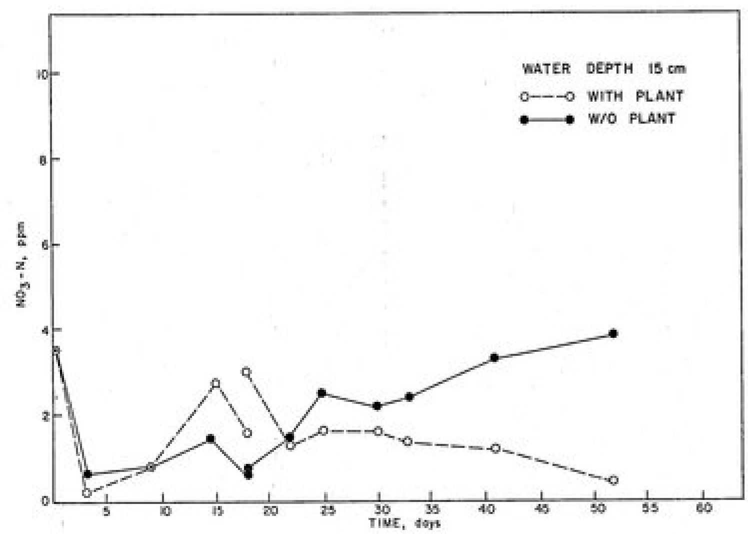



Figure 54. Nitrate nitrogen present in flooded soil core inoculated with ammonium at day 0 and day 18.

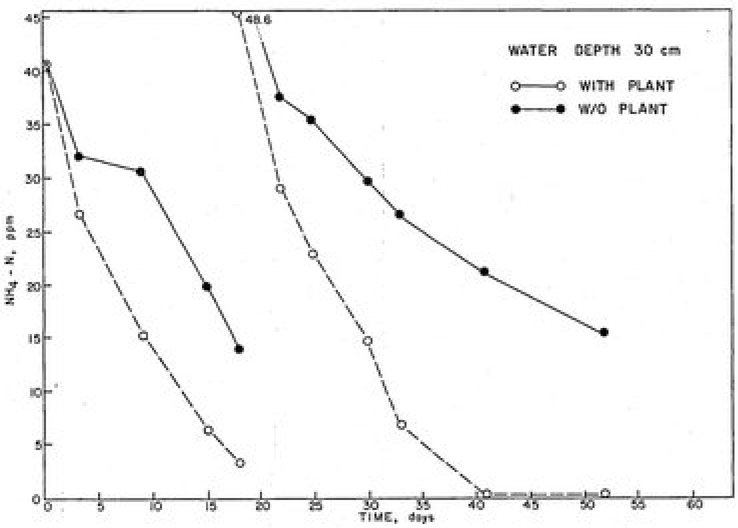



Figure 55. Ammoniacal nitrogen remaining in flooded soil core inoculated with ammonium at day 0 and day 18.

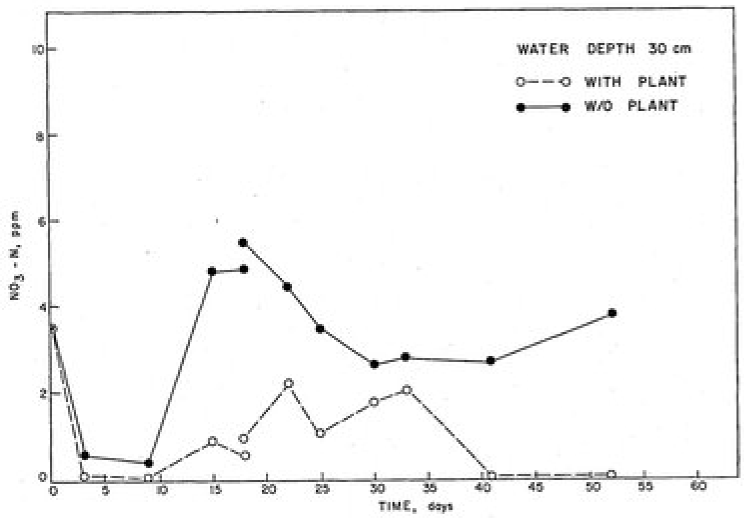



Figure 56. Nitrate nitrogen present in flooded soil core inoculated with ammonium at day 0 and day 18.

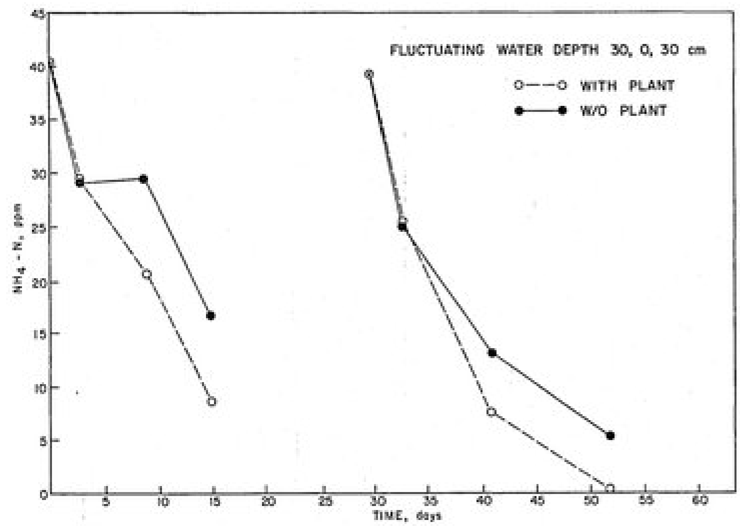



Figure 57. Ammoniacal nitrogen remaining in intermittently flooded soil core inoculated with ammonium at day 0 and day 30.

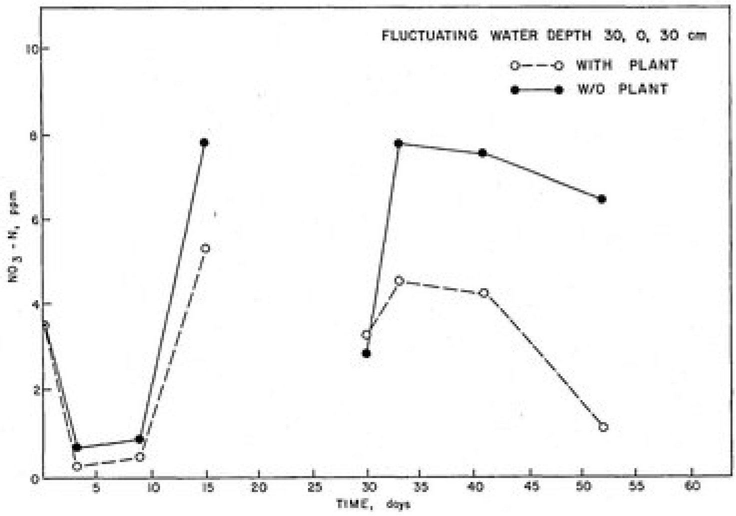



Figure 58. Nitrate nitrogen present in intermittently flooded soil core inoculated with ammonium at day 0 and day 30.

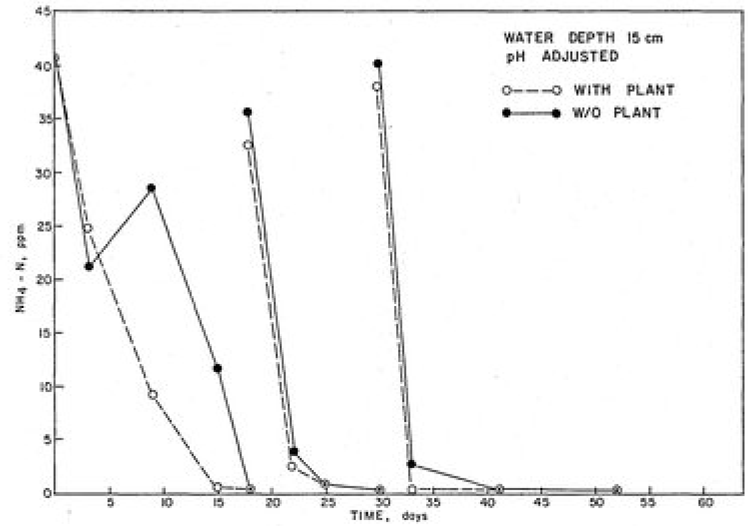



Figure 59. Ammoniacal nitrogen remaining in flooded soil core inoculated with ammonium at Day 0, Day 18, and Day 30. Lime was added to maintain a nearly neutral pH.

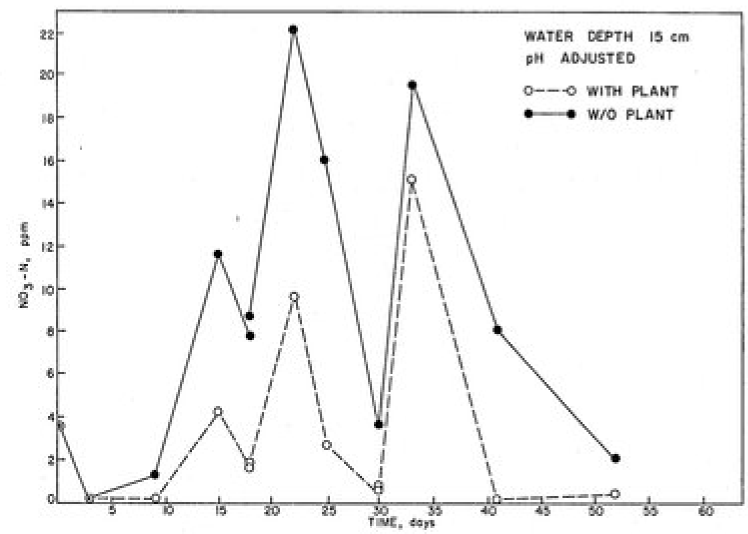



Figure 60. Nitrate nitrogen present in flooded soil core inoculated with ammonium nitrogen at day 0, day 18, and day 30. Lime was added to maintain a nearly neutral pH.

Table 46. Ammonium removal rates in laboratory studies using columns containing ammonium amended sewage effluent overlying 45 cm of peaty marsh soil.

| Treatment | | With Plant | Without Plant | With Plant | Without Plant |
|---|---|---|---|---|---|
| | | Mg N/column·day | | g N/m$^2$·day | |
| 15 cm water depth | | 3.8 | 1.8 | 0.49 | 0.23 |
| 30 cm water depth | | 4.4 | 2.8 | 0.57 | 0.36 |
| Fluct water depth: | 30-0-30 | 5.9 | 6.0 | 0.77 | 0.78 |
| 15 cm water depth: | pH adj. | 11.1 | 12.1 | 1.43 | 1.57 |

period for the same reasons noted for the 15-cm water depth columns. Allowing the columns to go through alternate wet-dry periods, i.e., approximately 15 days with 30 cm water depth followed by 15 days without water and then adding water to a 30 cm water depth for another 15-day period, resulted in a slightly higher ammonium removal rate than the stable 30 cm water depth (Fig. 57 and Table 46). There was essentially no difference between columns with and without plants. Apparently the dry period allowed a higher population of nitrifying organisms to develop that were able to compete effectively for ammonium with the plants. This conclusion is also suggested by the higher amounts of nitrate observed in these columns (Fig. 58). Rapid increases in nitrate concentrations were observed after rewet ting the columns, with concentrations highest in the columns without plants.

Increasing the pH had the most significant effect on increasing the ammonium removal rate (Fig. 59 and Table 46 ). Ammonium concentrations decreased from about 40 mg N/l to less than 5 mg N/l within three days. The fact that nitrification was responsible for much of this decrease was indicated by the high (20 mg N/l) nitrate concentrations observed in the overlying water. Nitrifying bacteria are most efficient at a pH between 7.0 and 8.3 and are considerably inhibited by pH values below 5. There were also no significant differences in ammonium removal rate with or without plants because the bacteria were competing successfully with plants for the ammonium. The effect of the plants was, however, very evident from the nitrate concentrations (Fig. 60). Nitrate concentrations were consistently lower in the presence of plants.

A tabular summary of the above data along with data from control columns is given in Tables 47 and 48. Control columns consisted of secondarily treated wastewater to a 15-cm depth overlying marsh soil with no treatment except aeration. Ammonium and nitrate concentrations in the controls with and without plants remained relatively low throughout the study period. Some minor fluctuations in both ammonium and nitrate concentrations were noted in the columns without plants. This suggests that plants dampen the effect of occasional, naturally occurring, low level flushes of nitrogen from the marsh soils.

Table 47. Ammonium concentration data in soil:water columns of nitrification experiment.

| Treatment | Days | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 3 | 9 | 15 | 18 | 18' | 22 | 25 | 30 | 30' | 33 | 41 | 52 |
| | ppm $NH_4$-N | | | | | | | | | | | | |
| Control | | | | | | | | | | | | | |
| w/plant | <0.05 | 0.34 | <0.05 | 0.60 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | ---- | <0.05 | <0.05 | <0.05 |
| w/o plant | <0.05 | 0.92 | 3.15 | 1.79 | 0.17 | <0.05 | <0.05 | <0.05 | <0.05 | ---- | <0.05 | <0.05 | <0.05 |
| pH adj | | | | | | | | | | | | | |
| w/plant | 40.6 | 24.6 | 9.1 | 0.43 | <0.05 | 32.2 | 2.38 | 0.60 | <0.05 | 37.8 | <0.05 | <0.05 | <0.05 |
| w/o plant | 40.6 | 21.1 | 28.4 | 11.7 | 0.08 | 35.4 | 3.80 | 0.68 | <0.05 | 40.0 | 2.18 | <0.05 | <0.05 |
| 15 cm | | | | | | | | | | | | | |
| w/plant | 40.6 | 21.4 | 13.8 | 1.92 | <0.05 | 32.4 | 15.4 | 9.65 | 4.78 | ---- | 3.20 | 0.68 | <0.05 |
| w/o plant | 40.6 | 22.8 | 21.7 | 20.6 | 22.2 | 48.4 | 36.1 | 30.5 | 22.8 | ---- | 19.4 | 11.8 | 3.54 |
| 30 cm | | | | | | | | | | | | | |
| w/plant | 40.6 | 26.4 | 15.1 | 6.10 | 3.12 | 45.4 | 28.8 | 22.6 | 14.5 | ---- | 6.64 | <0.05 | <0.05 |
| w/o plant | 40.6 | 32.0 | 30.3 | 19.6 | 13.6 | 48.6 | 37.3 | 35.3 | 29.4 | ---- | 26.3 | 29.8 | 15.1 |
| Fluct | | | | | | | | | | | | | |
| w/plant | 40.6 | 29.6 | 20.7 | 8.40 | ----[a] | ---- | ---- | ---- | ---- | 39.1 | 25.2 | 7.43 | <0.05 |
| w/o plant | 40.6 | 29.0 | 29.6 | 16.7 | ---- | ---- | ---- | ---- | ---- | 39.2 | 24.7 | 12.8 | 5.09 |

[a] Overlying water removed from day 15 to day 30.

Table 48. Nitrate nitrogen concentration data in soil:water columns of nitrification experiment.

| Treatment | Days 0 | 3 | 9 | 15 | 18 | 18' | 22 | 25 | 30 | 30' | 33 | 41 | 52 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ppm $NO_3$-N | | | | | | | | | | | | |
| Control | | | | | | | | | | | | | |
| w/plant | 2.27 | <0.05 | 0.34 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | 0.60 | ---- | <0.05 | 0.51 | 2.61 |
| w/o plant | 2.27 | 0.22 | <0.05 | 0.94 | <0.05 | 0.34 | <0.05 | 0.26 | 1.36 | ---- | <0.05 | <0.05 | 0.07 |
| pH adj | | | | | | | | | | | | | |
| w/plant | 3.50 | 0.38 | 0.17 | 4.36 | 1.80 | 1.62 | 9.58 | 2.69 | 0.51 | 0.76 | 15.0 | <0.05 | 0.40 |
| w/o plant | 3.50 | 0.34 | 1.20 | 11.7 | 7.73 | 8.62 | 22.0 | 16.0 | 3.50 | 3.54 | 19.4 | 7.94 | 2.04 |
| 15 cm | | | | | | | | | | | | | |
| w/plant | 3.50 | 0.22 | 0.72 | 2.73 | 1.54 | 2.99 | 1.28 | 1.58 | 1.58 | ---- | 1.32 | 1.16 | 0.40 |
| w/o plant | 3.50 | 0.64 | 0.80 | 1.41 | 0.60 | 0.72 | 1.47 | 2.48 | 2.18 | ---- | 2.39 | 3.29 | 3.79 |
| 30 cm | | | | | | | | | | | | | |
| w/plant | 3.50 | 0.09 | <0.05 | 0.85 | 0.51 | 0.94 | 2.22 | 1.02 | 1.75 | ---- | 2.05 | <0.05 | 0.08 |
| w/o plant | 3.50 | 0.51 | 0.38 | 4.82 | 4.91 | 5.46 | 4.48 | 3.46 | 2.64 | ---- | 2.82 | 2.73 | 3.80 |
| Fluct | | | | | | | | | | | | | |
| w/plant | 3.50 | 0.26 | 0.43 | 5.30 | ----[a] | ---- | ---- | ---- | ---- | 3.24 | 4.50 | 4.23 | 1.06 |
| w/o plant | 3.50 | 0.65 | 0.84 | 7.77 | ---- | ---- | ---- | ---- | ---- | 2.86 | 7.78 | 7.50 | 6.42 |

[a]Overlying water removed from day 15 to day 30.

In situ investigations. Since nitrification did not appear to occur naturally in the water alone but did when in contact with soil in the column experiments, an in situ study was proposed to determine the location of and the rates at which this oxidative process would occur in the soil profile. To accomplish this, polyethylene bags containing marsh soil amended with ammonium were placed at shallow (8 cm) and deep (30 cm) positions in the marsh. Results depicted graphically in Fig. 61 show an initial increase in ammonium concentrations for both depths, with a leveling off in the deep samples and slowly declining concentration for the shallow samples. Stable, high ammonium concentrations in the samples from the deep site were probably first limited by oxygen, since site data at the time of sampling showed dissolved oxygen approaching zero, which was too low to support any nitrification (Table 49). The slow rate of ammonium removal and slight increase of nitrate (Fig. 62) in shallow samples could have been the result of several factors. Although very important, pH was probably not the primary limiting factor since ammonium removal by nitrification has been shown to occur in the column studies without pH adjustment. Oxygen concentrations of the overlying water at the sampling sites over the 27-day period varied from almost 0-2.7 mg/l. No overlying water was present on two sampling dates, and therefore shallow sites were exposed to the atmospheric oxygen concentration. Ammonium concentrations in the shallow samples show a slow, steady decline, which does not reflect these changing oxygen values. Since ammonium removal by nitrification was not stimulated when the water was low and the site exposed to atmospheric concentration of oxygen, ambient oxygen was not likely limiting. Rather, oxygen diffusing into the polyethylene sample bags was probably being used for organic matter decomposition first, with little left for nitrification. This is in keeping with reports (Patrick and Reddy 1976) that indicate that under oxygen-limited conditions, readily decomposable organic compounds will be oxidized first, followed by nitrification. Original work using these polyethylene bags in nitrification studies (Eno 1960) was carried out on well-drained mineral soils, presumably of low oxygen demand. Later work characterizing the rate of oxygen diffusion through polyethlene was

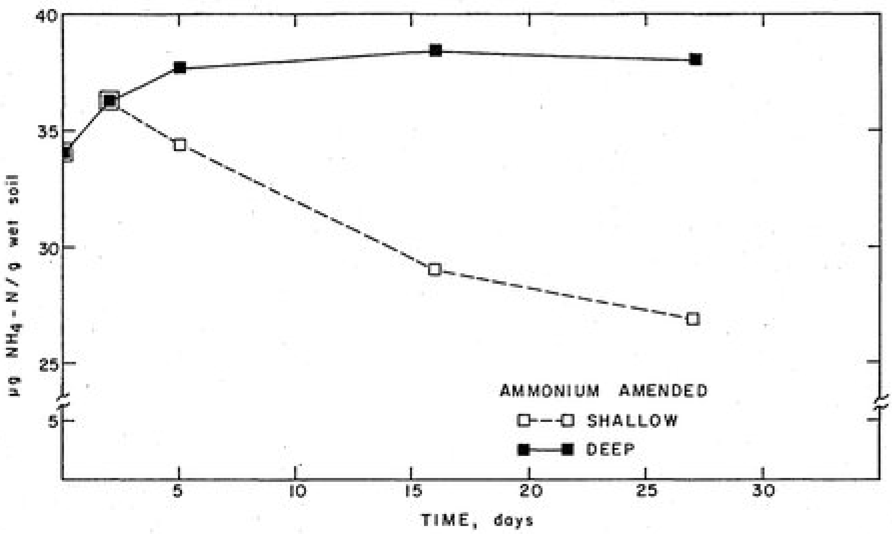



Figure 61. Ammonium concentrations in ammonium-amended marsh soil after in situ incubation in polyethylene bags.

Table 49. Ammonium, nitrate, dissolved oxygen, pH, and groundwater levels determined after in situ incubation in soil samples (amended and unamended with ammonium) in polyethylene bags.

| Treatment | Days 0 | 2 | 5 | 8 | 16 | 19 | 27 |
|---|---|---|---|---|---|---|---|
| | $\mu g$ $NH_4$-N per gram soil (on wet weight basis)† | | | | | | |
| Control, shallow | 0.3 | 1.9 | 1.2 | 1.2 | 2.4 | --- | 4.0 |
| Control, deep, lime | 3.3 | --- | --- | 9.8 | --- | 10.8 | 11.8 |
| Nitrification, shallow | 34.3 | 36.2 | 34.5 | --- | 29.0 | --- | 26.8 |
| Nitrification, deep | 34.3 | 36.2 | 37.4 | --- | 38.1 | --- | 37.9 |
| | $\mu g$ $NO_3$-N per gram soil (on wet weight basis)† | | | | | | |
| Control, shallow | <0.05 | 0.4 | <0.05 | 0.1 | 0.4 | --- | 0.4 |
| Control, deep, lime | 0.4 | --- | --- | 0.1 | --- | 1.6 | 1.5 |
| Nitrification, shallow | 0.5 | 0.5 | 0.9 | --- | 1.9 | --- | 1.2 |
| Nitrification, deep | 0.5 | 2.4 | 0.2 | --- | 1.9 | --- | 2.0 |
| | Dissolved oxygen, ppm | | | | | | |
| Control, shallow (site) | 0.6 | 1.5 | 2.7 | 1.8 | 0.6 | --- | 0.5 |
| Control, deep, lime (site) | 0.4 | --- | --- | 0.4 | --- | 0.5 | |
| Nitrification, shallow (site) | 0.6 | 1.9 | ‡ | --- | 0.7 | --- | 1.1 |
| Nitrification, deep (site) | 0.4 | 0.5 | 0.3 | --- | 0.5 | --- | 0.3 |
| | pH | | | | | | |
| Control, shallow | 4.8 | 4.6 | 4.6 | 4.7 | 4.6 | --- | 4.7 |
| Control, shallow (site) | --- | 4.9 | 4.8 | 4.8 | 4.9 | --- | 4.9 |
| Control, deep, lime | 4.8 | --- | --- | 6.4 | --- | 6.6 | |
| Control, deep, lime (site) | 4.6 | --- | --- | 4.9 | --- | 4.8 | |
| Nitrification, shallow | 4.8 | 4.3 | 4.3 | --- | 4.5 | --- | 4.5 |
| Nitrification, shallow (site) | --- | 4.9 | 4.9 | --- | --- | --- | --- |
| Nitrification, deep | 4.8 | 4.2 | 4.4 | --- | 4.6 | --- | 4.6 |
| Nitrification, deep (site) | --- | 4.4 | 4.8 | --- | 4.8 | --- | 4.6 |
| | -Water level in reference to soil surface (cm)- | | | | | | |
| Average over-all sites | +3 | −4 | −10 | −15 | +15 | --- | +5 |

† Organic soils containing 93% moisture.
‡ No floodwater present.

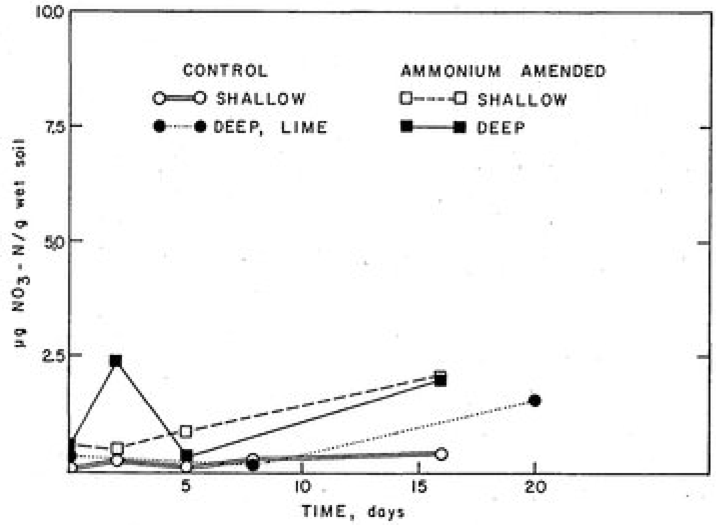



Figure 62. Nitrate concentrations in marsh soil amended with ammonium and/or lime after in situ incubation in polyethylene bags.

done in deionized water using ammonium and nitrate-amended deionized-water-filled bags (Struble 1977). No work has been done to date to determine if the rate of decomposition, and therefore oxygen demand, of organic matter is affected by incubation in polyethethylene bags.

Preliminary microbiological investigations indicated that after 27 days of incubation, no autotrophic nitrifiers were present in shallow samples. Yet they do exist in the natural marsh at both depths in very low numbers (Table 50). It is possible that the nitrifiers were eliminated or selected against in the sampling and incubation process due to the low oxygen status in the bags or to the depth from which bulk soil placed in the bag was taken, rather than to the actual incubation. Nitrifiers are usually found in the top 2 cm, so it is treated as a strictly interface process rather than shallow or deep (Chen et al. 1972; Voltz et al. 1975). This work also supports the conclusion that since nitrification was not occurring naturally in the water or significantly at shallow soil depths, and not at all deeper in the soil, it must have been occurring only at the interface. Matulewich et al. (1975) found 75% greater nitrifier populations at the interface in an organic sediment than at a 10 cm depth. Another consideration is the type of nitrifier. In shallow soil samples from the Clermont marsh, considerably higher numbers of heterotrophs (Tusneem and Patrick 1971) than autotrophs (Terry and Nelson 1975) were found (Table 50). However, less ammoniumoxidation is carried out by the heterotrophic nitrifiers since they derive no energy from the reaction (Alexander 1977). Tate (1977) reported that heterotrophic nitrifiers may play a significant role in organic soils. Slow ammonium removal with no appearance of nitrate could also be due to nitrate assimilation or denitrification. Roots (absent from this experiment) could also play an important role in nitrification if they transport oxygen to the rhizosphere in sufficient quantities to support this process. If heterotrophic nitrification is significant, root exudates would further enhance the process by providing an easily assimilated organic carbon source.

Table 50. Total, nitrifying and denitrifying bacterial populations in marsh soils obtained directly from the marsh and in soils incubated in situ in polyethylene bags for 27 days.

| Treatment | Number of microorganisms | | | |
|---|---|---|---|---|
| | Total | Nitrifiers | | Denitrifiers |
| | | Autotrophs (Nitrosomonas)* | Heterotrophs | |
| | - - - - -organisms per gram of dry soil - - - - - - | | | |
| Natural marsh: | | | | |
| Shallow root | $38.x10^7$ | 450 | $3x10^7$ | $33x10^4$ |
| rootless | $5.6x10^7$ | 1200 | ---- | $1.8x10^4$ |
| Deep | $3.5x10^7$ | 91 | $6x10^6$ | $2.0x10^4$ |
| In day 27 polyethylene bags: | | | | |
| Control, shallow | $1.6x10^7$ | 0 | $2.5x10^6$ | ---- |
| Nitrific., shallow | $1.7x10^7$ | 0 | $7x10^5$ | ---- |
| Control, deep, lime | $21x10^7$ | ---- | ---- | $6.1x10^4$ |
| Denitrific., deep | $2.3x10^7$ | ---- | ---- | $1700x10^4$ |

*<u>Nitrobacter</u> counts undetermined due to heterotrophic growth overrunning the broth tubes.

In summary, nitrification rates in the marsh are important because they control the amount of treated wastewater ammonium that will be converted to nitrate. This nitrate, along with that already present in the treated wastewater, will then be subject to removal through denitrification as well as plant assimilation. In practical terms, results from soil:water column studies indicate that the marsh has the potential to remove from 0.5 to 0.6 g $NH_4$-N/$m^2$·day (approximately equivalent to 5-6 pounds per acre per day) in its natural state, via nitrification and plant assimilation.

Denitrification

Laboratory experiments. Preliminary laboratory denitrification studies were conducted to obtain approximate rates and to ascertain how they would be affected by the presence or absence of soil, associated cations, and water source. Since there were no plants present in this preliminary study and negatively charged soil particles were not likely to adsorb negatively charged nitrate ions, the most plausible nitrate removal processes were denitrification and microbial immobilization. The former was generally the dominant reaction, but the latter has been shown to account for a third of the total nitrate removed (Chen et al. 1972).

The data (Table 51) show linear decline in nitrate concentrations with time for all soil:water treatements. Removal rates did not appear to be affected either by the water source or by the corresponding cation. Solutions not in contact with soil showed no appreciable change (any observed increase was due to evaporation), which was in agreement with work done by Engler et al. (1976). This was due primarily to the absence of a readily available organic carbon source and to oxygen diffusion.

Results from a 56-day soil:water column denitrification study are shown in Figs. 63-66. Nitrate nitrogen was applied to the overlying aerated waters in two increments, and ammonium and nitrate concentrations were monitored (Tables 52 and 53). Treatments were the same as in the nitrification study. The ammonium and nitrate concentrations in the control columns remained at a low level comparable to the background marsh, which was less than 1 mg/l with slight

Table 51. Nitrate removal from water alone and in contact with soil, incubated in the laboratory.

| Treatment | Days 0 | 2 | 5 | 11 |
|---|---|---|---|---|
| | -------$NO_3$-N, ppm----------- | | | |
| $Ca(NO_3)_2$ in deionized water (no soil) | 40.5 | 41.8 | 41.3 | 42.3 |
| $KNO_3$ in deionized water (no soil) | 45.0 | 45.2 | 46.6 | 47.3 |
| $KNO_3$ in oxid pond water (no soil) | 51.6 | 53.0 | 54.7 | 58.0 |
| $KNO_3$ in marsh water (no soil) | 43.2 | 44.9 | 44.8 | 49.2 |
| $Ca(NO_3)_2$ in deionized water (over soil) | 40.5 | 30.9 | 25.5 | 12.2 |
| $KNO_3$ in deionized water (over soil) | 45.0 | 33.9 | 26.3 | 15.0 |
| $KNO_3$ in oxid pond water (over soil) | 51.6 | 43.0 | 30.0 | 21.5 |
| $KNO_3$ in marsh water (over soil) | 43.2 | 35.0 | 26.5 | 14.8 |
| | -------% $NO_3$-N remaining------ | | | |
| $Ca(NO_3)_2$ in deionized water (over soil) | 100.0 | 76.3 | 63.0 | 30.1 |
| $KNO_3$ in deionized water (over soil) | 100.0 | 75.2 | 58.4 | 33.4 |
| $KNO_3$ in oxid pond water (over soil) | 100.0 | 83.3 | 58.2 | 41.6 |
| $KNO_3$ in marsh water (over soil) | 100.0 | 81.0 | 61.3 | 34.3 |

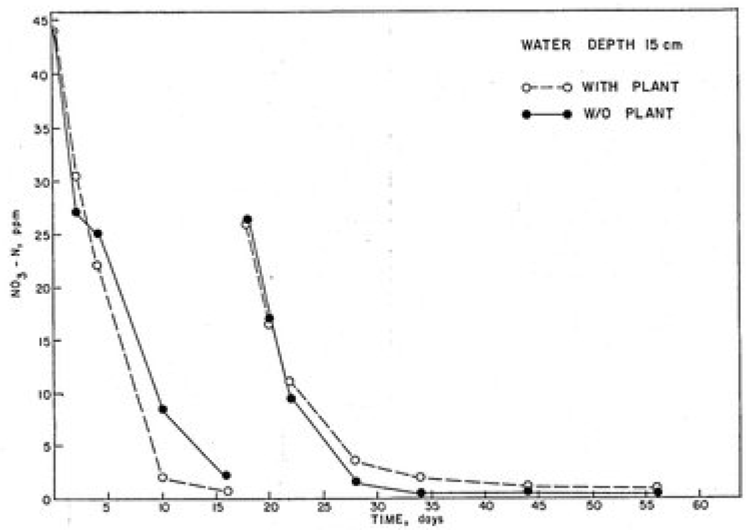



Figure 63. Nitrate nitrogen remaining in flooded soil core inoculated with nitrate nitrogen at day 0 and day 18.

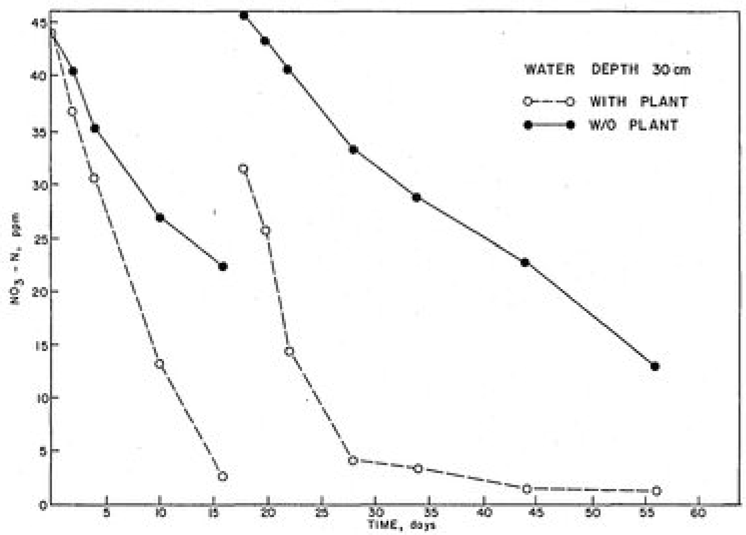



Figure 64. Nitrate nitrogen remaining in flooded soil core inoculated with nitrate nitrogen at day 0 and day 18.

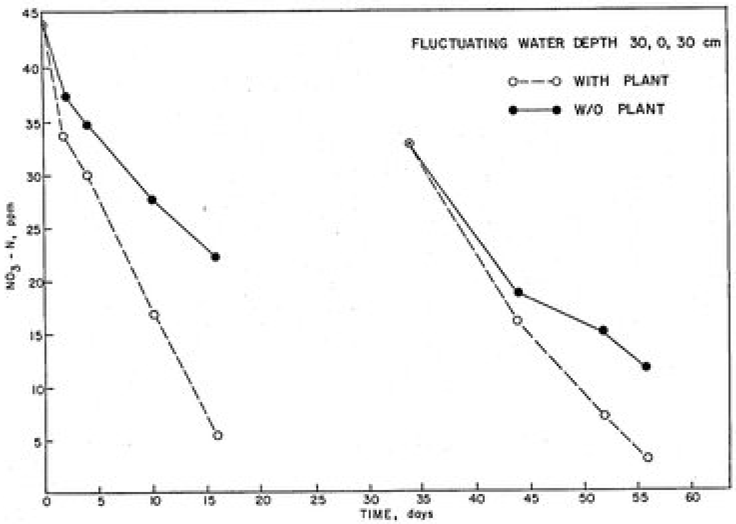



Figure 65. Nitrate nitrogen remaining in intermittently flooded soil core inoculated with nitrate nitrogen at day 0 and day 34.

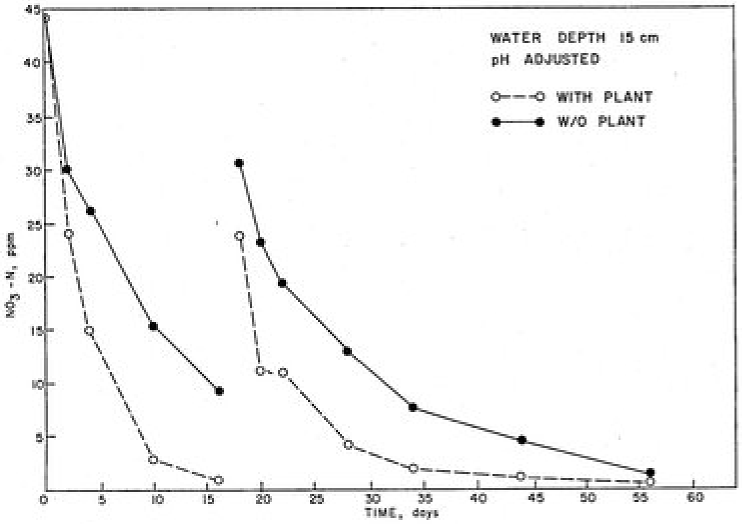



Figure 66. Nitrate nitrogen remaining in flooded soil inoculated with nitrate nitrogen at day 0 and day 18. Lime was added to maintain a nearly neutral pH.

Table 52. Ammonium concentration data in soil:water columns of denitrification experiment.

| Treatment | Days | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 2 | 4 | 10 | 16 | 18 | 20 | 22 | 28 | 34 | 44 | 52 | 56 |
| | ppm $NH_4$-N | | | | | | | | | | | | |
| Control | | | | | | | | | | | | | |
| w/plant | 1.15 | 0.80 | 0.42 | <0.05 | <0.05 | 0.37 | 0.10 | 0.10 | <0.05 | <0.05 | 0.64 | ---- | 0.11 |
| w/o plant | 1.15 | 0.74 | 0.58 | <0.05 | 0.22 | <0.05 | 0.11 | 0.10 | 0.22 | <0.05 | 0.10 | ---- | 0.16 |
| pH adj | | | | | | | | | | | | | |
| w/plant | 0.83 | 3.24 | 2.44 | <0.05 | <0.05 | 0.16 | <0.05 | 0.26 | <0.05 | <0.05 | <0.05 | ---- | 0.04 |
| w/o plant | 0.83 | 0.69 | 0.48 | 0.06 | <0.05 | 0.16 | 0.05 | 0.42 | <0.05 | <0.05 | 0.16 | ---- | 0.12 |
| 15 cm | | | | | | | | | | | | | |
| w/plant | 0.83 | 1.17 | 0.80 | <0.05 | <0.05 | 0.16 | 0.16 | 0.11 | <0.05 | <0.05 | 0.22 | ---- | 0.07 |
| w/o plant | 0.83 | 4.15 | 1.01 | 0.16 | <0.05 | 0.53 | 0.16 | <0.05 | <0.05 | 0.11 | <0.05 | ---- | 0.11 |
| 30 cm | | | | | | | | | | | | | |
| w/plant | 0.83 | 1.01 | 1.17 | <0.05 | <0.05 | <0.05 | 0.16 | 0.05 | <0.05 | <0.05 | <0.05 | ---- | 0.12 |
| w/o plant | 0.83 | 2.50 | 2.45 | 0.48 | 0.26 | <0.05 | 0.58 | 0.48 | <0.05 | <0.05 | 0.16 | ---- | 0.10 |
| Fluct | | | | | | | | | | | | | |
| w/plant | 0.83 | 2.29 | 1.44 | 0.11 | <0.05 | ----[a] | ---- | ---- | ---- | 0.39 | <0.05 | 0.80 | 0.22 |
| w/o plant | 0.83 | 1.17 | 1.01 | 0.06 | <0.05 | ---- | ---- | ---- | ---- | 0.39 | 0.54 | 1.17 | 0.12 |

[a]Overlying water removed from day 16 to day 33.

Table 53. Nitrate nitrogen concentration data in soil:water columns of denitrification experiment.

| Treatment | Days 0 | 2 | 4 | 10 | 16 | 18 | 20 | 22 | 28 | 34 | 44 | 52 | 56 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ppm $NO_3$-N | | | | | | | | | | | | |
| Control | | | | | | | | | | | | | |
| w/plant | 5.79 | 0.16 | 0.26 | 0.10 | 0.22 | 0.10 | <0.05 | 0.32 | 0.28 | 0.42 | 0.90 | ---- | 0.30 |
| w/o plant | 5.79 | 2.96 | 1.80 | 0.16 | <0.05 | <0.05 | <0.05 | <0.05 | 0.10 | <0.05 | 0.74 | ---- | 0.12 |
| pH adj | | | | | | | | | | | | | |
| w/plant | 43.8 | 24.0 | 14.9 | 2.88 | 0.96 | 23.7 | 11.1 | 11.0 | 4.20 | 1.92 | 1.06 | ---- | 0.44 |
| w/o plant | 43.8 | 29.8 | 26.2 | 15.2 | 9.16 | 30.4 | 23.2 | 19.3 | 12.8 | 7.56 | 4.47 | ---- | 1.29 |
| 15 cm | | | | | | | | | | | | | |
| w/plant | 43.8 | 30.4 | 21.8 | 1.97 | 0.53 | 25.8 | 16.4 | 11.0 | 3.46 | 1.81 | 1.06 | ---- | 0.60 |
| w/o plant | 43.8 | 27.1 | 25.0 | 8.38 | 2.02 | 26.2 | 16.8 | 9.15 | 1.49 | 0.21 | 0.43 | ---- | 0.50 |
| 30 cm | | | | | | | | | | | | | |
| w/plant | 43.8 | 36.8 | 30.6 | 13.0 | 2.61 | 31.4 | 25.6 | 14.2 | 3.99 | 3.24 | 1.38 | ---- | 1.06 |
| w/o plant | 43.8 | 40.4 | 35.2 | 26.7 | 22.3 | 45.6 | 43.3 | 40.6 | 33.0 | 28.7 | 22.6 | ---- | 12.6 |
| Fluct | | | | | | | | | | | | | |
| w/plant | 43.8 | 33.9 | 30.0 | 16.6 | 5.32 | ----[a] | ---- | ---- | ---- | 32.6 | 15.8 | 6.90 | 2.78 |
| w/o plant | 43.8 | 37.6 | 34.8 | 27.5 | 22.0 | ---- | ---- | ---- | ---- | 32.6 | 18.5 | 14.8 | 11.2 |

[a]Overlying water removed from day 16 to day 33.

random variations. The columns amended with nitrate also showed low concentrations of ammonium in the overlying waters, probably due to background values.

Nitrate removal in the 15-cm water depth columns (Fig 63) was rapid enough that there was no appreciable difference between those with or without plants (4.7 and 4.6 mg N/col·day, respectively). The 30 cm water depth treatment exhibited an equivalent or slower rate than did the 15 cm teatment. When compared on a mass basis, the removal rate of the 30 cm depth treatment (5.8 mg N/col·day) with plants was higher than either 15 cm depth treatment. The 30 cm treatment without plants was the slowest of the four (2.6 mg N/col·day), probably because it was more dependent on diffusion to bring the nitrate into the soil than the treatments with plants, since plants may "pump" water containing nitrate down into the soil.

This same effect and similar rates appeared again with the fluctuating water level treatments. Those without plants and dependent solely on diffusion had a rate of 2.8 mg N/col·day when they temporarily had 30 cm of water, which was comparable to 2.6 mg N/col·day obtained for those constantly poised at 30 cm. Since nitrate removal by denifrification is an anaerobic process, fluctuating the water level and thus exposing the soil to the atmosphere was not expected to enhance the process as it did for the oxygen-requiring nitrification, except perhaps by increasing carbon availability. In keeping with these expectations, nitrate removal in the fluctuating water level with plants was 4.4 mg N/col·day as compared to removal for a constantly poised 30 cm depth with plants of 5.8 mg N/col·day.

The effect of adjusting the pH with lime was also lost, since lime was applied on the surface of the soil, and denitrification occurred in sites further down in the profile. In a natural marsh system, it would not be feasible to incorporate the lime into the soil since this would kill plants, compact soil, etc., uncless some type of plant harvest was already being conducted. The rates for the experiment with plant (3.6 mg N/col·day) and without plant (1.3 mg N/col·day) were lower than the rates for the same water level unlimed.

Nitrate removal rates obtained from the straight line portion of the graphed data were comparable but slightly lower than rates obtained by Engler et al. (1974) in a similar experiment (Table 54).

In situ investigations. Nitrate removal under natural conditions as a function of depth and incorporated lime was investigated by in situ incubation of nitrate and lime-amended marsh soil in polyethlylene bags (Table 55). Soils amended with nitrate showed rapid nitrate removal, with 25 mg/l $NO_3$-N being removed in two to eight days, depending on the treatment (Fig. 67). Limed soils amended with nitrate and placed deep in the profile removed 12.8 µg N/g wet soil·day. When this is compared to a similarly placed but unlimed sample in which 5.1 µg N/g wet soil·day was removed, it is obvious that liming enhanced the removal rate. This indicates that denitrification was limited by the natural soil pH of 4.7. This is in agreement with other work which indicated that acidity in peat was the main limiting factor for denitrification (King and Morris 1972). This immediate stimulation of denitrification by raising the pH is also in direct evidence that at least most of the nitrate removal occurred biologically rather than chemically, since the latter is inhibited at higher pH values. Another interesting aspect of liming that occurred in earlier column studies was increased ammonification shown by limed treatments (Fig. 68). This ammonium accumulation did not occur in shallow samples due to the presence of some small amount of oxygen, but did occur under completely anaerobic (i.e., deeper) conditions and was stimulated by increased ammonification due to liming (Howeler and Bouldin 1971). Redman and Patrick (1965) and Reneau (1977) also reported ammonium accumulation due to organic matter degradation under anaerobic conditions. Some ammonium could also have originated from assimilatory nitrate reduction (Stanford et al. 1975) since more accumulated in the nitrate-amended than in the unamended treatment.

The effect of depth on nitrate removal rates is shown by comparing data for unlimed shallow sites (3.06 µg N/g·day) to unlimed deep sites (5.13 µg N/g·day). Slower nitrate removal at shallow sites is likely due to greater oxygen diffusion at shallow sites and is not to be seen as conflicting with earlier data showing higher carbohydrates and denitrifying populations at shallow depths.

Table 54. Nitrate removal rates in laboratory studies using columns containing nitrate amended sewage effluent overlying 45 cm of peaty marsh soil.

| Treatment | With Plant | Without Plant | With Plant | Without Plant |
|---|---|---|---|---|
| | Mg N/column·day | | $gN/m^2 \cdot day$ | |
| 15 cm water | 4.7 | 4.6 | 0.61 | 0.60 |
| 30 cm water depth | 5.8 | 2.6 | 0.75 | 0.34 |
| Fluct water dpeth: 30-0-30 cm | 4.4 | 2.8 | 0.57 | 0.36 |
| 15 cm water depth: pH adj. | 3.6 | 1.3 | 0.47 | 0.17 |
| 7.6 cm water depth[a] | --- | 6.1[a] | --- | 0.79[a] |

[a]Obtained experimentally by Engler and Patrick (1974).

Table 55. Ammonium, nitrate, dissolved oxygen, pH, and groundwater levels determined after in situ incubation of soil samples (amended and unamended with nitrate) in polyethylene bags.

| Treatment | Days 0 | 2 | 5 | 8 | 16 | 19 | 27 |
|---|---|---|---|---|---|---|---|
| | $\mu g$ $NH_4$-N per gram soil (on wet weight basis)† | | | | | | |
| Control, shallow | 0.3 | 1.9 | 1.2 | 1.2 | 2.4 | --- | 4.0 |
| Control, deep, lime | 3.3 | --- | --- | 9.8 | --- | 10.8 | 11.8 |
| Denitrification, shallow | 1.1 | 3.6 | 1.7 | 2.5 | 2.7 | --- | --- |
| Denitrification, deep | 1.1 | 3.9 | 4.7 | 6.4 | 8.9 | --- | 8.7 |
| Denitrification, deep, lime | 2.1 | 8.1 | 12.1 | 14.1 | 19.3 | --- | --- |
| | $\mu g$ $NO_3$-N per gram soil (on wet weight basis)† | | | | | | |
| Control, shallow | <0.05 | 0.4 | <0.05 | 0.1 | 0.4 | --- | 0.4 |
| Control, deep, lime | 0.4 | --- | --- | 0.1 | --- | 1.6 | 1.5 |
| Denitrification, shallow | 27.2 | 11.4 | 8.5 | 2.7 | 0.2 | --- | --- |
| Denitrification, deep | 27.2 | 13.0 | 1.6 | 0.3 | 0.6 | --- | 0.6 |
| Denitrification, deep, lime | 28.7 | 3.0 | <0.05 | 0.2 | 1.0 | --- | --- |
| | Dissolved oxygen, ppm | | | | | | |
| Control, shallow (site) | 0.6 | 1.5 | 2.7 | 1.8 | 0.6 | --- | 0.5 |
| Control, deep, lime (site) | 0.4 | --- | --- | 0.4 | --- | 0.5 | |
| Denitrification, shallow (site) | 0.6 | 4.2 | 1.3 | ‡ | 0.6 | --- | --- |
| Denitrification, deep (site) | 0.4 | 0.3 | 0.3 | 0.3 | 0.1 | --- | 0.4 |
| Denitrification,deep,lime(site) | 0.4 | 0.4 | 0.2 | 0.4 | 0.4 | --- | --- |
| | pH | | | | | | |
| Control, shallow | 4.8 | 4.6 | 4.6 | 4.7 | 4.6 | --- | 4.7 |
| Control, shallow (site) | --- | 4.9 | 4.8 | 4.8 | 4.9 | --- | 4.9 |
| Control, deep, lime | 4.8 | --- | --- | 6.4 | --- | 6.6 | |
| Control, deep, lime (site) | 4.6 | --- | --- | 4.9 | --- | 4.8 | |
| Denitrification, shallow | 4.8 | 4.5 | 4.6 | 4.7 | 4.8 | --- | --- |
| Denitrification, shallow (site) | --- | 4.8 | 5.0 | 4.8 | 5.2 | --- | --- |
| Denitrification, deep | 4.8 | 4.5 | 4.7 | 4.8 | 5.0 | --- | 5.0 |
| Denitrification, deep (site) | --- | 4.4 | 4.7 | 4.6 | 4.8 | --- | 4.8 |
| Denitrification, deep, lime | 4.8 | 6.2 | 6.5 | 6.4 | 6.4 | --- | --- |
| Denitrification, deep,lime(site) | --- | 4.5 | 4.5 | 4.6 | 4.8 | --- | --- |
| | -Water level in reference to soil surface (cm)- | | | | | | |
| Average over-all sites | +3 | -4 | -10 | -15 | +15 | --- | +5 |

† Organic soils containing 93% moisture.
‡ No floodwater present.

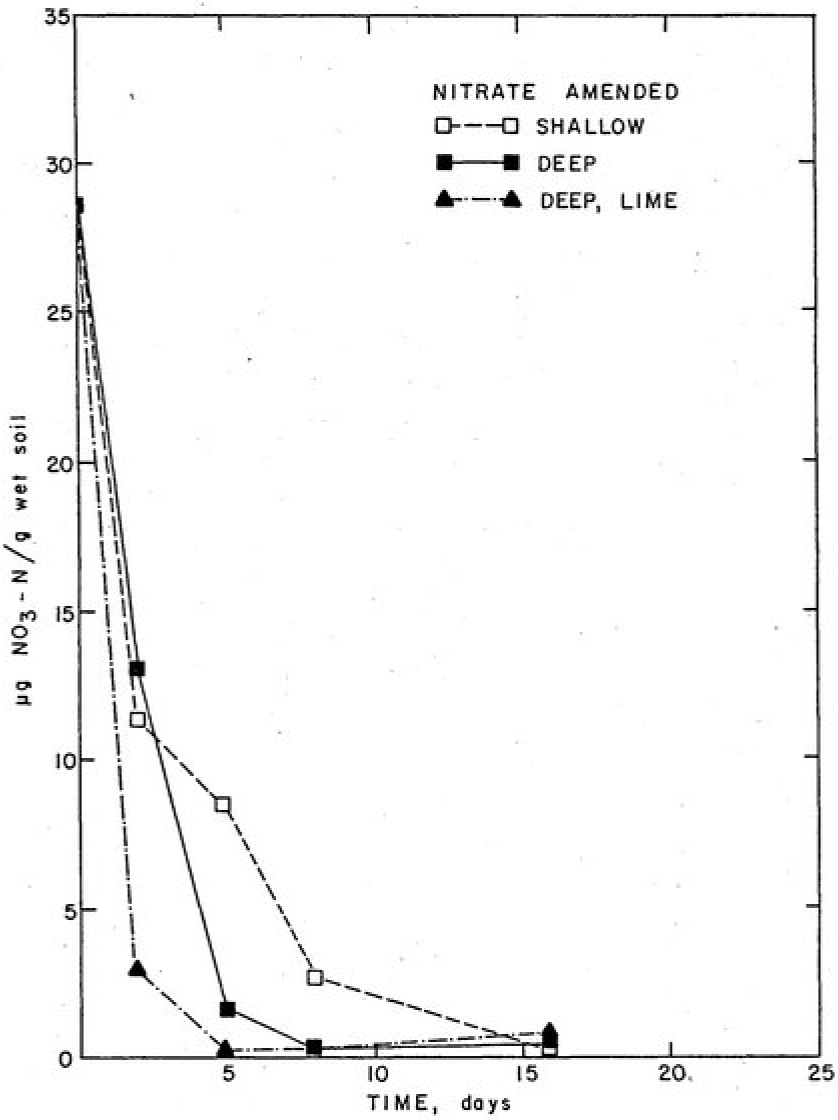



Figure 67. Nitrate removal from nitrate amended marsh soil after in situ incubation in polyethylene bags.

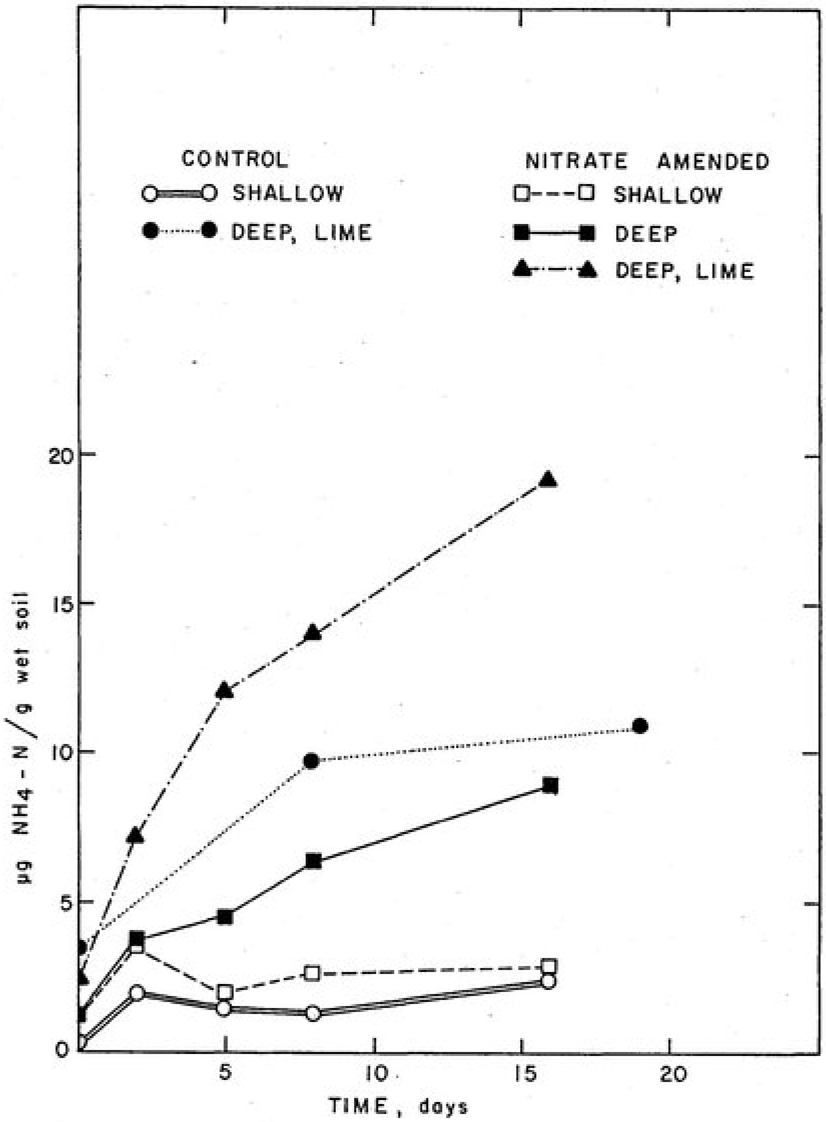



Figure 68. Ammonium production in marsh soil amended with nitrate and/or lime after in situ incubation in polyethylene bags.

The same bulk sample soil was placed in all bags for all treatments and therefore did not reflect the naturally occurring higher populations and concentration of carbohydrates. The bags were not permeable to ions or organisms. In fact, extractable carbohydrate concentrations were significantly lower (0.05 level) in the bags after 27 days of incubation than those naturally occurring in the marsh, i.e., 2450 mg/l in control lime (deep) compared to 4700 mg/l (shallow) natural. For this reason and the greater distance of diffusion, the increased denitrification at greater depth may not reflect natural conditions; it does, however, indicate a high potential for nitrate removal.

An attempt was also made to evaluate the kinetics of denitrification in these investigations. Rates of denitrificationin the in situ incubation studies appeared to be independent of nitrate concentration until the concentration approached zero, indicating zero-order kinetics. This was in agreement with work by Reddy et al. (1978) on a saturated soil with no floodwater present, which indicated the zero-order kinetic rate was due to the fact that the nitrate was in direct contact with the active denitrification sites in the soil. The situation is somewhat different when the nitrate is present in the overlying water. In this case, the nitrate must diffuse from the water to the site of denitrification, which is the anaerobic soil zone. Data from the soil:water column studies did not show as clear a picture and appeared to be zero-order in some instances and greater than zero-order in others. It is likely that this was due to factors affecting the denitrification rate in addition to nitrate concentration, i.e., artificial aeration, presence of plants, etc. However, Phillips et al. (1978) and Reddy et al. (1978) reported that in the presence of floodwater, overall nitrate removal follows first-order kinetics because diffusion of nitrate from the floodwater into the soil limited the supply of nitrate to the active denitrifying zones. The effect was enhanced at low nitrate concentrations when a low concentration gradient was present, resulting in even less nitrate reaching the denitrifiers per unit of time. The implication is that to maximize denitrification--assuming other conditions are favorable, i.e., pH and carbon--

no floodwater should be present to set up a concentration gradient that could slow the process.

In summary, nitrate removal by denitrification as well as by plant and microbial assimilation in the continuously or seasonably flooded marsh soil can serve as an important sink for the nitrate in treated wastewater. Results from soil:water column studies indicate that without changing any management practices, such as liming or water level manipulation, the marsh in Clermont could potentially remove 0.6 g $N/m^2 \cdot day$ from 15 cm of overlying water. This would be 40 kg of nitrate nitrogen/wk on one ha, with the marsh in its natural state. Using a treated wastewater nitrate concentration of 10 mg N/l, the marsh could effectively remove the nitrate from 40 cm (16 in.) of treated wastewater per week by either denitrification or plant assimilation.

## Nitrogen Fixation

Fixation of nitrogen gas by algae and bacteria in the marsh was not measured directly in this study. Few data are available for nitrogen fixation rates in freshwater wetlands. Bristow (1973) estimated that the organic sediment-plus-root system fixed roughly 10-20% of the nitrogen requirements of a stand of *Typha* sp. in a freshwater marsh in Canada. Stevenson (personal communication) determined that about 11.4% of the nitrogen requirements of a *Hibiscus* sp. stand in Maryland were supplied by nitrogen fixation. The *Hibiscus* grew in a brackish marsh that had been cut off from tidal exchange by a culvert.

Aerobic conditions (Bristow 1973) and the presence of high levels of ammonia in surrounding waters (Ohmori and Hattori 1974; Stewart 1973) have each been found to be inhibitory to nitrogen-fixing activity. Dierberg (personal communication) found fixation rates of only 0.12 g $N/m^2 \cdot yr$ in a Florida cypress dome receiving treated wastewater, as compared to 0.39 g $N/m^2 \cdot yr$ in a natural Florida cypress dome. Low rates of fixation would be expected for the Clermont marsh under the dry conditions observed during the first year due to aeration of peat and concomitant release of ammoniacal nitrogen by oxidizing peat. The addition of inorganic nitrogen to

Plot H (9.6 cm/wk treated wastewater) probably inhibited nitrogen fixation during both years. For the purposes of this report, nitrogen fixation was assumed to have been negligible during the dry year in both Plots C (4.4 cm/wk fresh water) and H. Fixation was assumed to be negligible during the wet year as well in Plot H. For the wet year in the freshwater plot, 15% of the nitrogen observed in standing stocks (aboveground live plus belowground) on the September 15, 1978 sampling date was assumed to have been supplied by nitrogen fixation. This yielded a rate of 5.84 g $N/m^2 \cdot yr$ fixed in the freshwater plot during the second (wet) year.

## Nitrogen Water Values

Belowground nitrogen water values. Results for organic nitrogen analyses (total Kjeldahl nitrogen minus ammoniacal nitrogen) are graphed in Figs. 69-72 for the composite treated wastewater samples, the samples from wells in the peat and sand layers, and the samples taken at stations C4 and HIW (see Figs. 2 and 5.)

Nearly all of the wells exhibited high levels of organic nitrogen (approximately 2-4 mg N/l) at the outset of the study, June 1977. The record of water table heights in the marsh plots (see Fig. 14) shows the water table was approximately 0.5 m below the surface of the peat at this time. The lower water table greatly increased the availability of oxygen to the peat lying above the water table. A ready supply of both oxygen and water promotes oxidation of peat under the "dry" conditions. Thus, there may have been some release of organic and inorganic nitrogen stored in the peat during the dry period. Also, continued evapotranspiration from the marsh in the absence of heavy rains would have tended to concentrate any compounds present in the interstitial waters of the peat.

The three medium depth peat wells, W22M, W24M, and W23M, located in the northwest corner of the low (1.5 cm/wk), medium (3.7 cm/wk), and high-rate (9.6 cm/wk) treated wastewater plots, respectively, exhibited similar concentration trends during the period of June 1977 through November 1977 (see Figs. 70 and 71). The natural levels of organic nitrogen in medium depth wells (see Fig. 69 for wells W1M, W2M, and W8M) were comparable to those levels measured in

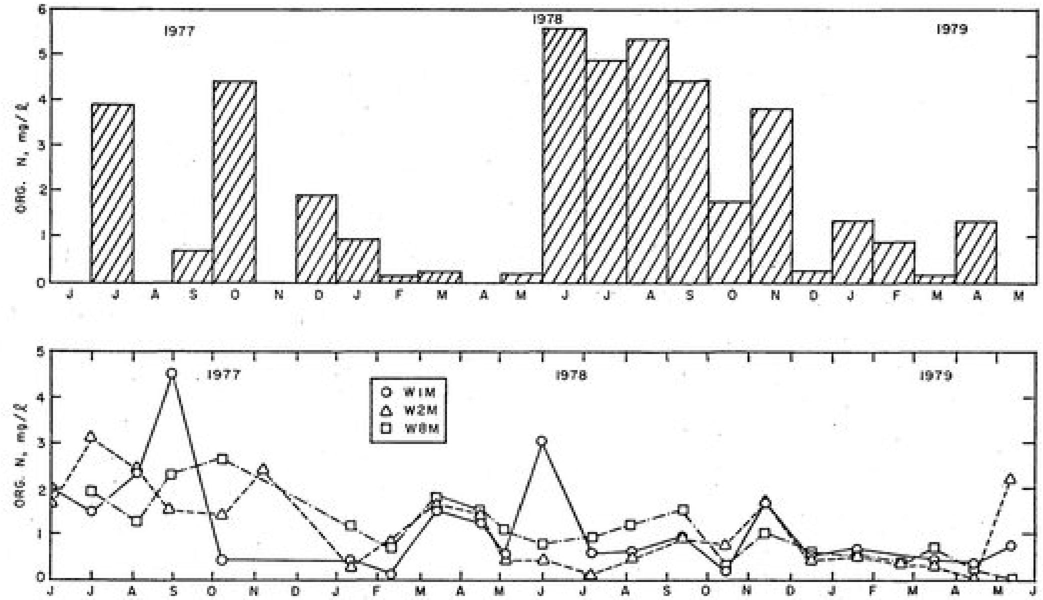



Figure 69. Organic nitrogen concentrations in the treated wastewater (average values - upper chart) and the medium-depth natural wells. See Fig. 5 for sampling locations.

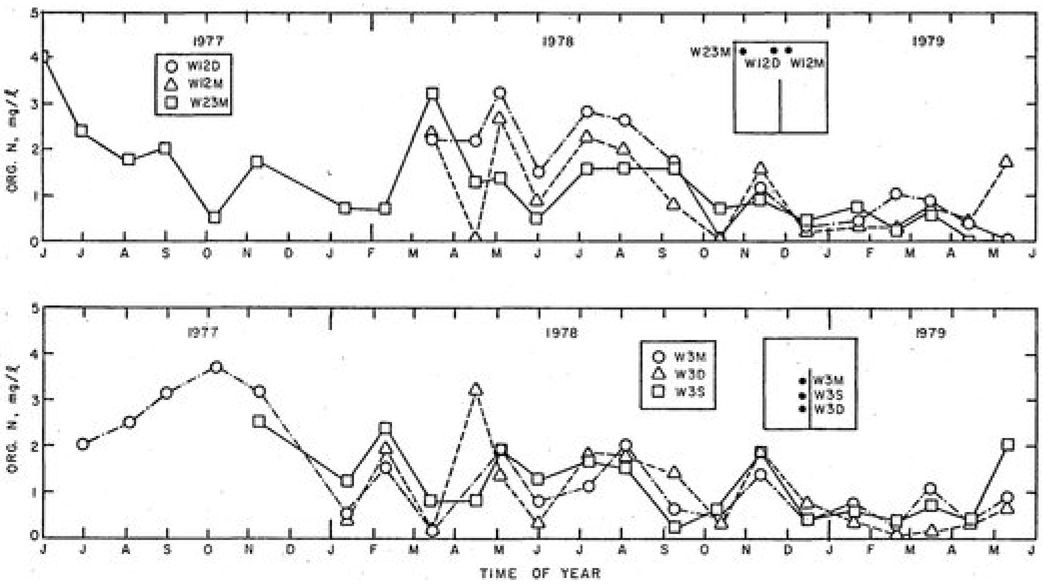



Figure 70. Organic nitrogen concentrations in the wells in Plot H (9.6 cm/wk of treated wastewater).

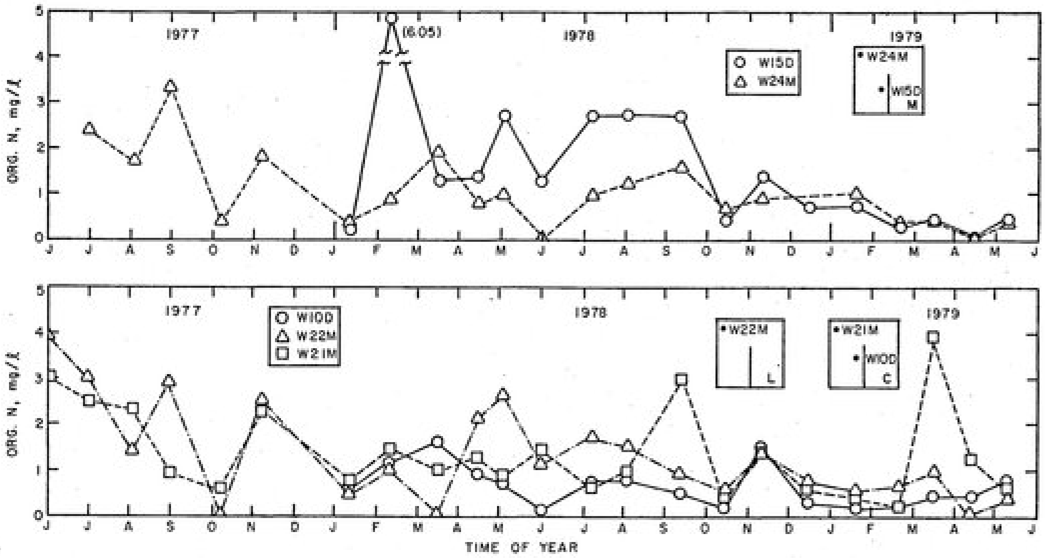



Figure 71. Organic nitrogen concentrations for the wells in Plot C (4.4 cm/wk of fresh water) and Plots L and M (1.5 and 3.7 cm/wk of treated wastewater).

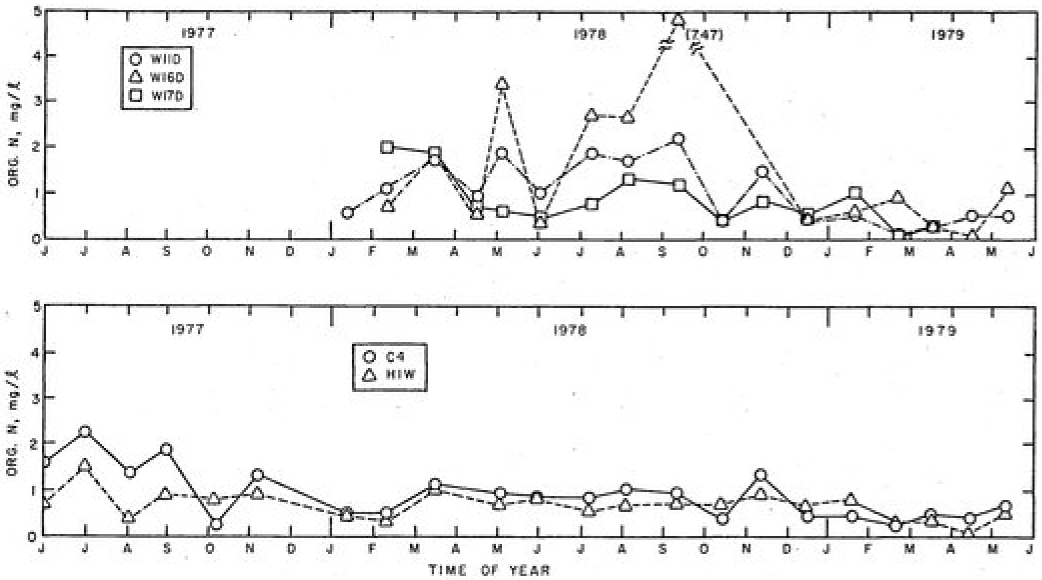



Figure 72. Organic nitrogen concentrations in deep natural wells (upper chart), the Palatlakaha River (lower chart, C4) and Lake Hiawatha (lower chart, HIW). See Figs. 2 and 5 for sampling locations.

the experimental plots. Analysis of variance showed no significant difference ($\alpha$ = 0.01) among natural well W2M and the northwest corner wells of Plots C (W21M), L (W22M), M (W24M), or H (W23M) during either the first or second years of the study. A significant ($\alpha$ = 0.05) removal of the organic nitrogen in applied treated wastewater occurred in Plot H during the second (wet) year as determined by concentration data for either well W3M, directly beneath the application pipe, or well W23M, in the northwest corner of Plot H.

Measured concentrations of ammoniacal nitrogen for the applied treated wastewater, the wells located in the experimental plots, the wells in the undisturbed areas of the marsh, and the adjacent channel and lake are plotted in Figs. 73-76. Generally, all wells, both inside and outside of the experimental plots, exhibited concentrations of ammoniacal nitrogen well below those levels measured in the applied wastewater. As shown in Fig. 73, there was considerable variation in the concentration of $NH_3$-N contained in the applied wastewater from one month to the next.

Some of the major nitrogen transformations in the marsh waters were discussed at the beginning of this chapter. In the subsurface waters of the marsh, the concentration of ammoniacal nitrogen was expected to be influenced by : 1. the amount of $NH_3$-N applied in the treated wastewater; 2. generation of $NH_3$-N by the decomposition of litter and organic exudates of the marsh plants; 3. the nitrification process, whereby bacteria convert ammonia first to nitrite and then to nitrate; 4. uptake of $NH_3$-N directly by living plants; 5. the release of $NH_3$-N directly from living plants; and 6. the process of nitrogen fixation, which converts nitrogen gas from the atmosphere into dissolved ammoniacal nitrogen.

Natural medium-depth wells W1M, W2M, and W8M all exhibit low values of $NH_3$-N compared to applied treated wastewater. No significant differences ( $\alpha$ = .01) in ammonia content were detected among natural well W2M and the northwest corner wells of the four experimental plots for either the first or second years of the study. The natural medium-depth wells, along with the northwest corner wells of the plots, exhibited higher than average values for ammoniacal nitrogen during the initial dry period in the early summer of 1977. Pre-

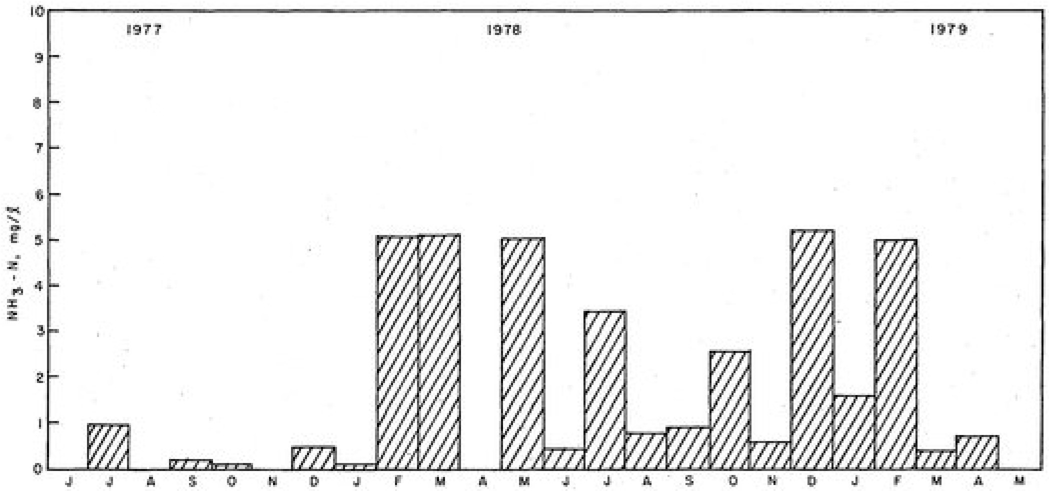



Figure 73. Composited ammonia nitrogen in the applied treated wastewater.

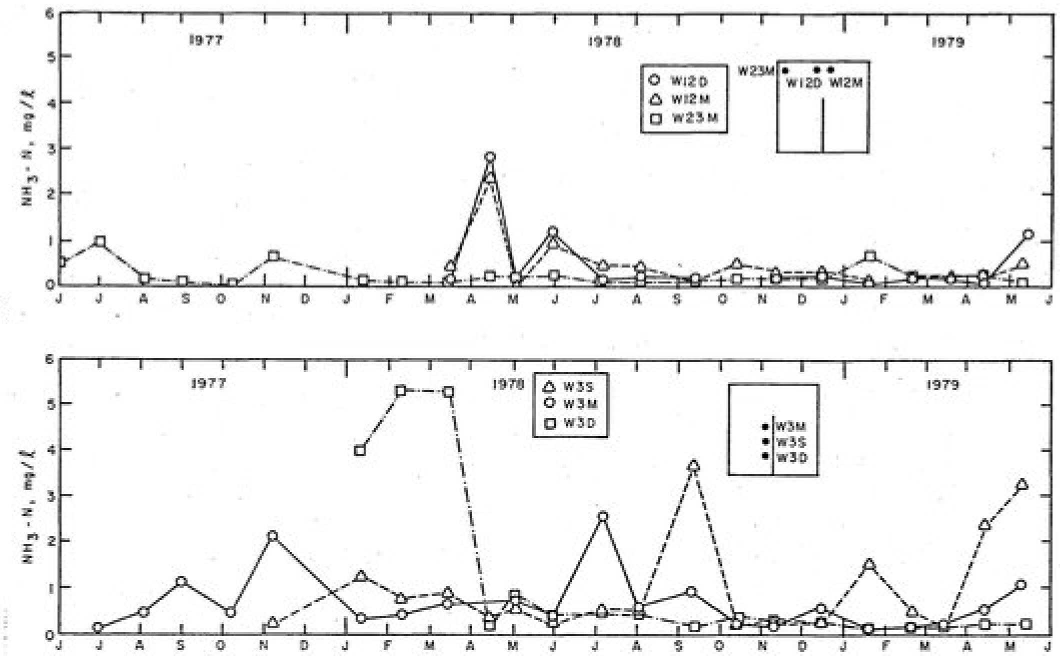



Figure 74. Ammonia nitrogen concentrations in the wells in Plot H (9.6 cm/wk of treated wastewater).

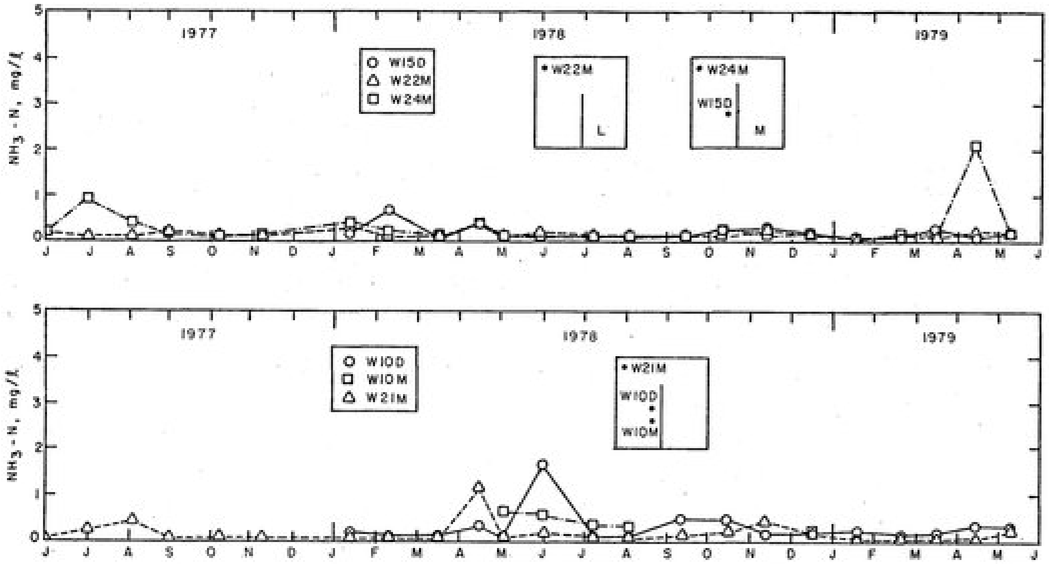



Figure 75. Ammonia nitrogen concentrations in wells in Plot L (1.5 cm/wk of treated wastewater), Plot M (3.7 cm/wk of treated wastewater) and Plot C (4.4 cm/wk of fresh water, lower chart).

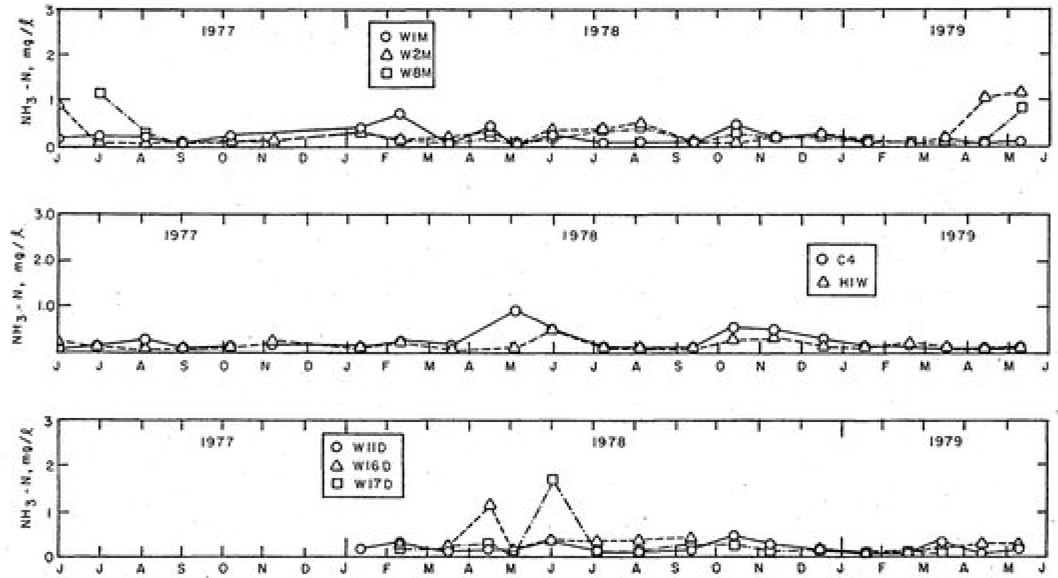



Figure 76. Ammonia nitrogen concentrations in the natural marsh wells, the Palatlakaha River (middle chart, C4), and Lake Hiawatha (middle chart, HIW). See Figs. 2 and 5 for sampling locations.

sumably, this increase was due to peat soil oxidation throughout the marsh at this time.

The highest levels of $NH_3$-N observed in subsurface waters throughout the study were found in Plot H in well W3D, located directly beneath the application pipe at the bottom of the peat layer, on the January, February, and March, 1978 sampling dates. Also in Plot H, well W3M, located directly beneath the application pipe, exhibited high (> 2 mg/l) $NH_3$-N content on November 1977 and July 1978. The shallow well at the center of Plot H, W3S, exhibited high $NH_3$-N content on September 1978 and on several dates in the spring of 1979. As discussed in the phosphorus considerations chapter of this report, the data from wells W3S and W3M were less reliable towards the end of the study, when leakage around these wells may have occurred. Thus the observed peaks may not be representative of the actual $NH_3$-N level at these depths near the application pipe in Plot H.

Analysis of the data for treated wastewater, well W3M, and well W23M revealed no significant difference ($\alpha = 0.05$) in ammonia content between the treated wastewater and these well samples during the first (dry) year. However, a significant reduction ($\alpha = 0.05$) in ammonia was observed for these two wells as compared with applied treated wastewater during the second (wet) year. Apparently, a net removal of applied ammonia was occurring in Plot H during the second year. The presence of standing water and algae during the second year accounts for the different results observed between the two years.

Measured concentrations of nitrate nitrogen and nitrite nitrogen were combined and graphed for applied treated wastewater, wells in the peat substrate, wells in the sand layer, one channel station, and Lake Hiawatha in Figs. 77-80. Note the different scale used for the treated wastewater bar graph as compared to all the other graphs.

Nitrate plus nitrite levels were low in all water samples from the bottom of the peat layer on most sampling dates. The average concentration of nitrate plus nitrite nitrogen was 0.1 mg/l in Plot

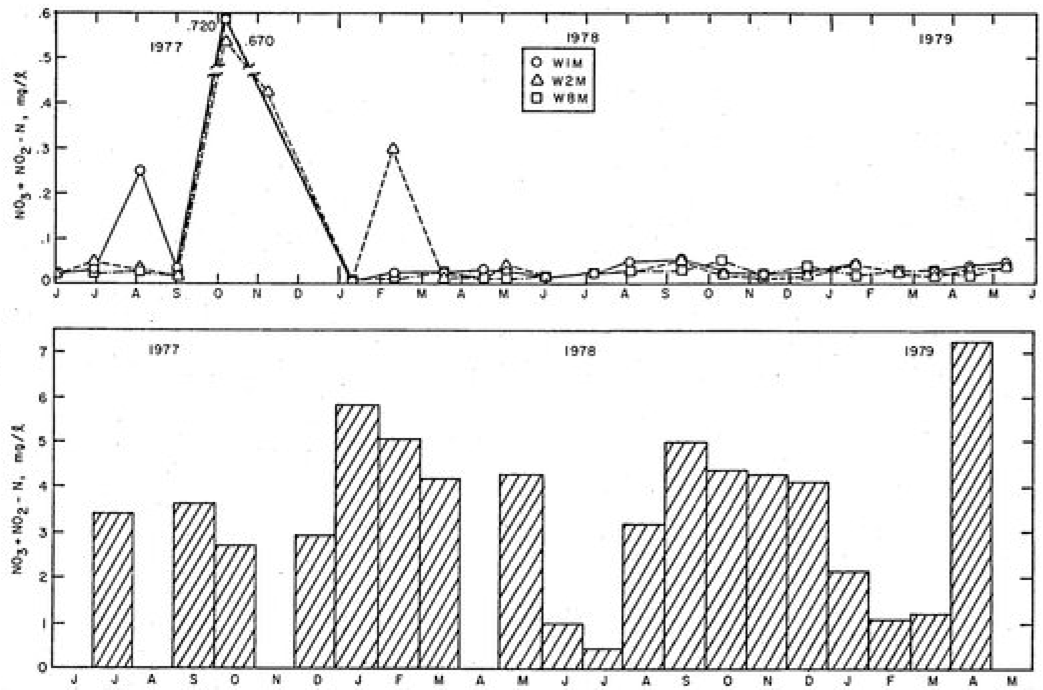





Figure 77. Nitrate + nitrite concentrations in natural marsh wells (upper chart) and treated wastewater (lower chart). See Fig. 5 for sampling locations.

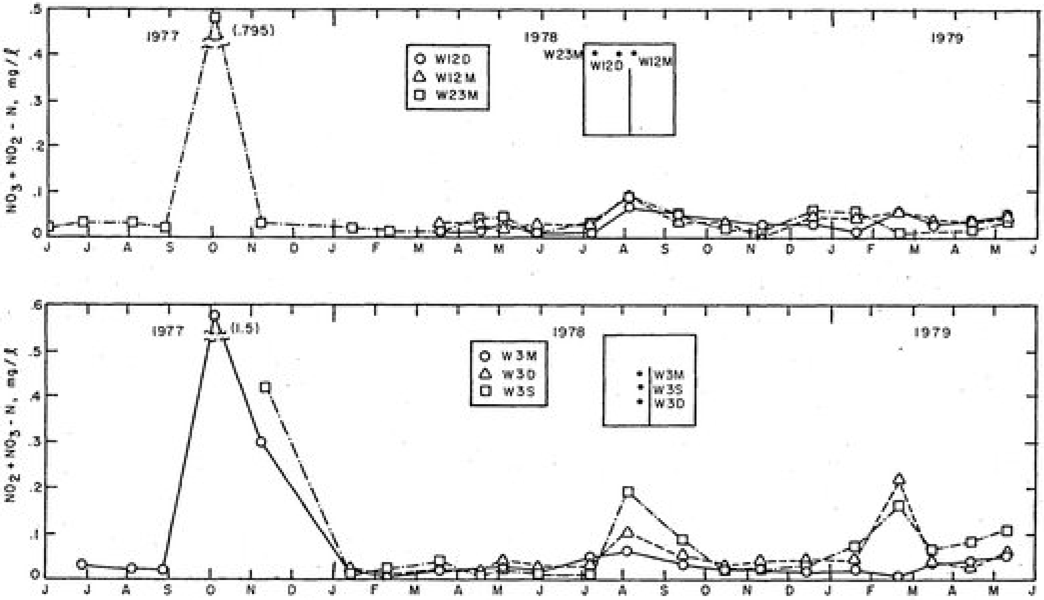



Figure 78. Nitrate + nitrite concentrations for wells in Plot H (9.6 cm/wk of treated wastewater).

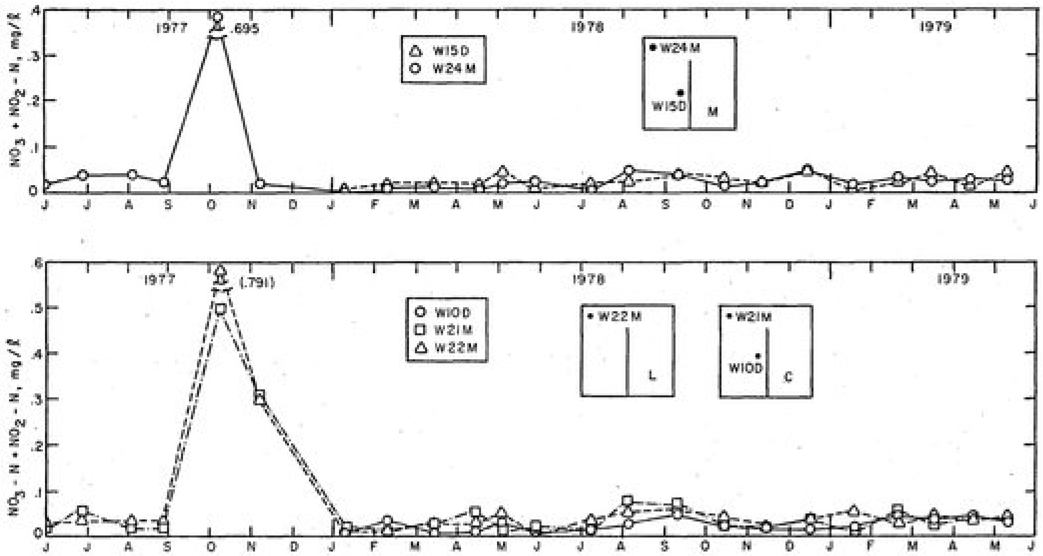



Figure 79. Nitrate + nitrite concentrations for wells in Plot C (4.4 cm/wk of fresh water), Plot L (1.5 cm/wk of treated wastewater), and Plot M (3.7 cm/wk of treated wastewater).

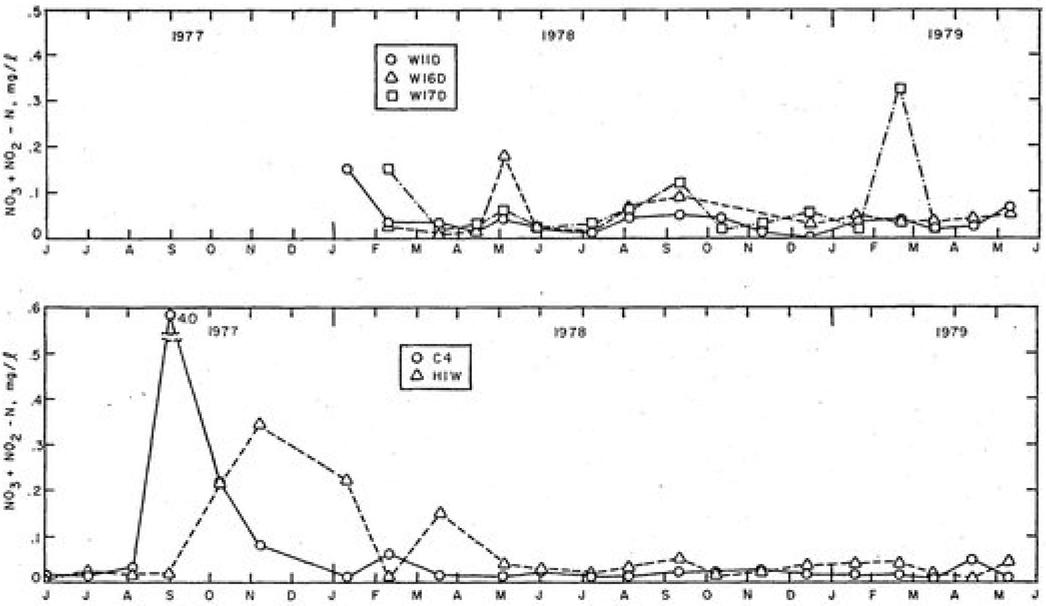



Figure 80. Nitrate + nitrite concentrations in deep natural marsh wells (upper chart), the Palatlakaha River (lower chart, C4), and Lake Hiawatha (lower chart, HIW). See Figs. 2 and 5 for sampling locations.

H in well W23M (northwest corner well) for the first year, while the average value was 3.92 mg/l for applied treated wastewater during this period. This striking reduction in nitrate plus nitrite content was due mainly to the denitrification process as discussed earlier in the description of denitrification studies. In denitrification, nitrate is utilized by microbes, which subsequently release the nitrogen in gaseous form, thereby removing nitrogen from the marsh system. During the second year, waters from well W23M had an even lower average nitrate plus nitrite nitrogen concentration, 0.03 mg/l. The treated wastewater had an average concentration of 2.88 mg/l during the second year.

Several other processes in addition to denitrification were probably important in regulating the amounts of nitrate and nitrite in subsurface waters during both years. Nitrifying microbes may convert $NH_3$-N to $NO_3$-N in the presence of oxygen. Oxidizing peat presumably released both organic nitrogen and ammonia when the water table was below the surface of the peat. Since oxygen was readily available to the peat above the water table, released $NH_3$-N could have been nitrified at this time. This would account for the higher levels of nitrate plus nitrite nitrogen observed in the peat throughout the marsh during the late fall of 1977. Nitrate nitrogen is readily consumed by living plants; this, too, accounts for the high nitrate plus nitrite removal rates found in the marsh.

Natural wells W1M, W2M, and W8M exhibited no concentration of nitrate plus nitrite nitrogen greater than 0.1 mg/l after February 1978 (see Fig. 77). The medium depth northwest corner wells of the experimental plots (W21M, W22M, W24M, and W23M for Plots C, L, M, and H, respectively) and the medium-depth well directly beneath the application pipe in Plot H (W3M) all exhibited no concentration of nitrate plus nitrite nitrogen greater than 0.1 mg/l after November 1977. Wells W12M and W12D, both located directly north of the application pipe in Plot H and first sampled in March 1978, at no time exhibited $NO_3$-N plus $NO_2$-N content greater than 0.1 mg/l. Well W3S, first sampled in November 1977, never exhibited a concentration of these two species greater than 0.2 mg/l after the November 1977 sample.

Overall, then, the most important variable affecting the removal of nitrate plus nitrite nitrogen in the waters of the peat was not the amount present in applied treated wastewater, but rather the height of the water table. All medium-depth wells, both inside and outside of the experimental plots, had higher nitrate content during the first, (dry) year and reduced nitrate plus nitrite levels during the second, (wet) year. When the water table was low (0.5 m below the surface of the peat), there was still a large reduction in the concentration of nitrate plus nitrite nitrogen observed for waters leaving the peat, relative to the concentration observed in applied treated wastewater.

Trends for total dissolved nitrogen content of belowground marsh water were governed primarily by organic nitrogen, which made up the bulk of the total on nearly all dates for all wells. The concentrations of total nitrogen in treated wastewater, wells in the peat substrate, wells in the sand layer, and the channel and lake stations are shown graphed in Figs. 81-85. The bar graph for total nitrogen in treated wastewater applied each month gives the speciation of that total for each month. High average levels of total dissolved nitrogen were found throughout the peat layer of the marsh. Natural medium-depth well W2M exhibited an average of 1.88 mg/l total nitrogen during the first (dry) year and 0.91 mg/l during the second (wet) year. Well W3M, directly beneath the treated wastewater application pipe in Plot H, had averages of 2.92 mg/l total nitrogen during the first year and 1.37 mg/l during the second year. In general there was much variation in total nitrogen content of any well from one month to the next. This resulted from the many sources and sinks for each species of nitrogen, as described in the first section of this chapter.

The proportions of the different nitrogen species that contributed to the total value for treated wastewater also varied considerably between months. However, the average composition of treated wastewater was similar for both years (Table 56). During the first

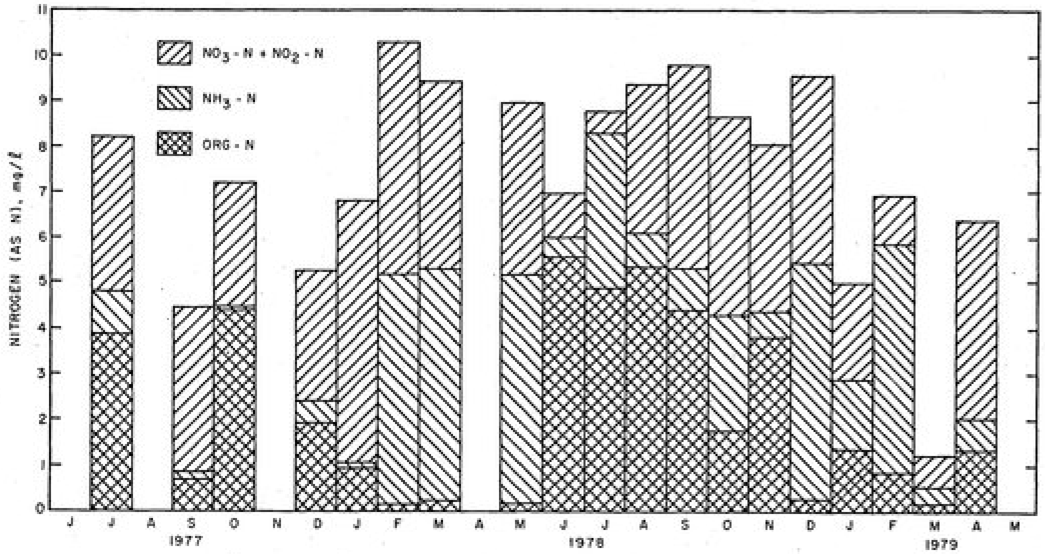



Figure 81. Breakdown of the nitrogen forms in the applied secondarily treated wastewater.

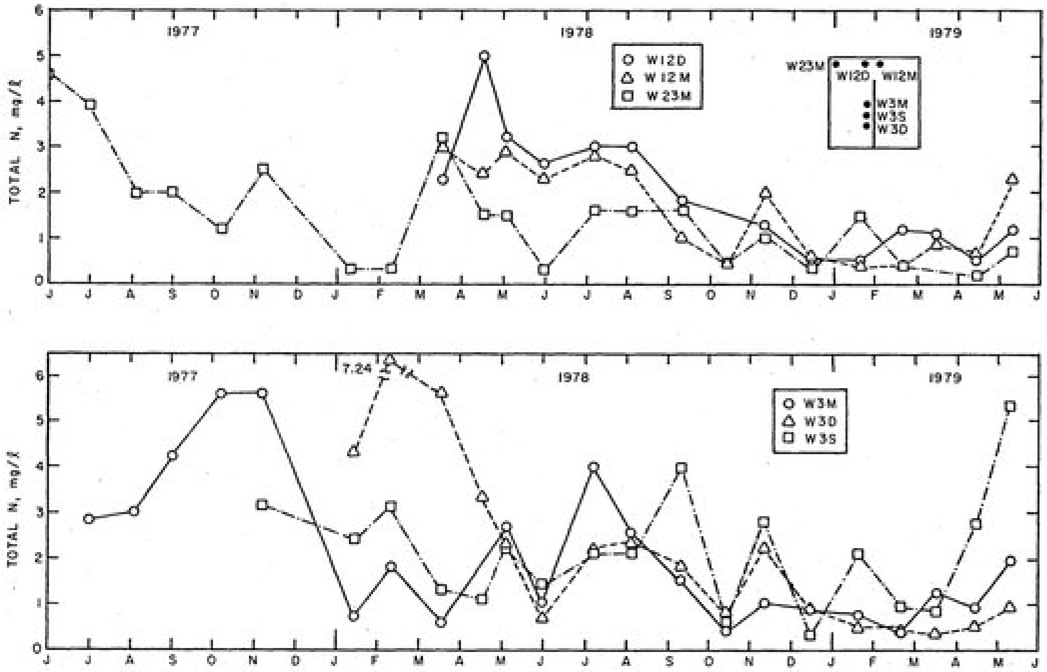



Figure 82. Total nitrogen concentrations for wells in Plot H (9.6 cm/wk of treated wastewater).

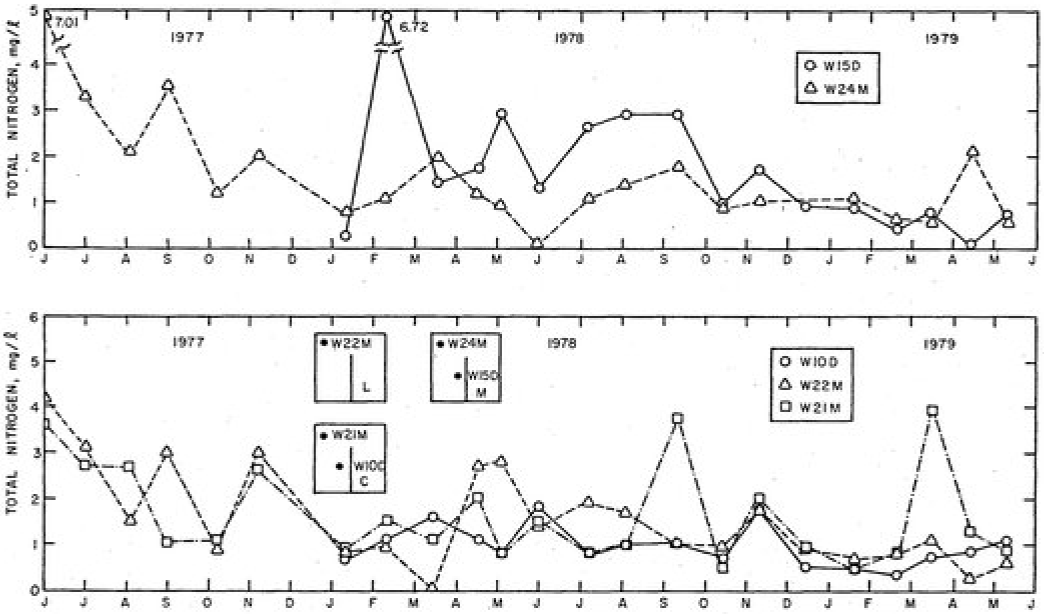



Figure 83. Total nitrogen concentrations for wells in Plot C (4.4 cm/wk of fresh water), Plot L (1.5 cm/wk of treated wastewater), and Plot M (3.7 cm/wk of treated wastewater).

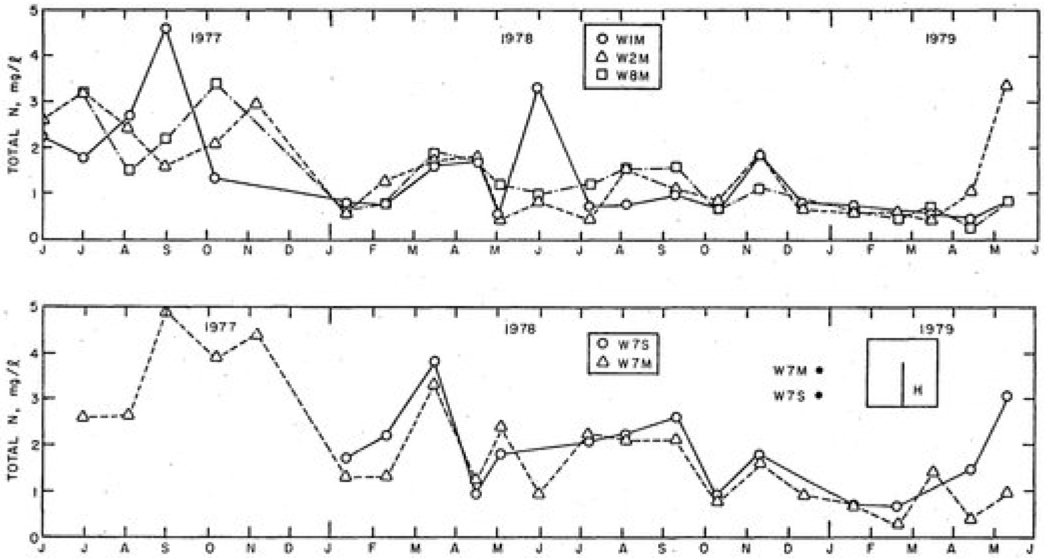



Figure 84. Total nitrogen concentrations in natural marsh wells (upper chart) and wells to the west of Plot H (9.6 cm/wk of treated wastewater). See Fig. 5 for the natural marsh sampling locations.

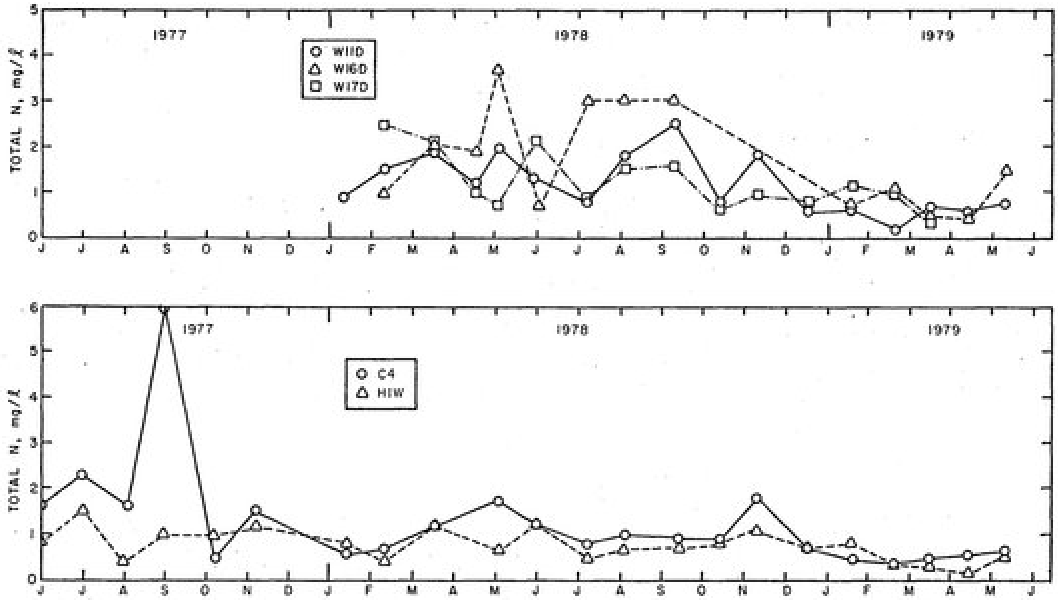



Figure 85. Total nitrogen concentrations in deep natural marsh wells (upper chart), the Palatlakaha River (lower chart, C4), and Lake Hiawatha (lower chart, HIW). See Figs. 2 and 5 for sampling locations.

Table 56. Average yearly concentrations of nitrogen in treated wastewater.

| May 1, 1977 - April 30, 1978 | Conc.(mg/l) | % of Total |
|---|---|---|
| $NO_3$-N + $NO_2$-N | 3.92 | 52.0 |
| $NH_3$-N | 1.67 | 22.2 |
| Org-N | 1.95 | 25.9 |
| Tot-N | 7.54 | 100.0 |
| May 1, 1978 - April 30, 1979 | | |
| $NO_3$-N + $NO_2$-N | 2.88 | 38.6 |
| $NH_3$-N | 2.22 | 29.8 |
| Org-N | 2.36 | 31.6 |
| Tot-N | 7.46 | 100.0 |

year, the average applied treated wastewater consisted of 52% nitrate plus nitrite, 22% ammonia, and 26% organic nitrogen. During the second year, those percentages were: 39% nitrate plus nitrite, 30% ammonia and 32% organic nitrogen. The average total nitrogen values were similar for the first and second years: 7.54 and 7.46 mg/l, respectively.

Overall, lower average total dissolved nitrogen values in marsh waters resulted during the second (wet) year than during the first (dry) year. This difference was due primarily to the lower water table and resultant oxidation of peat during the dry year. Since total nitrogen averages were similar for applied treated wastewater during the two years, a larger net reduction of nitrogen in applied treated wastewater was found during the second year.

A summary of results for treated wastewater, northwest corner medium-depth wells, natural well W2M, and the medium depth well beneath the application pipe in Plot H (W3M), are given Tables 57 and 58. Table 57 shows the average nitrogen content of northwest corner wells for each plot and the natural well W2M. Analysis of variance detected no significant differences ($\alpha = 0.05$) among any of these wells during either year for any of the nitrogen species measured. Thus, during both years for Plots L (1.5 cm/wk), M (3.7 cm/wk), and H (9.6 cm/wk), each form of nitrogen in applied treated wastewater was reduced to the background level by the time the applied water reached the northwest corner of the plot.

Table 58 exhibits the changes in concentrations of nitrogen species for applied treated wastewater in Plot H. Results are given for treated wastewater, the medium-depth well beneath the application pipe (W3M), and the northwest corner well (W23M). During the first year, there was a significantly lower ($\alpha = 0.05$) concentration of nitrate plus nitrite and of total nitrogen in the center well and the northwest corner well of Plot H as compared to the applied treated wastewater. During the second year, all nitrogen species in applied treated wastewater exhibited a significant net reduction in concentration by the time they reached either the center well or the northwest corner well. No significant differences were

Table 57. Average concentrations of nitrogen species for the natural marsh and the northwest corner medium-depth wells of Plots C, L, M, and H. All values in mg/l.

| | Natural Area (W2M) | Plot C (W21M) | Plot L (W22M) | Plot M (W24M) | Plot H (W23M) |
|---|---|---|---|---|---|
| May 1, 1977 - April 30, 1978 | | | | | |
| $NO_3$-N + $NO_2$-N | 0.136 | 0.088 | 0.116 | 0.085 | 0.104 |
| $NH_3$-N | 0.19 | 0.24 | 0.15 | 0.25 | 0.26 |
| Org-N | 1.56 | 1.52 | 1.83 | 1.96 | 1.80 |
| Tot-N | 1.88 | 1.85 | 2.09 | 2.29 | 2.16 |
| May 1, 1978 - April 30, 1979[a] | | | | | |
| $NO_3$-N + $NO_2$-N | 0.023 | 0.036 | 0.032 | 0.028 | 0.031 |
| $NH_3$-N | 0.27 | 0.15 | 0.15 | 0.08 | 0.20 |
| Org-N | 0.60 | 1.29 | 1.31 | 0.97 | 0.83 |
| Tot-N | 0.91 | 1.46 | 1.49 | 1.08 | 1.06 |

[a]Second year averages for Plots L and M are for the period 5/1/78 - 9/30/78 only.

Table 58. Average yearly concentrations of nitrogen species for treated wastewater and Plot H medium depth well W3M (directly beneath the application pipe) and W23M (in the northwest corner). All values in mg/l.

| | Treated Wastewater | Plot H Center (W3M) | Plot H Northwest Corner (W23M) |
|---|---|---|---|
| May 1, 1977 - April 30, 1978 | | | |
| $NO_3$-N + $NO_2$-N | 3.92 | 0.22 | 0.10 |
| * | a | b | b |
| $NH_3$-N | 1.67 | 0.66 | 0.26 |
| * | a | a | a |
| Org-N | 1.95 | 2.05 | 1.80 |
| * | a | a | a |
| Tot-N | 7.54 | 2.92 | 2.16 |
| * | a | b | b |
| May 1, 1977 - April 30, 1977 | | | |
| $NH_3$-N + $NO_2$-N | 2.88 | 0.03 | 0.03 |
| * | a | b | b |
| $NH_3$-N | 2.22 | 0.51 | 0.20 |
| * | a | b | b |
| Org-N | 2.36 | 0.82 | 0.83 |
| * | a | b | b |
| Tot-N | 7.46 | 1.37 | 1.06 |
| * | a | b | b |

*Appearance of the same letter in any two columns of this row indicates there was no significant difference detected ($\alpha = 0.05$) for this parameter between the sampling stations represented by those two columns.

detected ($\alpha = 0.05$) for the concentrations of any species of nitrogen between the center and northwest corner well of Plot H during either year.

Aboveground nitrogen water values. Organic nitrogen was the largest component of the total dissolved nitrogen found in aboveground waters. This same result was found for belowground water samples. The measured organic nitrogen values for surface stations directly beneath the application pipe in Plots C and H (C-I and H-I, respectively), near the perimeter but still within the boundaries of Plots C and H (C-O and H-O, respectively), and in the natural marsh, north of the experimental plots (N, the average of values for N1 and N2), are plotted in Figure 86. On all sampling dates except April 1979, organic nitrogen was found to be no more concentrated in Plot H than in the natural marsh as represented by the samples at station N. The highest value observed in Plot H was near the perimeter; a value of 2.4 mg/l was measured at station H-O during April 1979. The control plot (Plot C) exhibited unusually high organic nitrogen values in March and April of 1979, especially near the perimeter of that plot. The reasons for such high values are not known.

Figure 87 illustrates the measured concentrations of ammonium nitrogen in surface water. On certain dates the observed concentration near the application pipe or the perimeter of Plot H (stations H-I and H-O, respectively) were greater than the observed background value at station N. The greatest increase was observed in April of 1979. The inside region of Plot H exhibited a value of 1.0 mg/l ammonium on this date. However, on most dates, ammonium levels were found to be no higher in Plot H than in the natural marsh.

Measured concentrations of nitrate plus nitrite in surface water are shown in Fig. 88. There are no striking difference between the values measured at particular stations, except for those samples taken during March 1979. At this time, the values measured for Plot C and the natural marsh were considerably higher than the values measured for the inside or outside portions of Plot H. This was probably due both to rapid uptake of $NO_3^-$-N and $NO_2^-$-N by

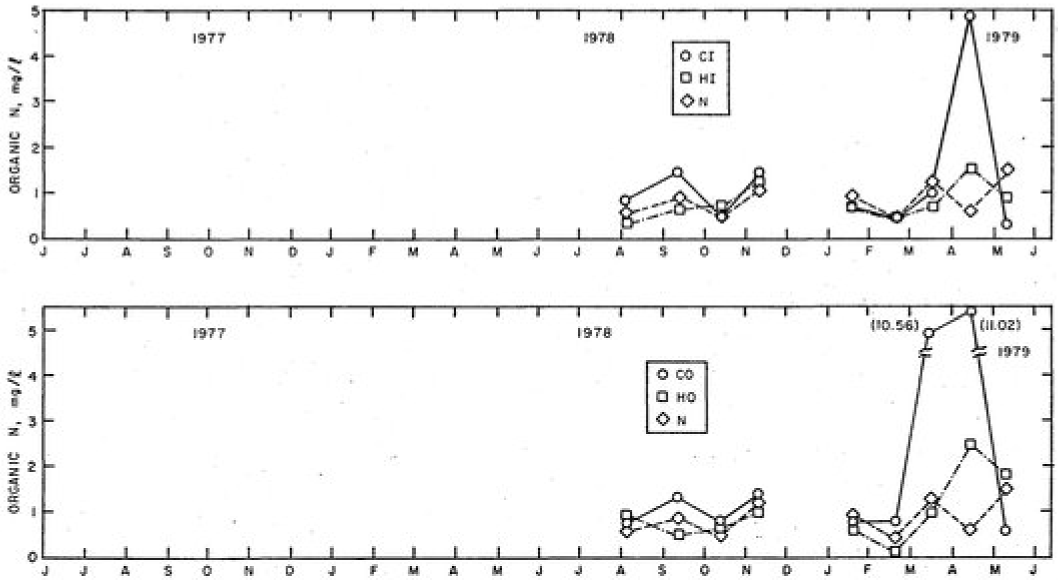



Figure 86. Organic nitrogen concentrations in surface water in Plots C, H, and the natural marsh. The inside values (near the distribution pipe) are denoted by "I", with "O" representing values outside the influence of the distribution pipe but still within the plot. No data means no surface water was present.

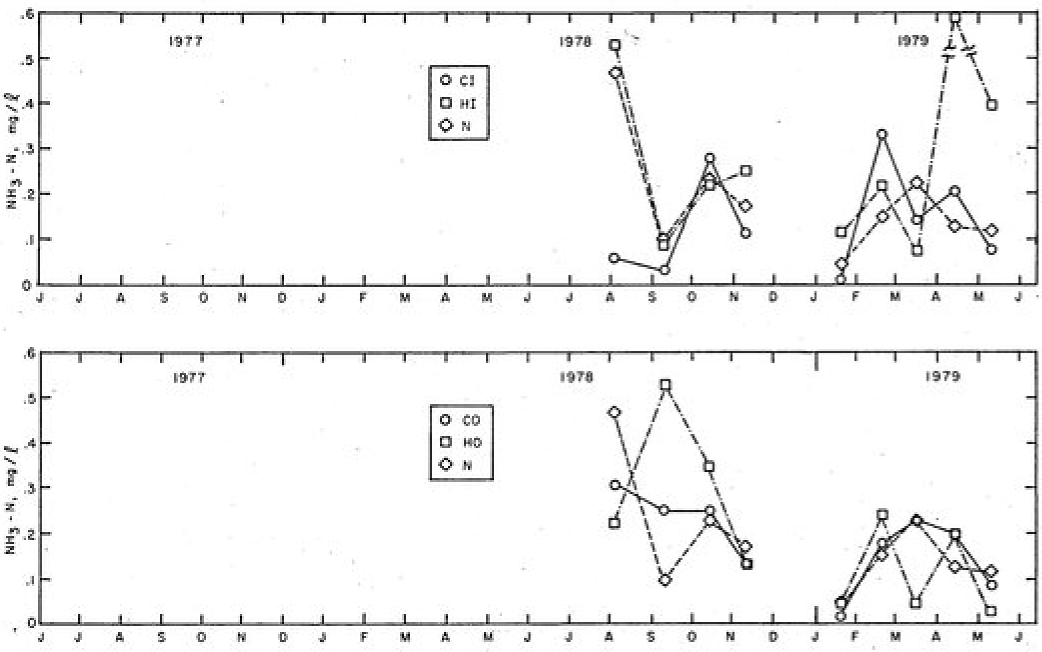



Figure 87. Ammonia concentrations in surface water in Plots C, H, and the natural marsh. The inside values (near the distribution pipe) are denoted by "I", with "O" representing values outside *the influence* of the distribution pipe but still within the plot. No data means no surface water was present.

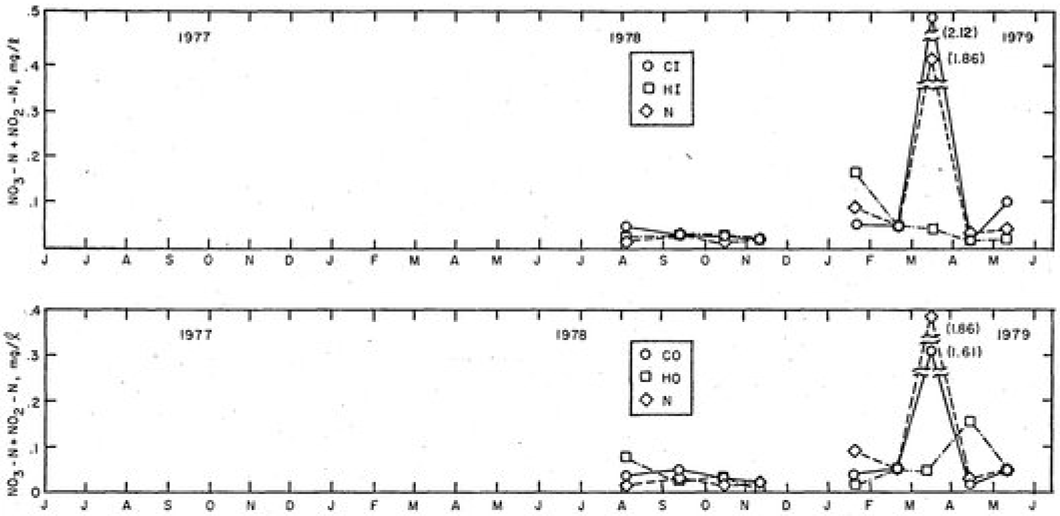



Figure 88. Nitrate + nitrite concentrations in surface water in Plots C, H, and the natural marsh. The inside values (near the distribution pipe) are denoted by "I", with "O" representing values outside the influence of the distribution pipe but still within the plot. No data means no surface water was present.

algae and rooted plants in Plot H and to the rapid denitrification presumed to occur in this plot. The high values observed in Plot C and the natural marsh may have been due to increased decomposition of litter, followed by nitrification as temperatures rose in March 1979.

Total nitrogen values for the surface water samples are graphed in Fig. 89. The values observed for Plot H during the wet year were not significantly different from the values observed for the natural marsh. The values for Plot C, the freshwater control plot, were significantly higher than the values for the natural marsh in March and April of 1979. This is the same trend as observed for organic nitrogen. As with belowground water samples, organic nitrogen was the main component of total dissolved nitrogen in surface waters throughout the marsh.

A summary of average nitrogen concentrations found in surface samples during periods of standing water in the marsh is shown in Table 59. Analysis of variance revealed no significant difference ($\alpha = .05$) in nitrate plus nitrite content among the surface stations in Plots C, H, or the natural marsh. Ammoniacal nitrogen was found to be significantly higher ($\alpha = 0.05$) beneath the discharge pipe in Plot H than in the natural marsh. However, the difference was not large: 0.32 mg $NH_3$-N/l compared to 0.18 mg $NH_3$-N/l in the natural marsh. The perimeter of the freshwater plot (Plot C) exhibited a significantly higher ($\alpha = 0.05$) average concentration of organic nitrogen and of total nitrogen than Plot H or the natural marsh. No significant difference in ammoniacal or total nitrogen was detected between the surface water of Plot H and the natural marsh ($\alpha = 0.05$). Apparently, all forms of nitrogen in applied treated wastewater were reduced to background levels by the time the applied water reached the perimeter of the plot. Table 60 shows how all nitrogen species in both inside and outside region surface samples from Plot H were significantly ($\alpha = 0.05$) reduced from the levels of nitrogen in applied treated wastewater. Nitrate plus nitrite, organic nitrogen, and total nitrogen in treated wastewater were reduced to essentially background levels at the site of their application. Such removal

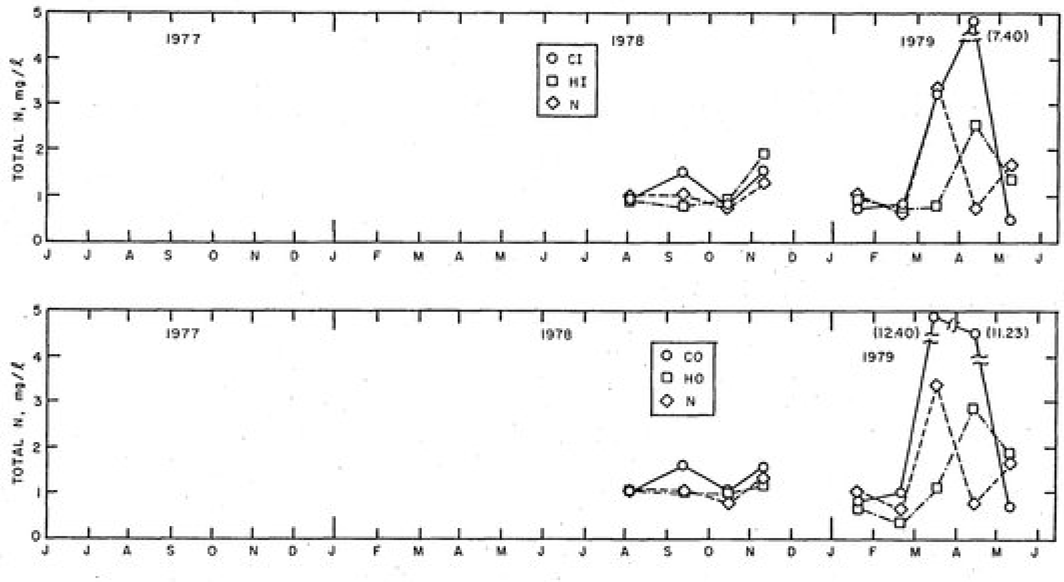



Figure 89. Total nitrogen concentrations in surface water in Plots C, H, and the natural marsh The inside values (near the distribution pipe) are denoted by "I", with "O" representing values outside the influence of the distribution pipe but still within the plot. No data means no surface water was present.

Table 59. Average concentrations of nitrogen species in surface waters of the natural marsh and the inside and outside regions of the 4.4 cm/wk freshwater (Plot C) and 9.6 cm/wk treated wastewater (Plot H) plots.

| | Plot H Inside (H-I) | Plot H Outside (H-O) | Plot C Inside (C-I) | Plot C Outside (C-O) | Natural Marsh (N) |
|---|---|---|---|---|---|
| <u>August 1, 1978 - April 30, 1979</u> | | | | | |
| $NO_3$-N + $NO_2$-N | 0.04 | 0.05 | 0.27 | 0.21 | 0.24 |
| * | a | a | a | a | a |
| $NH_3$-N | 0.32 | 0.19 | 0.12 | 0.20 | 0.18 |
| * | a | a,b | a,b | a,b | b |
| Org-N | 0.73 | 1.01 | 1.56 | 3.04 | 0.85 |
| * | b | b | a,b | a | b |
| Tot-N | 1.10 | 1.25 | 1.95 | 3.45 | 1.26 |
| * | b | b | a,b | a | b |

*Appearance of the same letter in any two columns of this row indicates there was no significant difference detected ($\alpha$ = .05) for this parameter between the sampling stations represented by those two columns.

Table 60. Average concentrations of nitrogen species in treated wastewater and Plot H surface stations H-I (directly beneath the application pipe) and H-O (near the western perimeter of the plot). All values in mg/l.

| | Treated Wastewater | Surface Plot H Center (H-I) | Surface Plot H Perimeter (H-O) |
|---|---|---|---|
| May 1, 1978 - April 30, 1979 | | | |
| $NO_3$-N + $NO_2$-N | 2.88 | 0.05 | 0.05 |
| * | a | b | b |
| $NH_3$-N | 2.22 | 0.31 | 0.22 |
| * | a | b | b |
| Org-N | 2.36 | 0.71 | 0.91 |
| * | a | b | b |
| Tot-N | 7.46 | 1.07 | 1.18 |
| * | a | b | b |

*Appearance of the same letter in any two columns of this row indicates there was no significant difference detected ($\alpha$ = .05) for this parameter between the sampling stations represented by those two columns.

occurred rapidly; as desribed in the Methods chapter, all surface samples were collected within 24 hours of treated wastewater and fresh water application.

Probable reasons for the rapid nitrogen removal observed include nitrification/denitrification at the peat/surface-water interface and uptake by algae growing near the application pipe. Algal biomass contains nitrogen and phosphorus in approximately a 10:1 molar ratio, while the treated wastewater had a nitrogen to phosphorus ratio of approximately 2:1. Hence nitrogen was in short supply for algal growth relative to phosphorus at the site of application. If algal growth was limited primarily by available nitrogen, any nitrogen applied in a useable form would have disappeared rapidly from surface waters as it was incorporated into algal biomass. Senescent algae, which sank to the peat substrate, would then have constituted a net sink for nitrogen. At the peat/surface-water interface, nitrification followed by denitrification could have removed ammonium released by decomposition of the dead algae.

## Nitrogen Vegetation Values

Nitrogen aboveground vegetation values. Although storages of phosphorus in biomass were not large compared to phosphorus applied in treated wastewater, such storage constituted a major net sink for nitrogen in plots receiving treated wastewater. Nitrogen is taken up through the roots of growing rooted plants and is incorporated into the cell biomass of growing algae and floating plants such as *Lemna* spp. (duckweed). The potential importance of algal nitrogen uptake was discussed in the water quality section of this chapter. This section will deal with nitrogen storage in above and belowground live and dead biomass of rooted plants in the marsh during the dry and wet years.

Measured storage of aboveground live biomass nitrogen is summarized in Table 61 for Plots C (4.4 cm/wk fresh water), M (3.7 cm/wk treated wastewater) and H (9.6 cm/wk treated wastewater). The net

Table 61. Aboveground live biomass nitrogen storage for the entire region of each plot (area-weighted average of inside and outside regions of each plot).

| Date | Time Interval (days) | Plot C Storage ($g\ N/m^2$) | Plot C Rate of[a] Change | Plot M Storage ($g\ N/m^2$) | Plot M Rate of[a] Change | Plot H Storage ($g\ N/m^2$) | Plot H Rate of[a] Change |
|---|---|---|---|---|---|---|---|
| 4/25/77 | | 3.78 | | 3.80 | | 3.88 | |
| | 46 | | +26.52 | | +17.17 | | +52.39 |
| 6/10/77 | | 5.00 | | 4.59 | | 6.29 | |
| | 28 | | - 3.93 | | +26.07 | | +172.14 |
| 7/8/77 | | 4.89 | | 5.32 | | 11.11 | |
| | 34 | | +139.71 | | +77.94 | | +46.76 |
| 8/11/77 | | 9.64 | | 7.97 | | 12.70 | |
| | 35 | | -17.14 | | +77.71 | | + 8.86 |
| 9/15/77 | | 9.04 | | 10.69 | | 13.01 | |
| | 79 | | -89.37 | | | | |
| 12/3/77 | | 1.98 | | --- | | --- | -74.11 |
| | 79 | | -18.48 | | -33.92 | | |
| 2/20/78 | | 0.52 | | --- | | 1.30 | |
| | 54 | | +53.33 | | | | +86.67 |
| 4/15/78 | | 3.40 | | 3.50 | | 5.98 | |
| | 71 | | +70.56 | | +154.65 | | +89.44 |
| 6/25/78 | | 8.41 | | 14.48 | | 12.33 | |
| | 85 | | +21.65 | | -47.18 | | -24.82 |
| 9/18/78 | | 10.25 | | 10.47 | | 10.22 | |
| | 88 | | | | | | |
| 12/15/78 | | --- | -39.74 | --- | | --- | -14.87 |
| | 64 | | | | | | |
| 2/17/79 | | 4.21 | | --- | | 7.96 | |

[a]Rate of change is given in $mg\ N/m^2 \cdot day$

rate of uptake (+) or release (-) of nitrogen from this storage between each sampling date is given. All values are area-weighted (25-75) averages of the "inside" and "outside" sampling regions in each respective plot. Peak storage was observed on the same date in Plots M and H during the first, dry year; 10.69 g $N/m^2$ and 13.01 g $N/m^2$, respectively, on September 15, 1977. Peak storage was attained slightly earlier in the freshwater plot (Plot C) during that year: 9.64 g $N/m^2$ on August 11, 1977. The highest rate of nitrogen assimilation by aboveground live biomass was exhibited by Plot H during the first year, between June and July 1977. During this period, 1.72 g $N/m^2 \cdot day$ were removed in Plot H. Fastest net assimilation occurred for the freshwater plot (Plot C) and the medium-rate treated wastewater plot (Plot M) at a later period during that year; 1.40 g $N/m^2 \cdot day$ and 0.77 g $N/m^2 \cdot day$, respectively, between July 1977 and August 1977. The differences between plots in timing of peak assimilation, and in timing of peak storage, corresponded to the different patterns of net production in the plots during the first year.

Second (wet) year nitrogen assimilation and storage in aboveground live biomass appeared to follow similar patterns in the medium and high rate treated wastewater plots. Both exhibited a maximum net storage on the June 1978 sampling date, and both exhibited fastest assimilation between April and June 1978 during the wet year. Peak storage and peak assimilation rates were higher in Plot M than in Plot H during the second year. Values for peak storage during the wet year were 14.48 g $N/m^2$ for Plot M and 12.33 g $N/m^2$ for Plot H; values for peak assimilation were 1.55 g $N/m^2 \cdot day$ for Plot M and 0.89 g $N/m^2 \cdot day$ for Plot H. Plot C exhibited its highest net assimilation between April and June 1978 during the second year, but attained peak nitrogen storage in aboveground live biomass in September 1978, which was later than for the plots receiving treated wastewater.

Analysis of variance showed nitrogen stored in aboveground live biomass in Plot H was significantly greater ($\alpha = 0.05$) than nitrogen storage for aboveground live biomass in either Plot M or Plot C during the first year. There was a detectable difference ($\alpha = 0.01$) between inside and outside location among the plots during the first year; values near the pipe (inside regions) were significantly greater ($\alpha = 0.05$) than values near the plot perimeters (outside regions). During the second year, no significant difference was detected among the plots for live aboveground biomass nitrogen storage. However, the values near the discharge pipes were still significantly higher ($\alpha = 0.05$) than the values near the perimeters of the plots.

Table 62 shows the storages and rate of change in storage for dead aboveground biomass (litter). As with Table 61, the area-weighted average of computed values for the inside and outside portions of each of Plots C, M, and H are given. In each of the plots, the observed maximum storage of nitrogen in the litter component over the two-year study period occurred on April 15, 1978; the value on this date was greater in Plot M than in Plots C or H. Analysis of variance for aboveground dead biomass nitrogen storage yielded significant ($\alpha = 0.05$) differences between any two plots compared for the first year. Plot H had significantly higher storage than Plot M, which in turn had significantly higher storage than Plot C. During the second year, Plot M had a significantly higher ($\alpha = 0.05$) storage than either Plot H or Plot C. While there was a significantly greater storage ($\alpha = .05$) of aboveground dead biomass nitrogen near the discharge pipes in the plots during the first year, no such difference was detected during the second year. All plots exhibited a net increase in storages of nitrogen in aboveground dead biomass during the first year (April 25, 1977 - April 15, 1978): +16.71 g N/$m^2$, +10.09 g N/$m^2$, and +7.94 g N/$m^2$ for Plots M, H, and C, respectively. Thus, Plot M, rather than Plot H, exhibited the largest net increase in storage in this component during the first year. During the second year (April 15, 1978 - February 20, 1979), a net decrease in storage of aboveground dead biomass nitrogen was exhibited for Plots H and C: -5.68 g N/$m^2$ and -7.35 g N/$m^2$, respectively.

Table 62. Aboveground dead biomass nitrogen storage for the entire region of each plot (area-weighted average of inside and outside regions of each plot).

| Date | Time Interval (days) | Plot C Storage (g N/m²) | Plot C Rate of Change[a] | Plot M Storage (g N/m²) | Plot M Rate of Change[a] | Plot H Storage (g N/m²) | Plot H Rate of Change[a] |
|---|---|---|---|---|---|---|---|
| 4/25/77 | | 9.88 | | 8.04 | | 5.86 | |
| | 46 | | -59.13 | | -58.70 | | +14.13 |
| 6/10/77 | | 7.16 | | 5.34 | | 6.51 | |
| | 28 | | -46.43 | | -80.71 | | +65.00 |
| 7/8/77 | | 5.86 | | 3.08 | | 8.33 | |
| | 34 | | +64.41 | | +56.47 | | +47.65 |
| 8/11/77 | | 8.05 | | 5.00 | | 9.95 | |
| | 35 | | -65.14 | | +259.43 | | +37.71 |
| 9/15/77 | | 5.77 | | 14.08 | | 11.27 | |
| | 79 | | +36.58 | | | | |
| 12/3/77 | | 8.66 | | --- | | --- | +12.09 |
| | 79 | | +29.49 | | +50.33 | | |
| 2/20/78 | | 10.99 | | --- | | 13.18 | |
| | 54 | | +126.48 | | | | +51.30 |
| 4/15/78 | | 17.82 | | 24.75 | | 15.95 | |
| | 71 | | -102.68 | | -137.75 | | -103.66 |
| 6/25/78 | | 10.53 | | 14.97 | | 8.59 | |
| | 85 | | -25.88 | | -85.18 | | +25.29 |
| 9/18/78 | | 8.33 | | 7.73 | | 10.75 | |
| | 88 | | +15.80 | | | | -32.95 |
| 12/15/78 | | 9.72 | | --- | | 7.85 | |
| | 64 | | +11.72 | | | | +37.81 |
| 2/17/79 | | 10.47 | | --- | | 10.27 | |

[a]Rate of change is given as mg $N/m^2 \cdot day$.

The composite of both live and dead aboveground biomass nitrogen storage is shown in Table 63. For the two-year study period, maximum storage was attained on April 15, 1978, in Plots C and H, and on June 25, 1978, in Plot M. Plot M exhibited the largest peak storage of live plus dead aboveground biomass nitrogen. Peak values were 29.44 g $N/m^2$, 21.93 g $N/m^2$, and 21.22 g $N/m^2$ for Plots M, H, and C, respectively.

The data indicated significant quantities of nitrogen (about 10 g $N/m^2$) were stored in aboveground live biomass as compared to the amount applied to Plot H over one year (about 30 g $N/m^2$; see nitrogen budget section). Thus, harvest of aboveground biomass near the time of peak standing crop could remove significant quantities of the applied nitrogen. The best time for harvest would depend on when maximum nitrogen storage in this component took place. The data suggest that peak nitrogen storage was attained earlier in the treated wastewater plots than peak biomass was attained in the control plot. Harvest in the early summer would be most appropiate for maximum nitrogen removal. However, this may not result in significantly better nitrogen renovation as calculated by nitrogen mass outflow in exported waters. Denitrification was shown to be a effective removal mechanism for applied nitrogen. Root growth might ultimately be stifled by yearly biomass harvest. Since roots were implicated as an energy source for denitrification in the marsh, that process might not proceed as well if plants were harvested yearly. Harvesting might also inflict severely physical damage to the marsh ecosystem depending on the type of harvesting method.

<u>Nitrogen belowground vegetation values</u>. Data for nitrogen stored in belowground live plus dead biomass are summarized in Table 64. Peak nitrogen storage in this compartment was found in August 1977 for the inside portion of Plot H (130.42 g $N/m^2$). There was an apparent decrease in stored belowground biomass nitrogen between August 1977 and September 1978 in Plots C and H. When an area-weighted mean of the inside region and outside region measurements for Plots C, M, and H was taken, a net decrease in belowground biomass nitrogen storage was seen from April to September 1978 in

Table 63. Aboveground live plus dead biomass nitrogen storage for the entire region of each plot (area-weighted average of inside and outside regions of each plot).

| Date | Time Interval (days) | Plot C | | Plot M | | Plot H | |
|---|---|---|---|---|---|---|---|
| | | Storage (g N/m²) | Rate of[a] Change | Storage (g N/m²) | Rage of[a] Change | Storage (g N/m²) | Rate of[a] Change |
| 4/25/77 | | 13.65 | | 11.84 | | 9.74 | |
| | 46 | | -32.17 | | -41.52 | | +66.74 |
| 6/10/77 | | 12.17 | | 9.93 | | 12.81 | |
| | 28 | | -50.71 | | -54.64 | | +236.43 |
| 7/8/77 | | 10.75 | | 8.40 | | 19.43 | |
| | 34 | | +204.12 | | +134.41 | | +94.71 |
| 8/11/77 | | 17.69 | | 12.97 | | 22.65 | |
| | 35 | | -82.00 | | +336.86 | | +46.57 |
| 9/15/77 | | 14.82 | | 24.76 | | 24.28 | |
| | 79 | | -52.91 | | | | |
| 12/3/77 | | 10.64 | | --- | | --- | -62.03 |
| | 79 | | +11.01 | | +16.42 | | |
| 2/20/78 | | 11.57 | | --- | | 14.48 | |
| | 54 | | +179.81 | | | | +137.96 |
| 4/15/78 | | 21.22 | | 28.24 | | 21.93 | |
| | 71 | | -32.25 | | +16.90 | | -14.08 |
| 6/25/78 | | 18.93 | | 29.44 | | 20.93 | |
| | 85 | | -4.12 | | -132.12 | | + 0.47 |
| 9/18/78 | | 18.58 | | 18.21 | | 20.97 | |
| | 88 | | | | | | |
| 12/15/78 | | --- | -25.72 | --- | | --- | -18.03 |
| | 64 | | | | | | |
| 2/17/79 | | 14.67 | | --- | | 18.23 | |

[a]Rate of change is given as mg $N/m^2 \cdot day$.

Table 64. Below ground live plus dead biomass nitrogen in the inside region of the plots.

| Date | Time Interval (days) | Plot C Storage (g N/m$^2$) | Plot C Rate of Change[a] | Plot M Storage (g N/m$^2$) | Plot M Rate of Change[a] | Plot H Storage (g N/m$^2$) | Plot H Rate of Change[a] |
|---|---|---|---|---|---|---|---|
| 8/11/77 | | 56.55 | | --- | | 130.42 | |
| | 193 | | +0.100 | | --- | | -0.259 |
| 2/20/78 | | 75.85 | | --- | | 80.40 | |
| | 54 | | -0.425 | | --- | | -0.927 |
| 4/15/78 | | 52.88 | | 52.84 | | 30.36 | |
| | 71 | | -0.093 | | -0.179 | | +0.205 |
| 6/25/78 | | 46.26 | | 40.14 | | 44.88 | |
| | 85 | | -0.147 | | +0.072 | | +0.026 |
| 9/18/78 | | 33.77 | | 46.29 | | 47.08 | |
| | 152 | | -0.010 | | +0.010 | | -0.089 |
| 2/17/79 | | 32.31 | | 47.74 | | 33.58 | |
| Below ground live plus dead biomass nitrogen storage for the entire region of the plots (area-weighted average of inside and outside regions of each plot). | | | | | | | |
| 4/15/78 | | 55.04 | | 51.68 | | 61.92 | |
| | 71 | | -0.203 | | -0.125 | | -0.269 |
| 6/25/78 | | 40.65 | | 42.84 | | 42.79 | |
| | 85 | | -0.141 | | +0.040 | | -0.014 |
| 9/18/78 | | 28.67 | | 46.27 | | 41.58 | |
| | 152 | | +0.108 | | --- | | -0.013 |
| 2/17/79 | | 45.12 | | --- | | 39.54 | |

[a]Rate of change is expressed as g N/m$^2$·day.

each of these plots. Analysis of variance for belowground biomass nitrogen storage during the second year showed no significant differences in the values observed among the plots ($\alpha = 0.05$) and no significant effect ($\alpha = 0.05$) of proximity to the discharge pipe in the plots. There was a significant effect of time ($\alpha = 0.01$) on the values observed during the second year, as indicated by the net decrease in storage between April and September 1978 in each plot.

Nitrogen vegetation summary. Summary graphs for above and belowground biomass nitrogen storage for the inside portions of Plots H and C are presented in Figs. 90 and 91. Live and dead root storage was the major component of total biomass nitrogen in these two regions. The especially large storage of nitrogen in root biomass for the inside region of Plot H in August 1977 was reflected in the large total biomass storage exhibited at this time. Apparently, much of the nitrogen in applied treated wastewater was assimilated directly at the site of application in Plot H during the dry year. The roots were above the water table during the growing season of that year. The subsequent loss of total biomass nitrogen after August 1977 implies a net transfer of nitrogen from biomass to water and any newly deposited peat. Peat production was not measured in this study. Nitrogen transferred to water was subject to microbial transformation and some ultimate removal by denitrification. Dying root tissue could have provided a readily useable carbon source for denitrifiers; thus denitrification could have been enhanced as roots died back. Total biomass nitrogen stocks increased between April 1978 and June 1978, indicating a net assimilation of applied nitrogen. A slow decline in total stocks was observed after June 1978. The second-year drop in biomass nitrogen stocks was less than during the first year. However, this does not imply that there was a slower rate of peat production. Peat could have been continually produced even when biomass stocks were observed to be constant. If loss of biomass to new peat were balanced by new biomass production, no net change in total biomass would be observed.

The inside region of Plot C exhibited a different seasonal trend for total biomass nitrogen than Plot H. This was due primar-

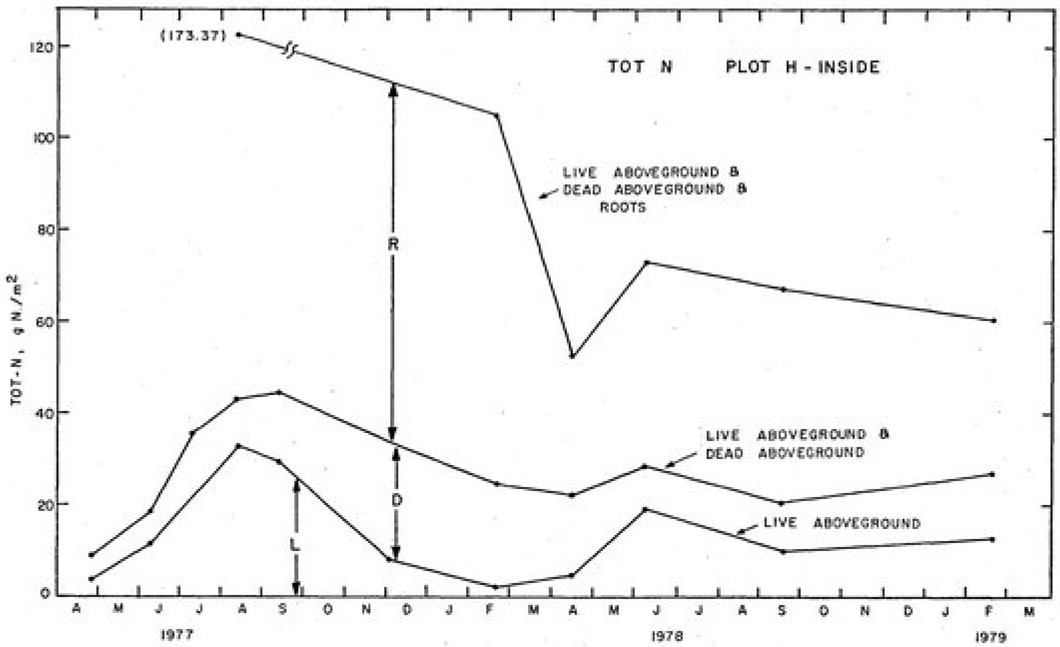



Figure 90. Total nitrogen content in aboveground and belowground biomass in Plot H (9.6 cm/wk of treated wastewater) near the distribution pipe. "R" represents the root fraction, "D" represents the dead aboveground fraction, and "L" represents the live aboveground fraction.

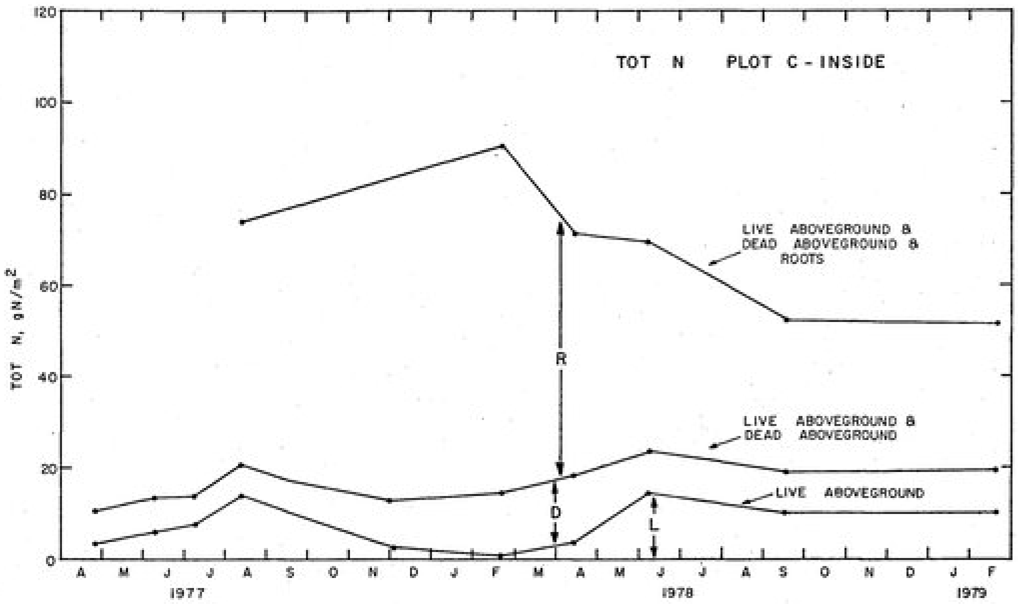



Figure 91. Total nitrogen content in aboveground and belowground biomass in Plot C (4.4 cm/wk of fresh water) near the distribution pipe. "R" represents the root fraction, "D" represents the dead aboveground fraction, and "L" represents the live aboveground fraction.

ily to the different seasonal pattern of belowground biomass in this plot. As shown in Fig. 91, net assimilation of nitrogen into total biomass was indicated for August 1977 - February 1978. Persistent net release was indicated after this period.

Biomass nitrogen summaries for the entire regions of Plots H, M, and C are given in Figs. 92-94. As shown, all exhibit a net decline in total biomass nitrogen between April 1978 and February 1979, the period for which the total region belowground data were available. This suggests a net deposition of nitrogen in new peat during the second year for each plot.

Nitrogen in Peat

Total nitrogen content of peat was determined using samples of peat taken from Plot C, Plot H, and the natural area of the marsh. Results are given in Table 65. Analysis of variance for these samples showed no significant difference ($\alpha = 0.10$) in nitrogen content with respect to either depth interval (0-25 cm, 25-50 cm, 50-75 cm, respectively) or location in the marsh.

Exchangeable ammonium of peat was analyzed for samples taken on September 1978 and February 1979. An estimate of the total ammonium adsorbed to the peat complex in Plot C, Plot H, and the natural area on each of these two dates was obtained. The values obtained for the 50-75 cm depth interval at each sampling site were considered representative of the peat layer between 50 cm and 150 cm at this location. Area-weighted averages for Plots C and H were obtained using samples from the inside and outside regions of each of these plots. Results are shown in Table 66. Apparently, this storage of nitrogen was a minor component in the total nitrogen budget of the marsh. Furthermore, there was no significant difference ($\alpha = 0.05$) in the adsorbed ammonium value between Plot H and either Plot C or the natural area. The nitrogen content of peat, as measured by total nitrogen or exchangeable ammonium, was not affected by the application of treated wastewater to the marsh during the two years of this study.

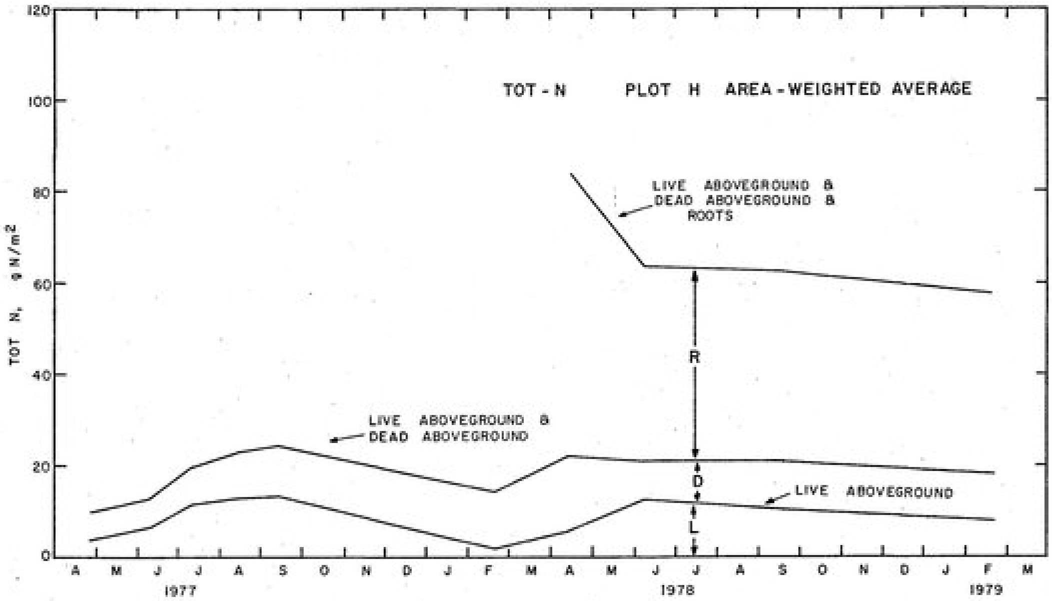



Figure 92. Total nitrogen content in aboveground and belowground biomass in Plot H. The values were area weighted by adding 25% of the "inside" value to 75% of the "outside" value ("inside" and "outside" the influence of the distribution pipe). Loading was 9.6 cm/wk of treated wastewater. "R" represents the root fraction, "D" represents the dead aboveground fraction, and "L" represents the live aboveground fraction.

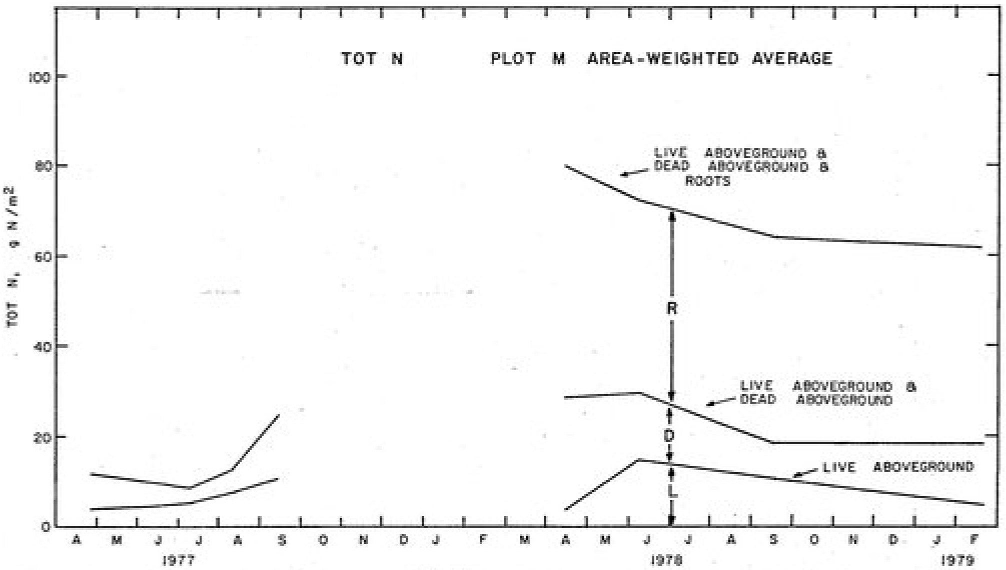



Figure 93. Total nitrogen content in aboveground and belowground biomass in Plot M. The values were area weighted by adding 25% of the "inside" value to 75% of the "outside" values ("inside" and "outside" the invluence of the distribution pipe). Loading was 3.7 cm/wk of treated wastewater. "R" represents the root fraction, "D" represents the dead aboveground fraction, and "L" represents the live aboveground fraction.

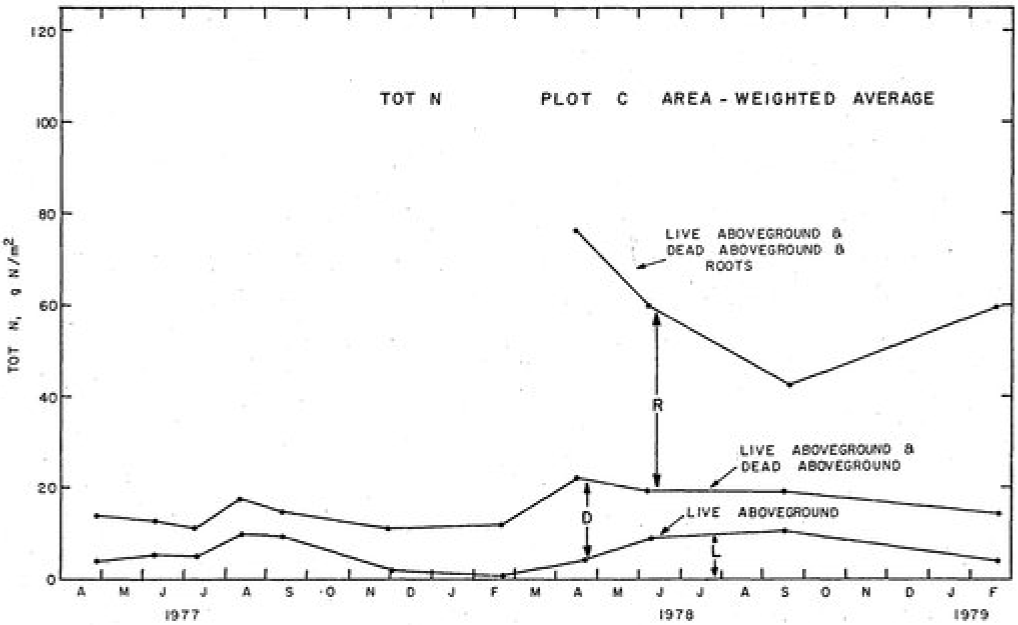



Figure 94. Total nitrogen content in aboveground and belowground biomass in Plot C. The values were area weighted by adding 25% of the "inside" value to 75% of the "outside" value ("inside" and "outside" the influence of the distribution pipe). Loading was 4.4 cm/wk of fresh water. "R" represents the root fraction, "D" represents the dead aboveground fraction, and "L" represents the live aboveground fraction.

Table 65. Total nitrogen content of peat in the marsh as % of dry weight.

| | % Nitrogen | n |
|---|---|---|
| Freshwater Control Plot (Plot C) | 2.63 | 16 |
| High-rate Treated Wastewater Plot (Plot H) | 2.53 | 16 |
| Natural Area | 2.39 | 16 |

No significant difference was detected among these averages ( = 0.10).

Table 66. Adsorbed ammonium in the peat complex. Values ± 1 S.E. (g $N/m^2$).

| Location | Sampling date 9/15/78 | n | 2/17/79 | n |
|---|---|---|---|---|
| Plot C | 0.327 ± .082 | 6 | 0.478 ± .123 | 6 |
| Plot H | 0.568 ± .179 | 6 | 0.501 ± .113 | 6 |
| Natural area | 0.272 ± .027 | 3 | 0.289 ± .025 | 3 |

No significant difference was detected among any of these averages ($\alpha$ = .05).

Plant Decomposition and Nitrogen

Nitrogen results for the decomposition experiment performed during the first year of the marsh study are shown in Figs. 95 and 96. Three types of plant material were studied: Sagittaria lancifolia leaves; S. lancifolia stems; and Panicum, a grass. Fig. 95 presents the average concentration of nitrogen found in the material that remained in litter bags collected on each sampling date. The figure indicates that the concentration of nitrogen in decomposing plant matter tended toward a constant value with time. This "ultimate" concentration value was comparable to the value observed for peat in the marsh (see Table 65). The average concentration of nitrogen in remaining Sagittaria leaf matter was consistently higher than the average concentration of nitrogen in remaining stem matter or remaining Panicum. The latter two categories exhibited roughly the same average concentration of nitrogen after November 1977.

The measured concentration of nitrogen in the dry matter of each collected litter bag and the percentage of the original dry weight remaining in that bag were used to derive the amount of nitrogen present in each collected bag relative to the amount present before any decomposition occurred. The average percentage of original nitrogen mass remaining in the litter samples collected on each sampling date is presented for the three plant categories described above in Fig. 96. This figure suggests that roughly half of the original nitrogen content of the plant samples remained after a year of decomposition under relatively dry conditions. Very little additional loss of nitrogen or dry matter appeared to be occurring by the end of that one-year period.

As described in the Methods chapter, the decomposition experiment conducted during the second (wet) year employed subsamples of the dead aboveground biomass collected on June 25, 1978. Three sets of litter bags were set up for each of Plots C, M, and H. Litter collected from each plot was returned to the same plot. Figure 97

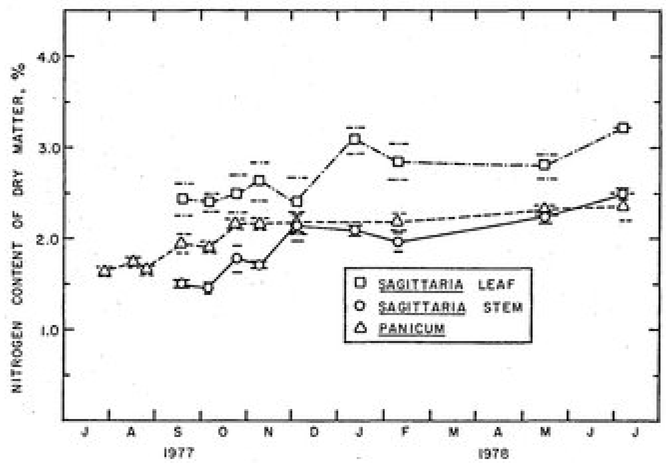



Figure 95. Average nitrogen content of dry matter remaining in litter bags on each sampling date. The experiment was conducted for the "dry" year. Values are ± 1 S.E.

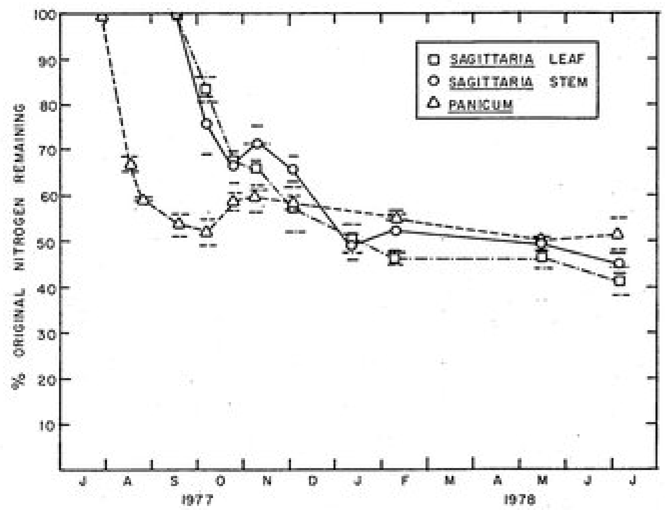



Figure 96. Percentage of original nitrogen mass content of litter bags remaining on each sampling date. The experiment was conducted for the "dry" year. Values are ± 1 S.E.

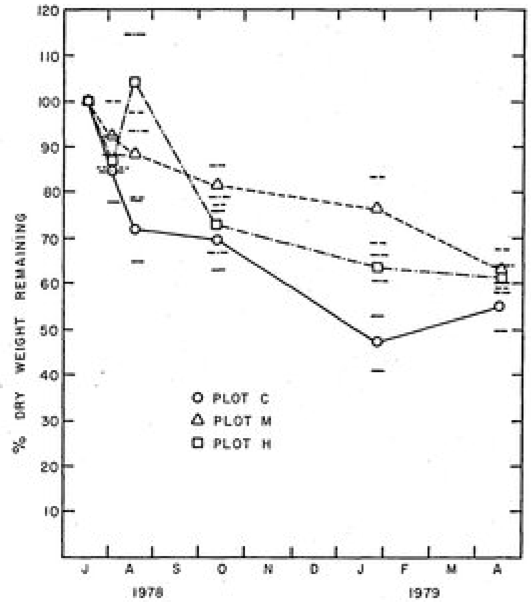



Figure 97. Percentage of original dry weight remaining in litter bags on each sampling date. The experiment was conducted for the "wet" year. Values are ± 1 S.E.

shows the average percentage of original dry matter remaining for each of the three plots on each sampling date. A decrease to approximately 60% of the original dry matter content was seen in each plot after nine months of decomposition. The water table was consistently above the surface of the peat after the first month of this decomposition experiment. The apparent weight gain during August 3-18, 1978, for the litter in Plot H was probably due to the inherent error of the experimental technique. There may have been some discrepancy between the actual wet to dry weight ratio of a particular litter sample and the estimated value employed to compute dry weight loss.

Figure 98 illustrates the average concentration of nitrogen in the decomposing litter during the wet year. The concentration appears to head towards an average value of approximately 2.5% of the remaining dry weight. This value is essentially equivalent to the value observed for peat in the marsh (see Table 65). The average concentration value for Plot H was nearly always slightly higher than the values for either Plot C or Plot M.

The average percentage of original nitrogen mass remaining in litter samples on each sampling date is shown in Fig. 99. Calculation of these values suffered from the same uncertainties as were involved in estimating the dry matter loss and were discussed previously. Although the concentration of nitrogen in litter had a nearly constant value after the first three months (see Fig. 98), the litter kept losing dry matter throughout the nine month observation period. Hence, there was a noticeable net loss of nitrogen from litter occurring even after nine months under wet conditions.

There is some indication from Fig. 99 that loss of nitrogen from dead aboveground biomass (litter) proceeded at a slower rate in Plot M than in Plot H under wet conditions. This is consistent with the observed larger accumulation of aboveground dead biomass and associated nitrogen in Plot M (3.7 cm/wk treated wastewater) than in Plot H (9.6 cm/wk treated wastewater) during the two-year study period.

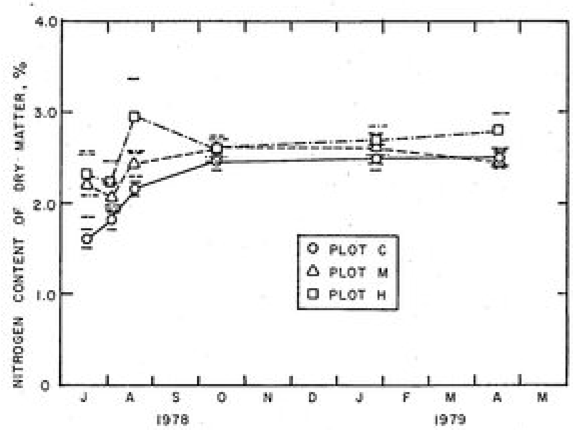



Figure 98. Average nitrogen content of dry matter remaining in litter bags on each sampling date. The experiment was conducted for the "wet" year. Values are ± 1 S.E.

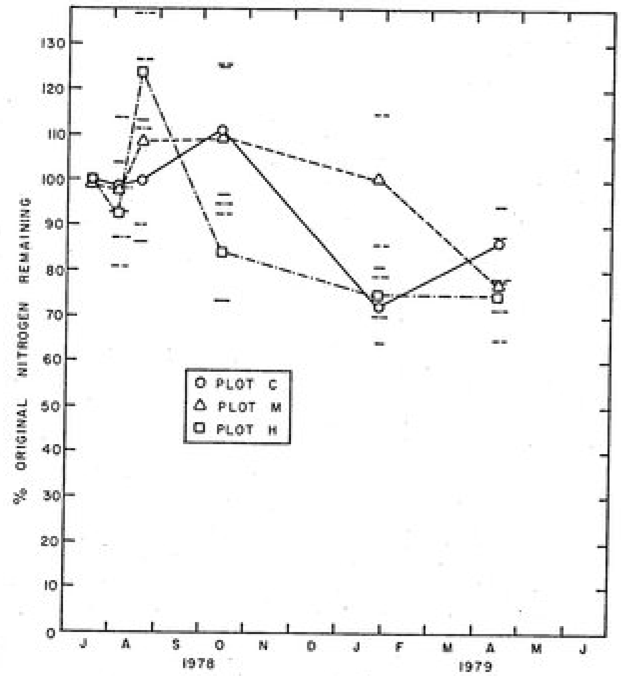



Figure 99. Percentage of original nitrogen mass content of litter bags remaining on each sampling date. The experiment was conducted for the "wet" year. Values are ± 1 S.E.

## Nitrogen Budgets for Plots H and C

### Treated Wastewater Nitrogen Loading

Measured average concentrations of nitrate plus nitrite, ammonium, organic and total nitrogen in applied treated wastewater for each month are shown in Table 67. Using the recorded volume of water applied to Plot H (two-year average of 9.6 cm/wk treated wastewater) each month, loadings of the nitrogen species were derived. The computed loadings are also given in Table 67. A total of 31.51 g $N/m^2$ was applied during the first year, 26.7% of which was bound in organic form. During the second year, 37.57 g $N/m^2$ were applied, 34.1% of it bound in organic form.

### Freshwater Nitrogen Loading

The average concentrations of nitrogen species in applied fresh water were computed for the periods 1977-1978 and 1979, respectively. The two periods were treated separately because fresh water supplied to Plot C (4.4 cm/wk fresh water) was pumped from a different municipal well after December 1978. The average values are given in Table 68. These values, along with the measured volumes of fresh water applied to Plot C each month, were used to obtain the monthly nitrogen loadings in fresh water to Plot C. The loadings are given in Table 69. Only 2.80 g $N/m^2$ were applied during the first year, 73.0% as organic-N, and 2.11 g $N/m^2$ were applied during the second year, 70.2% of it as organic-N.

### Rainfall Nitrogen Loading

Average concentrations of nitrate plus nitrite nitrogen, ammonium nitrogen, organic nitrogen, and total nitrogen in wet precipitation for the period 1977-1978 are listed in Table 70.

Table 67. Nitrogen loading to Plot H in applied treated wastewater.

| Month | Treated waste-water volume (cm) | Concentration (mg N/l) | | | | Mass Applied (g N/m$^2$·mo) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $NO_3^-$ + $NO_2^-$ | $NH_3$ | Org N | Tot N | $NO_3^-$ + $NO_2^-$ | $NH_3$ | Org N | Tot N |
| May 77 | 41.5 | 0.007[a] | 0.125[a] | 0.98[a] | 1.11[a] | 0.003 | 0.052 | 0.41 | 0.46 |
| Jun | 50.9 | 1.75[b] | 0.045[b] | 0.56[b] | 2.36[b] | 0.891 | 0.023 | 0.29 | 1.20 |
| Jul | 40.7 | 3.40 | 0.93 | 3.87 | 8.20 | 1.384 | 0.379 | 1.58 | 3.34 |
| Aug | 49.6 | 3.51[c] | 0.54[c] | 2.29[c] | 6.33[c] | 1.741 | 0.268 | 1.14 | 3.14 |
| Sep | 51.1 | 3.61 | 0.15 | 0.70 | 4.46 | 1.845 | 0.077 | 0.36 | 2.28 |
| Oct | 42.2 | 2.70 | 0.09 | 4.40 | 7.19 | 1.139 | 0.038 | 1.86 | 3.03 |
| Nov | 41.2 | 2.81[c] | 0.29[c] | 3.16[c] | 6.24[c] | 1.158 | 0.119 | 1.30 | 2.57 |
| Dec | 50.9 | 2.91 | 0.48 | 1.91 | 5.29 | 1.481 | 0.244 | 0.97 | 2.69 |
| Jan 78 | 40.7 | 5.78 | 0.08 | 0.94 | 6.80 | 2.352 | 0.033 | 0.38 | 2.77 |
| Feb | 40.7 | 5.05 | 5.06 | 0.12 | 10.23 | 2.055 | 2.059 | 0.05 | 4.16 |
| Mar | 21.8 | 4.60 | 5.10 | 0.21 | 9.47 | 1.003 | 1.112 | 0.05 | 2.06 |
| Apr | 41.4 | 4.18[d] | 5.06[d] | 0.19[d] | 9.21[d] | 1.731 | 2.095 | 0.08 | 3.81 |
| May | 46.2 | 3.76 | 5.01 | 0.17 | 8.94 | 1.737 | 2.315 | 0.08 | 4.13 |
| Jun | 45.9 | 0.99 | 0.42 | 5.58 | 6.99 | 0.454 | 0.193 | 2.56 | 3.21 |
| Jul | 41.1 | 0.46 | 3.42 | 4.88 | 8.76 | 0.189 | 1.406 | 2.01 | 3.60 |
| Aug | 51.3 | 3.26 | 0.76 | 5.34 | 9.36 | 1.672 | 0.390 | 2.74 | 4.80 |
| Sep | 41.1 | 4.98 | 0.89 | 4.42 | 10.29 | 2.047 | 0.366 | 1.82 | 4.23 |
| Oct | 41.1 | 4.35 | 2.54 | 1.76 | 8.65 | 1.788 | 1.044 | 0.72 | 3.56 |
| Nov | 41.1 | 4.27 | 0.58 | 3.80 | 8.05 | 1.755 | 0.238 | 1.56 | 3.31 |
| Dec | 41.1 | 4.12 | 5.19 | 0.24 | 9.55 | 1.693 | 2.133 | 0.10 | 3.93 |
| Jan 79 | 41.1 | 2.12 | 1.56 | 1.33 | 5.01 | 0.871 | 0.641 | 0.55 | 2.06 |
| Feb | 32.7 | 1.07 | 4.98 | 0.87 | 6.92 | 0.350 | 1.628 | 0.28 | 2.26 |
| Mar | 32.7 | 0.69 | 0.39 | 0.12 | 1.20 | 0.226 | 0.128 | 0.04 | 0.39 |
| Apr | 32.7 | 4.37 | 0.69 | 1.32 | 6.38 | 1.429 | 0.226 | 0.43 | 2.09 |

[a]Unfrozen samples.
[b]Average of July 1977 and September 1977 samples.
[c]Average of October 1977 and December 1977 samples.
[d]Average of March 1978 and May 1978 samples.

Table 68. Average nitrogen content of fresh water applied to Plot C (4.4 cm/wk) (mg/l).

| Time Period | $NO_3^-$-N + $NO_2^-$-N | $NH_3$ -N | Organic N | Total N |
|---|---|---|---|---|
| 1977-1978 | 0.278 | 0.102 | 1.028 | 1.408 |
| 1979 | 0.035 | 0.063 | 0.087 | 0.186 |

Table 69. Nitrogen loading to Plot C (4.4 cm/wk fresh water) (g $N/m^2 \cdot mo$).

| Month | Fresh water Volume (cm) | $NO_3^+$ $NO_2$ | $NH_3$ | Org | Tot N |
|---|---|---|---|---|---|
| May 77 | 15.3 | .043 | .016 | .157 | .215 |
| Jun | 19.8 | .055 | .020 | .204 | .279 |
| Jul | 15.5 | .043 | .016 | .159 | .218 |
| Aug | 15.8 | .044 | .016 | .162 | .222 |
| Sep | 19.1 | .053 | .019 | .196 | .269 |
| Oct | 18.1 | .050 | .018 | .186 | .255 |
| Nov | 14.9 | .041 | .015 | .153 | .210 |
| Dec | 19.2 | .053 | .020 | .197 | .270 |
| Jan 78 | 15.2 | .042 | .016 | .156 | .214 |
| Feb | 15.2 | .042 | .016 | .156 | .214 |
| Mar | 15.4 | .043 | .016 | .158 | .217 |
| Apr | 15.4 | .043 | .016 | .158 | .217 |
| May | 21.7 | .060 | .022 | .223 | .306 |
| Jun | 16.0 | .044 | .016 | .164 | .225 |
| Jul | 15.4 | .043 | .016 | .158 | .217 |
| Aug | 19.3 | .054 | .020 | .198 | .272 |
| Sep | 15.4 | .043 | .016 | .158 | .217 |
| Oct | 15.4 | .043 | .016 | .158 | .217 |
| Nov | 15.4 | .043 | .016 | .158 | .217 |
| Dec | 15.4 | .043 | .016 | .158 | .217 |
| Jan 79 | 15.4 | .005 | .010 | .013 | .029 |
| Feb | 34.9 | .012 | .022 | .030 | .065 |
| Mar | 34.9 | .012 | .022 | .030 | .065 |
| Apr | 34.9 | .012 | .022 | .030 | .065 |

Table 70. Nitrogen in bulk precipitation.

| | $NO_2$-N + $NO_3$-N | $NH_3$-N | Organic N | Total N |
|---|---|---|---|---|
| Wet precipitation[a] (mg/l) | 0.202 | 0.108 | 0.331 | 0.641 |
| Dry fallout[a] ($g/m^2 \cdot$month) | 0.007 | 0.004 | 0.015 | 0.026 |

[a]Values were obtained from data collected for Lake Apopka, 20 km to the west of Clermont (Hendry, pers. comm.).

Also listed in Table 70 are the average values for dry fallout of nitrogen during this period. Using the measured rainfall for each month in the research marsh and the average concentration of nitrogen species in wet precipitation given in Table 70, estimates of monthly nitrogen loading by wet precipitation were obtained. The average dry fallout value from Table 70 was then added to obtain bulk precipitation loading values for each month. Results are shown in Table 71. During the first year, 1.03 g $N/m^2$ were supplied to the marsh in bulk precipitation and 1.20 g $N/m^2$ were supplied during the second year. This was a significant input as compared to the freshwater loading of Plot C, but insignificant as compared to the treated wastewater loading of Plot H.

Nitrogen Fixation

As discussed in the Nitrogen Considerations section, nitrogen fixation was assumed to be negligible in Plot H during both years of this study. Fixation was assumed to be negligible in Plot C during the dry year, with a value of 5.84 g $N/m^2 \cdot yr$ during the wet year. Values derived for the growing season and dieback periods of the wet year assumed this rate to be uniform throughout the wet year.

Changes in Aboveground Biomass Nitrogen

Averages of nitrogen in total live, total dead, and total live plus dead aboveground biomass for the inside and outside regions of Plots H and C were weighted by area to yield average values for each entire plot (see Methods). Results were given in Tables 61, 62, and 63. Also shown were the rate of change in total nitrogen storage for each of these categories between successive sampling periods. This provided an estimate of net flux of nitrogen into these compartments between samplings. Shown in Table 72 is a summary of the net changes in aboveground biomass nitrogen storage in Plots H and C for the growing season and dieback period of the first and second years of the study, respectively.

As discussed in the Nitrogen Considerations section, a net increase for nitrogen stored in aboveground dead biomass was

Table 71. Nitrogen loading in bulk precipitation throughout the research marsh (g $N/m^2 \cdot month$).

| Month | Rain (cm) | $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N |
|---|---|---|---|---|---|
| May 1977 | 2.1 | .011 | .006 | .022 | .039 |
| June | 5.5 | .018 | .010 | .033 | .061 |
| July | 21.8 | .051 | .028 | .087 | .166 |
| August | 16.2 | .040 | .021 | .069 | .130 |
| September | 13.9 | .035 | .019 | .061 | .115 |
| October | 2.8 | .013 | .007 | .024 | .044 |
| November | 8.2 | .024 | .013 | .042 | .079 |
| December | 10.4 | .028 | .015 | .049 | .093 |
| January 1978 | 7.2 | .022 | .012 | .039 | .072 |
| February | 14.9 | .037 | .020 | .064 | .122 |
| March | 6.6 | .020 | .011 | .037 | .068 |
| April | 1.8 | .011 | .006 | .021 | .038 |
| May | 14.4 | .036 | .020 | .063 | .118 |
| June | 27.6 | .063 | .034 | .106 | .203 |
| July | 32.8 | .073 | .039 | .124 | .236 |
| August | 6.5 | .020 | .011 | .037 | .068 |
| September | 7.9 | .023 | .013 | .041 | .077 |
| October | 4.6 | .016 | .009 | .030 | .055 |
| November | 0.0 | .000 | .000 | .000 | .000 |
| December | 8.9 | .025 | .014 | .044 | .063 |
| January 1979 | 17.8 | .043 | .023 | .074 | .140 |
| February | 5.0 | .017 | .009 | .032 | .058 |
| March | 10.0 | .027 | .015 | .048 | .090 |
| April | 13.3 | .034 | .018 | .059 | .111 |

Table 72. Changes in aboveground biomass nitrogen storage for Plots C (4.4 cm/wk fresh water) and H (9.6 cm/wk treated wastewater) (g N/m$^2$·time period).

| | Plot C | | | Plot H | | |
|---|---|---|---|---|---|---|
| | Live | Dead | Live & Dead | Live | Dead | Live & Dead |
| Dry Year | | | | | | |
| Growing season | | | | | | |
| (4/25/77-8/11/77) | +5.86 | -1.83 | +4.04 | +8.82 | +4.09 | +12.90 |
| Dieback | | | | | | |
| (8/11/77-2/20/78) | -9.12 | +2.94 | -6.18 | -11.40 | +3.23 | -8.17 |
| Entire year | | | | | | |
| (4/25/77-4/15/78) | -0.38 | +7.94 | +7.57 | +2.10 | +10.09 | +12.19 |
| Wet Year | | | | | | |
| Growing Season | | | | | | |
| (4/15/78-9/15/78) | +6.85 | -9.49 | -2.64 | +4.24 | -5.21 | -0.96 |
| Dieback | | | | | | |
| (9/15/78-2/17/79) | -6.04 | +2.14 | -3.90 | -2.26 | -0.48 | -2.74 |
| Partial year | | | | | | |
| (4/15/78-2/17/79) | +0.81 | -7.35 | -6.54 | +1.98 | -5.69 | -3.70 |
| Both Years | | | | | | |
| (4/25/77-2/17/79) | +0.43 | +0.59 | +1.02 | +4.08 | +4.40 | +8.49 |

exhibited in both the freshwater plot and the high-rate treated wastewater plot during the first (dry) year. Reasons for such a net accumulation throughout the marsh were given. The most important factor contributing to the net storage appeared to be the dry conditions; decomposition was probably limited by insufficient water during part of that year. Much of the net gain of aboveground dead biomass nitrogen in Plots H and C was lost during the second year, when the water table was above the surface of the peat. Part of the observed loss was due to deposition of new peat, as well as loss of nitrogen to surrounding waters.

Changes in Belowground Biomass Nitrogen

Area-weighted average values for nitrogen stored in belowground biomass (i.e., live and dead roots) for Plots H and C were used to estimate uptake and release of nitrogen by this compartment. Results are shown in Table 73. Yearly data were available only for the second year, during which time a net loss of nitrogen from belowground biomass was observed. As with aboveground dead biomass, at least some of the observed loss represented transfer of nitrogen as newly deposited peat.

Nitrogen Adsorption by Soil

Additional uptake of nitrogen by marsh peat may have occurred due to adsorption of ammonium ions onto cation exchange sites of the peat. The data presented in Table 66 showed the adsorption process to be an insignificant component in the nitrogen budgets of Plots H and C. Thus, adsorption of ammonia by peat soil did not constitute a significant net sink for applied nitrogen in this marsh. Also, ammonia content of marsh waters was not influenced seasonally by such adsorption.

Potential Denitrification

The potential denitrification rate of Plot H was derived from column studies, using the column of peat containing no plants and 15 cm of overlying nitrate-amended treated wastewater. This value was 0.6 g $N/m^2 \cdot day$ (see Table 54) and was utilized for

Table 73. Changes in nitrogen storage of belowground biomass (g N/m$^2$· time period).

| | Plot C | Plot H |
|---|---|---|
| Dry Year | | |
| Growing season[a] (4/25/77-8/11/77) | --- | --- |
| Dieback (8/11/77-2/20/78) | -19.30[b] | -50.02[c] |
| Entire Year[d] (4/25/77-4/15/78) | --- | --- |
| Wet Year | | |
| Growing Season (4/15/78-9/15/78) | -26.37 | -20.34 |
| Dieback (9/15/78-2/17/79) | +16.45 | - 2.04 |
| Partial year (4/15/78-2/17/79) | - 9.92 | -22.38 |

[a]Data not available.

[b]Value obtained from inside region of Plot C.

[c]Value obtained from inside region of Plot H.

[d]Data not available.

both wet and dry years. The potential denitrification rate for Plot C was determined from the in situ studies of denitrification conducted in the natural marsh. Using results obtained for nitrate-amended bags of soil placed at 8 cm and 30 cm depths, respectively, a value of 1.8 g $N/m^2 \cdot day$ was derived for the upper 45 cm of peat. This depth corresponds to the 45 cm length of peat columns used in column studies. The calculated rate was higher than the rates observed for columns with overlying treated wastewater. This occurred because the rate of nitrate diffusion through overlying water was limiting to denitrification in column studies. Hence, the potential rate of 1.8 g $N/m^2$ was more accurate for periods of low or absent standing water in Plot C than for periods of high water in this plot.

Export of Nitrogen in Outflowing Water

Outflow of water per monthly period in Plots H and C was computed as described in the Methods chapter. These results are reported in Tables 74-76. Calculated water outflows and representative concentrations of nitrogen for the outflowing water were utilized to get hydrologic export of nitrogen in each plot for each month. For the freshwater plot (Plot C), well W21M, located in the northwest corner at medium depth, was utilized for representative nitrogen content of exported water. Results are given in Table 76. For the high-rate, treated wastewater plot (Plot H), separate mass outflows of nitrogen during each month were computed using data from wells W3M and W23M. Well W3M was located at medium depth, directly beneath the treated wastewater discharge pipe in Plot H. If most of the applied treated wastewater flowed out of the peat and into the sand layer directly beneath the discharge pipe, nitrogen content of well W3M samples would have been representative of exported waters. Well W23M was located at medium depth in the northwest corner of Plot H. If most of the applied treated wastewater traveled horizontally and was uniformly distributed throughout the peat layer, nitrogen content measured in well W23M samples would have been representative of exported water. Chloride levels in water samples were utilized

Table 74. Nitrogen export from Plot H (9.6 cm/wk of treated wastewater) in outflowing water (well W3M used).

| Month | Outflow olume (cm) | Concentration (mg/l) | | | | Mass Outflow ( g N/m$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N | $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N |
| May 77 | 32.3 | 0.023[a] | 0.06[a] | 1.99[a] | 2.07[a] | .007 | .019 | .643 | .669 |
| Jun | 42.1 | 0.023 | 0.06 | 1.99 | 2.07 | .010 | .025 | .838 | .871 |
| Jul | 30.6 | 0.018 | 0.38 | 2.52 | 2.92 | .006 | .116 | .771 | .894 |
| Aug | 36.8 | 0.018 | 1.11 | 3.09 | 4.22 | .007 | .408 | 1.137 | 1.553 |
| Sep | 39.9 | 1.500 | 0.40 | 3.70 | 5.60 | .599 | .160 | 1.476 | 2.234 |
| Oct | 27.7 | 0.350 | 2.10 | 3.15 | 5.60 | .097 | .582 | .873 | 1.551 |
| Nov | 28.3 | 0.178[b] | 1.20[b] | 1.82[b] | 3.20[b] | .050 | .339 | .515 | .906 |
| Dec | 50.5 | 0.005 | 0.30 | 0.48 | 0.79 | .003 | .150 | .242 | .399 |
| Jan 78 | 44.2 | 0.008 | 0.35 | 1.50 | 1.86 | .004 | .155 | .663 | .822 |
| Feb | 48.1 | 0.014[c] | 0.46[c] | 0.82[c] | 1.30[c] | .007 | .221 | .394 | .625 |
| Mar | 25.1 | 0.019 | 0.57 | 0.13 | 0.73 | .005 | .143 | .033 | .183 |
| Apr | 39.3 | 0.013 | 0.65 | 1.86 | 2.52 | .005 | .255 | .731 | .990 |
| May | 37.6 | 0.009 | 0.25 | 0.74 | 1.00 | .003 | .094 | .278 | .376 |
| Jun | 32.8 | 0.045 | 2.53 | 1.13 | 3.89 | .015 | .830 | .371 | 1.276 |
| Jul | 25.9 | 0.057 | 0.51 | 2.01 | 2.58 | .015 | .133 | .521 | .668 |
| Aug | 22.0 | 0.052[d] | 0.70[d] | 1.31[d] | 2.06[d] | .011 | .154 | .288 | .453 |
| Sep | 36.5 | 0.046 | 0.89 | 0.60 | 1.54 | .017 | .325 | .219 | .562 |
| Oct | 40.5 | 0.013 | 0.07 | 0.39 | 0.47 | .005 | .028 | .158 | .190 |
| Nov | 36.2 | 0.018 | 0.11 | 1.35 | 1.48 | .007 | .040 | .489 | .536 |
| Dec 79 | 40.4 | 0.027 | 0.50 | 0.35 | 0.88 | .011 | .202 | .141 | .356 |
| Jan | 40.7 | 0.022 | 0.02 | 0.74 | 0.78 | .009 | .008 | .301 | .317 |
| Feb | 31.0 | 0.007 | 0.09 | 0.25 | 0.34 | .002 | .026 | .078 | .105 |
| Mar | 25.5 | 0.037 | 0.17 | 1.05 | 1.25 | .009 | .042 | .268 | .319 |
| Apr | 35.6 | 0.041 | 0.48 | 0.38 | 0.90 | .015 | .171 | .135 | .320 |

[a]June 1977 values used.

[b]Average of October 1977 and December 1977 values.

[c]Average of January 1978 and March 1978 values.

[d]Average of July 1978 and September 1978 values.

Table 75. Nitrogen export from Plot H (9.6 cm/wk of treated wastewater) in outflowing water (well W23M used).

| Month | Outflow Volume (cm) | Concentration (mg/l) | | | | Mass Outflow (g N/m$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N | $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N |
| May 77 | 32.3 | .006 | 0.47 | 3.98 | 4.46 | .002 | .152 | 1.286 | 1.441 |
| Jun | 42.1 | .027 | 0.93 | 2.42 | 3.38 | .011 | .392 | 1.019 | 1.423 |
| Jul | 30.6 | .024 | 0.14 | 1.76 | 1.92 | .007 | .043 | .539 | .588 |
| Aug | 36.8 | .018 | 0.06 | 2.04 | 2.12 | .007 | .022 | .751 | .780 |
| Sep | 39.9 | .795 | 0.03 | 0.52 | 1.35 | .317 | .012 | .207 | .539 |
| Oct | 27.7 | .190 | 0.63 | 1.72 | 2.54 | .053 | .175 | .476 | .704 |
| Nov | 28.3 | .101[a] | 0.35[a] | 1.21[a] | 1.67[a] | .029 | .100 | .342 | .473 |
| Dec | 50.5 | .012 | 0.08 | 0.70 | 0.79 | .006 | .039 | .354 | .399 |
| Jan 78 | 44.2 | .008 | 0.04 | 0.69 | 0.74 | .004 | .018 | .305 | .327 |
| Feb | 48.1 | .011[b] | 0.02[b] | 1.97[b] | 2.00[b] | .005 | .011 | .948 | .962 |
| Mar | 25.1 | .014 | 0.01 | 3.24 | 3.26 | .004 | .002 | .813 | .818 |
| Apr | 39.3 | .024 | 0.22 | 1.35 | 1.59 | .009 | .084 | .531 | .625 |
| May | 37.6 | .009 | 0.30 | 0.54 | 0.85 | .003 | .113 | .203 | .320 |
| Jun | 32.8 | .010 | 0.06 | 1.60 | 1.67 | .003 | .020 | .525 | .548 |
| Jul | 25.9 | .073 | 0.07 | 1.62 | 1.76 | .019 | .017 | .420 | .456 |
| Aug | 22.0 | .062[c] | 0.07[c] | 1.60[c] | 1.73[c] | .014 | .015 | .352 | .381 |
| Sep | 36.5 | .050 | 0.07 | 1.57 | 1.69 | .018 | .025 | .573 | .617 |
| Oct | 40.5 | .018 | 0.12 | 0.70 | 0.84 | .007 | .050 | .284 | .340 |
| Nov | 36.2 | .008 | 0.12 | 0.88 | 1.10 | .003 | .076 | .319 | .398 |
| Dec | 40.4 | .056 | 0.20 | 0.45 | 0.71 | .023 | .081 | .182 | .287 |
| Jan 79 | 40.7 | .056 | 0.67 | 0.76 | 1.49 | .023 | .273 | .309 | .606 |
| Feb | 31.0 | .010 | 0.16 | 0.20 | 0.37 | .003 | .048 | .062 | .115 |
| Mar | 25.5 | .019 | 0.13 | 0.00 | 0.15 | .005 | .034 | .000 | .038 |
| Apr | 35.6 | .035 | 0.05 | 0.61 | 0.69 | .012 | .016 | .217 | .246 |

[a]Average of October 1977 and December 1977 values used.

[b]Average of January 1978 and March 1978 values used.

[c]Average of July 1978 and September 1978 values used.

Table 76. Nitrogen export from Plot C (4.4 cm/wk of fresh water) in outflowing water.

| Month | Outflow Volume (cm) | Concentration (mg/l) $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N | Mass Outflow (g $N/m^2$) $NO_3$+ $NO_2$ | $NH_3$ | Org N | Tot N |
|---|---|---|---|---|---|---|---|---|---|
| May 77 | 5.9 | .012 | .020 | 3.03 | 3.06 | .001 | .001 | .179 | .181 |
| Jun | 11.4 | .057 | .180 | 2.47 | 2.71 | .006 | .021 | .282 | .309 |
| Jul | 15.4 | .017 | .400 | 2.30 | 2.72 | .003 | .062 | .354 | .419 |
| Aug | 7.4 | .015 | .060 | 0.94 | 1.02 | .001 | .004 | .070 | .075 |
| Sep | 13.9 | .480 | .020 | 0.58 | 1.08 | .067 | .003 | .081 | .150 |
| Oct | 9.3 | .280 | .030 | 2.27 | 2.58 | .026 | .003 | .211 | .240 |
| Nov | 6.9 | .148[a] | .054[a] | 1.49[a] | 1.69[a] | .010 | .004 | .103 | .117 |
| Dec | 19.0 | .016 | .078 | 0.70 | 0.80 | .003 | .015 | .133 | .152 |
| Jan 78 | 22.0 | .004 | .080 | 1.38 | 1.46 | .001 | .018 | .304 | .321 |
| Feb | 22.0 | .012[b] | .080[b] | 1.19[b] | 1.28[b] | .003 | .018 | .262 | .282 |
| Mar | 19.9 | .019 | .080 | 1.00 | 1.10 | .004 | .016 | .199 | .219 |
| Apr | 15.0 | .036 | .827 | 1.02 | 1.38 | .005 | .124 | .153 | .207 |
| May | 16.3 | .011 | .140 | 1.40 | 1.55 | .002 | .023 | .228 | .253 |
| Jun | 8.4 | .007 | .097 | 0.65 | 0.78 | .001 | .008 | .055 | .066 |
| Jul | 3.9 | .064 | .113 | 0.88 | 1.06 | .002 | .004 | .034 | .041 |
| Aug | -13.1 | .063[c] | .098[c] | 1.95[c] | 2.11[c] | -.008 | -.013 | -.255 | -.276 |
| Sep | 2.1 | .061 | .083 | 3.02 | 3.16 | .001 | .002 | .063 | .066 |
| Oct | 9.6 | .026 | .141 | 0.42 | 0.59 | .002 | .014 | .040 | .057 |
| Nov | 8.7 | .009 | .376 | 1.35 | 1.74 | .001 | .033 | .117 | .151 |
| Dec | 15.0 | .047 | .129 | 0.64 | 0.81 | .007 | .019 | .096 | .122 |
| Jan 79 | 15.6 | .009 | .005 | 0.45 | 0.46 | .001 | .001 | .070 | .072 |
| Feb | 33.5 | .106 | .505 | 0.19 | 0.76 | .036 | .169 | .064 | .255 |
| Mar | 28.3 | .021 | .002 | 3.91 | 3.93 | .006 | .001 | 1.107 | 1.112 |
| Apr | 39.0 | .032 | .005 | 1.25 | 1.29 | .012 | .002 | .488 | .503 |

[a]Average of October 1977 and December 1977 values.

[b]Average of January 1978 and March 1978 values.

[c]Average of July 1978 and September 1978 values.

as a tracer for applied treated wastewater (see Hydrologic Considerations). Results of tracer studies indicated that applied treated wastewater passed both wells W3M and W23M. It was not possible to determine the relative proportions of applied water passing either well in Plot H, however. Results calculated separately for both of the wells will be presented henceforth in this chapter. Monthly outflows determined using well W3M are presented in Table 74. Monthly outflows determined using well W23M are presented in Table 75.

Nitrogen inputs, outputs, and flows within Plots H and C are summarized for the first (dry) year in Tables 77 and 78, respectively, and for the second (wet) year in Tables 79 and 80, respectively. Treated wastewater, fresh water, precipitation, and hydrologic export represent total nitrogen values ($NO_3^-$, $NO_2^-$, $NH_3$, and organic nitrogen). Nitrogen in bulk precipitation comprised only 3.14% of the known inputs to Plot H (wastewater plus precipitation) during the first year, and 8.11% during the second year. In Plot C, however, nitrogen in bulk precipitation comprised 26.85% of the measured inputs (fresh water plus precipitation) during the first year, and 23.08% of measured and estimated inputs (fresh water plus precipitation plus fixation) during the second year. The potential denitrification value provides an upper limit to the amount of nitrogen that could have been removed yearly by this process. As shown for both years in either Plot H or Plot C, greater than 100% of nitrogen inputs could potentially have been removed by denitrification.

The "observed net removal" values shown for Plot H in Tables 77 and 79 were derived by taking the difference between the treated wastewater input and the mass export in outflowing waters. Percent removal was then derived by taking the net removal value as a percentage of treated wastewater input. All values given in parentheses utilized the mass outflow data for well station W3M, located directly beneath the discharge pipe in Plot H. The values not in parentheses are for the well station W23M, located in the northwest corner of Plot H. As shown, there is only a slight difference between the values for W23M and the values for W3M. This indicates

Table 77. Nitrogen budget for the dry year in Plot H (9.6 cm/wk treated wastewater).

| Flows | Seasonal Budgets: Growing[a] Season (g N/m$^2$·season) | Seasonal Budgets: Dieback[b] (g N/m$^2$·season) | Yearly[c] Budget (g N/m$^2$·year) | % of Inputs |
|---|---|---|---|---|
| Inputs | | | | |
| Treated[d] Wastewater | 8.14 | 17.50 | 31.51 | 96.83 |
| Precipitation[e] | 0.40 | 0.53 | 1.03 | 3.17 |
| Fixation[f] | 0 | 0 | 0 | 0 |
| Totals | 8.54 | 18.03 | 32.54 | 100.00 |
| Outputs | | | | |
| Export[g] | | | | |
| (W3M) | (3.99) | (6.54) | (11.70) | (35.96) |
| W23M | 4.23 | 3.40 | 9.08 | 27.90 |
| Litter[h] | 4.09 | 3.23 | 10.09 | 31.01 |
| Above ground[i] live | 8.82 | -11.40 | 2.10 | 6.45 |
| Roots[j] | --- | -50.02 | --- | --- |
| Soil adsorption[k] | 0 | 0 | 0 | 0 |
| Potential[l] denitrification | 64.80 | 115.80 | 219.00 | 673.02 |
| Total | | | | >100.00 |
| Observed net removal[m] | | | | |
| (W3M) | (4.15) | (10.96) | (19.81) | |
| W23M | 3.91 | 14.10 | 22.43 | |
| % Removal[n] | | | | |
| (W3M) | (51.02) | (62.65) | (62.88) | |
| W23M | 48.01 | 80.55 | 71.19 | |

[a]The growing season is here defined as 4/25/77-8/11/77.

[b]The dieback period is here defined as 8/11/77-2/20/78.

[c]The yearly period is here defined as 4/25/77-4/15/78.

[d]Derived from values in Table 67.

Table 77. Footnotes (continued)

[e]Derived from values in Table 71.

[f]See text.

[g]Derived from values in Tables 74 and 75. Well W3M was located beneath the discharge pipe. Well W23M was located in the northwestern corner.

[h]From Table 72.

[i]From Table 72.

[j]From Table 73. No value available for 4/25/77-8/11/77.

[k]See text.

[l]From column studies. See text.

[m]Treated wastewater input minus export.

[n]Observed net removal as percentage of treated wastewater input.

Table 78. Nitrogen budget for the dry year in Plot C (4.4 cm/wk freshwater).

| Flows | Seasonal Budgets: Growing Season[a] (g N/m$^2$·season) | Seasonal Budgets: Dieback[b] (g N/m$^2$·season) | Yearly[c] Budget (g N/m$^2$·year) | % of Inputs |
|---|---|---|---|---|
| Inputs | | | | |
| Freshwater[d] | 0.94 | 1.43 | 2.80 | 73.11 |
| Precipitation[e] | 0.40 | 0.53 | 1.03 | 26.89 |
| Fixation[f] | 0 | 0 | 0 | 0 |
| Totals | 1.34 | 1.96 | 3.83 | 100.00 |
| Outputs | | | | |
| Export[g] W21M | 0.98 | 1.26 | 2.67 | 69.71 |
| Litter[h] | -1.83 | 2.94 | 7.94 | 207.31 |
| Aboveground[i] live | 5.86 | -9.12 | -0.38 | -9.92 |
| Roots[j] | --- | -19.30 | --- | --- |
| Soil[k] adsorption | 0 | 0 | 0 | 0 |
| Potential[l] denitrification | 200.90 | 359.00 | 678.90 | 17,725.85 |
| Totals | | | | >100.00 |

[a]The growing season is here defined as 4/25/77-8/11/77.
[b]The dieback period is here defined as 8/11/77-2/20/78.
[c]The yearly period is here defined as 4/25/77-4/15/78.
[d]Derived from values in Table 69.
[e]Derived from values in Table 71.
[f]See text.
[g]Derived from values in Table 76. Well W21M was located in the northwestern corner.
[h]From Table 72.
[i]From Table 72.
[j]From Table 73. No value available for 4/25/77-8/11/77.
[k]See text.
[l]From in situ studies. See text.

Table 79. Nitrogen budget for the wet year in Plot H (9.6 cm/wk treated wastewater).

| Flows | Seasonal Budgets: Growing[a] Season (g N/m$^2$ season) | Seasonal Budgets: Dieback[b] (g N/m$^2$ season) | Yearly[c] Budget (g N/m$^2$ year) | % of Inputs |
|---|---|---|---|---|
| Inputs | | | | |
| Treated[d] wastewater | 23.78 | 15.12 | 37.57 | 96.90 |
| Precipitation[e] | 0.74 | 0.34 | 1.20 | 3.10 |
| Fixation[f] | 0 | 0 | 0 | 0.00 |
| Totals | 24.52 | 15.46 | 38.77 | 100.00 |
| Outputs | | | | |
| Export[g] (W3M) | (4.33) | (1.50) | (5.48) | (14.13) |
| W23M | 2.95 | 1.75 | 4.35 | 11.22 |
| Litter[h] | -5.21 | -0.48 | -5.69[i] | -14.65 |
| Aboveground[j] live | 4.24 | -2.26 | 1.98[i] | 5.11 |
| Roots[k] | -20.34 | -2.04 | -22.38[i] | -57.73 |
| Soil adsorption[l] | 0 | 0 | 0 | 0 |
| Potential[m] denitrification | 93.60 | 91.20 | 219.00 | 564.87 |
| Total | | | | >100.00 |
| Observed net removal[n] | | | | |
| (W3M) | (19.45) | (13.62) | (32.09) | |
| W23M | 20.83 | 13.37 | 33.22 | |
| % Removal[o] | | | | |
| (W3M) | (81.81) | (90.05) | (85.42) | |
| W23M | 87.61 | 88.45 | 88.42 | |

[a]Growing season is here defined as 4/15/78-9/18/78.

[b]Dieback period is here defined as 9/18/78-2/17/79.

[c]The yearly period is here defined as 4/15/78-4/15/79.

[d]Derived from values in Table 67.

Table 79. (Footnotes continued).

[e]Derived from values in Table 71.

[f]See text.

[g]Derived from values in Tables 74 and 75. Well W3M is located beneath the discharge pipe. Well W23M is located in the northwestern corner.

[h]From Table 72. See i.

[i]These values are for 4/15/78-2/17/79 only.

[j]From Table 72. See i.

[k]From Table 73. See i.

[l]See text.

[m]From column studies. See text.

[n]Treated wastewater input minus export.

[o]Observed net removal as percentage of treated wastewater input.

Table 80. Nitrogen budget for the wet year in Plot C (4.4 cm/wk freshwater).

| Flows | Seasonal Budgets: Growing Season[a] (g N/m$^2$·season) | Seasonal Budgets: Dieback[b] (g N/m$^2$·season) | Yearly[c] Budget (g N/m$^2$·year) | % of Inputs |
|---|---|---|---|---|
| Inputs | | | | |
| Freshwater[d] | 1.45 | 0.74 | 2.11 | 23.06 |
| Precipitation[e] | 0.74 | 0.34 | 1.20 | 13.11 |
| Fixation[f] | 2.50 | 2.43 | 5.84 | 63.83 |
| Totals | 4.69 | 3.51 | 9.15 | 100.00 |
| Outputs | | | | |
| Export[g] W21M | 0.36 | 0.66 | 2.42 | 26.45 |
| Litter[h] | -9.49 | 2.14 | -7.35[i] | -80.33 |
| Aboveground[j] live | 6.85 | -6.04 | -0.81[i] | -8.85 |
| Roots[k] | -26.37 | 16.45 | -9.92[i] | -108.42 |
| Soil[l] adsorption | 0 | 0 | 0 | 0 |
| Potential[m] denitrification | 290.20 | 282.70 | 678.90 | 7419.67 |
| Total | | | | >100.00 |

[a]Growing season is here defined as 4/15/78-9/18/78.
[b]Dieback period is here defined as 9/18/78-2/17/79.
[c]The yearly period is here defined as 4/15/78-4/15/79.
[d]Derived from values in Table 69.
[e]Derived from values in Table 71.
[f]See text.
[g]Derived from values in Table 76. Well W21M was located in the northwestern corner.
[h]From Table 72. See i.
[i]These values are for 4/15/78-2/20/79 only.
[j]From Table 72.
[k]From Table 73.
[l]See text.
[m]From in situ studies. See text.

that considerable removal of nitrogen from applied treated wastewater had been occurring even if most of the applied water flowed out directly beneath the application pipe.

Less total nitrogen was exported from Plot H during the second year than during the first year. This it is presumed was due primarily to the effects of a lower water table during the first year, as compared with the presence of standing water during the second year. Considerable removal of applied total nitrogen occurred in Plot H even during the dry year, however. A total of 71.19% of the applied total N was removed during the first year, while 88.42% of the applied total N was removed during the second year in this plot.

Shown in Fig. 100 are the amounts of nitrate plus nitrite, ammonium, and organic nitrogen that were applied to Plot H in treated wastewater during the growing season and dieback period of each year. Also shown in Fig. 100 are the export of nitrate plus nitrite, ammonium, and organic nitrogen in outflowing waters from Plot H for each time period. Mass outflow values in parentheses were computed using the data for well W3M, which was located in the center of Plot H directly beneath the discharge pipe; mass outflow values not in parentheses were computed using data for well W23M, which was located in the northwest corner of Plot H. Somewhat larger outflows of all nitrogen forms were computed for Plot H by using the center well (W3M) data than by using northwest corner well (W23M) data for the dieback period of the first year. Also, a larger outflow value for ammonium was obtained using the center well (W3M) data for the growing season of the second year than was obtained using the northwest corner well (W23M) for this period.

Figure 101 exhibits mass inflows of bound nitrogen species in applied fresh water and mass outflows of those species in exported water for Plot C. The same growing seasons and dieback periods are depicted as for the treated wastewater plot (see Fig. 100). The outflow values were computed using data for well W21M, located in

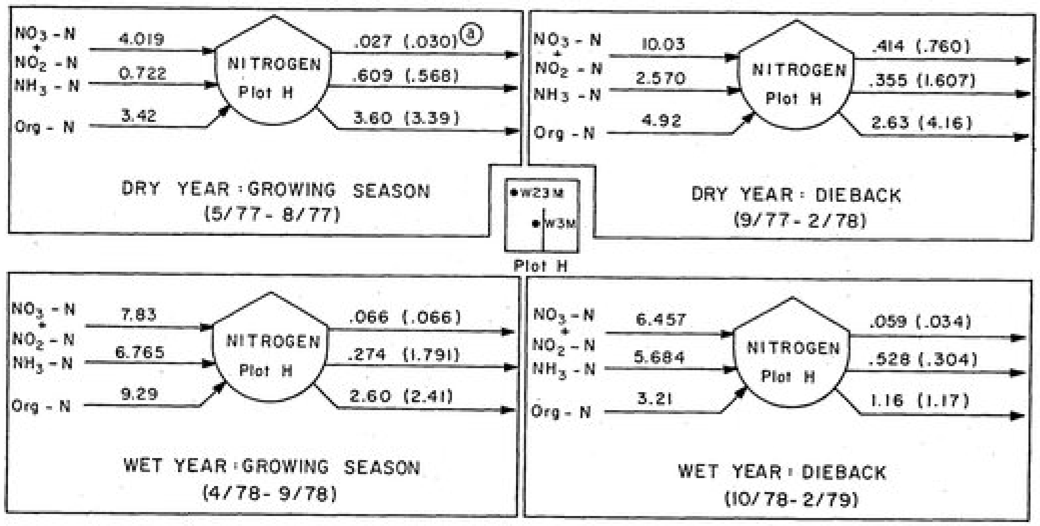



Figure 100. Treated wastewater loading and hydrologic export of nitrogen in Plot H (9.6 cm/wk of treated wastewater). All values in g $N/m^2$ per time period.

(a) All numbers in parentheses utilize mass outflow values derived for well W3M, located in the center of Plot H directly beneath the treated wastewater discharge pipe. These values were derived in Table 74. All other numbers utilize mass outflow values derived for well W23M, located in the northwest corner of Plot H. These values were derived in Table 75.

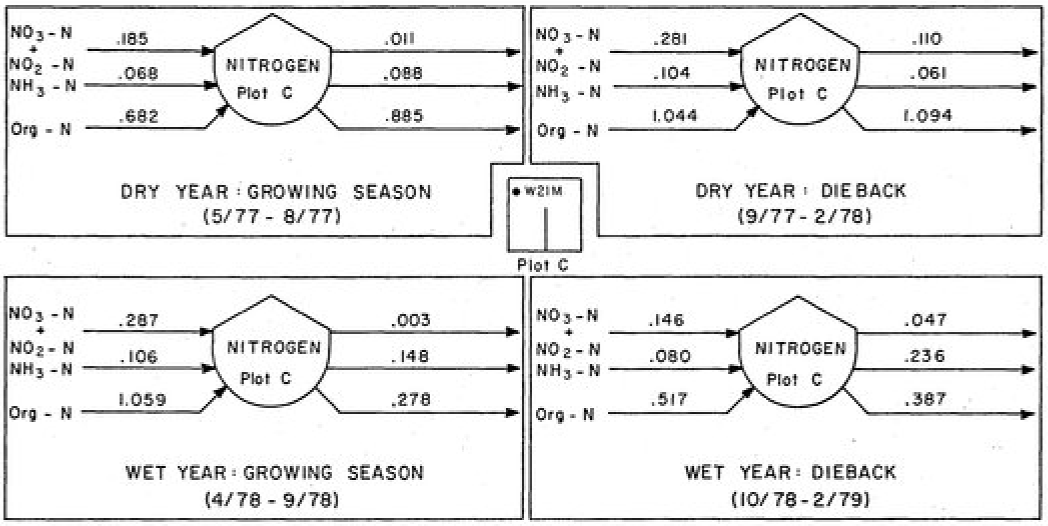



Figure 101. Freshwater loading and hydrologic export of nitrogen from Plot C (4.4 cm/wk of fresh water). All values in g N/$m^2$ per time period.

the northwest corner of Plot C. Mass outflow values for nitrate plus nitrite nitrogen were consistently lower than mass inflow values for applied fresh water. Mass outflow values for ammonia nitrogen in the control plot were slightly higher than the fresh-water aplication values on all occasions except for the dieback period of the first year. Organic nitrogen export from the control plot was slightly greater than the amount applied in fresh water during the growing season and dieback period of the first year. However, export was smaller than the amount applied in fresh water to the control plot during the growing season and dieback period of the second (wet) year.

Mass application and hydrologic export of bound nitrogen species for Plots H and C are given for each of the two entire years in Fig. 102. Considerable net removal of inorganic nitrogen species occurred in Plot H during both years, as computed by either the center well (W3M) data or the northwest corner well (W23M) data. Significant net removal of organic nitrogen occurred during the wet year for Plot H, but not for the dry year. Application and export of ammoniacal and organic nitrogen were roughly equivalent in Plot C during both years; perhaps a slightly greater amount was exported than was applied during these two years. Applied nitrate plus nitrite nitrogen was apparently removed by Plot C during both years, as it was in Plot H during both years.

Using the application and outflow mass values summarized in Figs. 100 and 102 for Plot H, percentage removal of the measured forms of bound nitrogen were computed for this plot during selected time intervals. Results are shown in Table 81. Values in parentheses were derived from the data for center well W3M; all other values were derived from the data for northwest corner well W23M. Efficiency of nitrate plus nitrite removal remained extremely high throughout the entire study period. Ammoniacal nitrogen removal was least efficient during the growing season of the dry year, but was highly efficient throughout the wet year. Both organic nitrogen removal and total nitrogen removal were least efficient during the growing season of the dry year, and were more efficient during the wet year than during the dry year. Overall, the

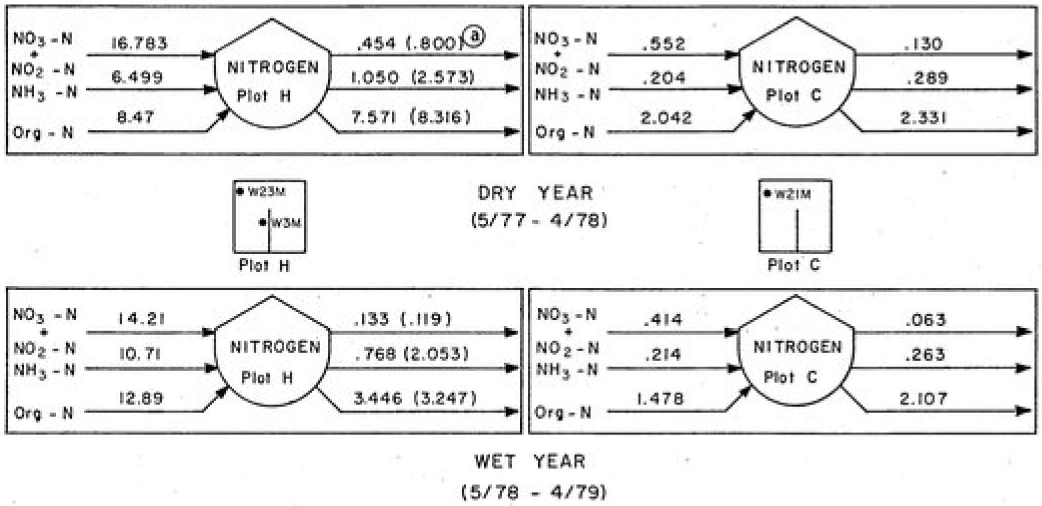



Figure 102. Treated wastewater and freshwater loadings and observed hydrologic export of nitrogen from Plot H (9.6 cm/wk of treated wastewater) and Plot C (4.4 cm/wk of fresh water) during wet and dry years. All values in g $N/m^2$ per time period.

ⓐ All numbers in parentheses utilize mass outflow values derived for well W3M, located in the center of Plot H directly beneath the treated wastewater discharge pipe. These values were derived in Table 74. All other numbers utilize mass outflow values derived for well W23M, located in the northwest corner of Plot H. These values were derived in Table 75.

Table 81. Percentage removal of nitrogen from treated wastewater applied to Plot H (9.6 cm/wk).

| Time Period | Percent Removal $NO_3$-N+ $NO_2$-N | $NH_3$-N | Org-N | Tot-N |
|---|---|---|---|---|
| Dry Year: | | | | |
| Growing season 5/1/77-8/31/77 | 99.33 (99.25)[a] | 15.65 (21.33) | -5.26 (0.88) | 48.01 (51.02) |
| Dieback 9/1/77-2/20/78 | 95.87 (92.42) | 86.19 (37.47) | 46.54 (15.45) | 80.55 (62.65) |
| Entire year 5/1/77-4/30/78 | 97.29 (95.23) | 83.84 (60.41) | 10.61 (1.82) | 71.19 (62.88) |
| Wet Year: | | | | |
| Growing season 4/1/78-9/30/78 | 99.16 (99.16) | 95.95 (73.53) | 72.01 (74.06) | 87.61 (81.81) |
| Dieback 10/1/78-2/28/79 | 99.09 (99.47) | 90.71 (94.65) | 63.86 (63.55) | 88.45 (90.05) |
| Entire Year 5/1/77-4/30/79 | 99.06 (99.16) | 92.83 (80.83) | 73.27 (74.81) | 88.42 (85.42) |

[a]All numbers in parentheses utilize mass outflow values derived for well W3M, located in the center of Plot H directly beneath the treated wastewater discharge pipe. These values were derived in Table 74. All other numbers utilize mass outflow values derived for well W23M, located in the northwest corner of Plot H. These values were derived in Table 75.

Clermont marsh appears to provide very efficient removal of inorganic nitrogen applied in treated wastewater, especially during wet periods.

## Total Organic Carbon, Suspended Solids, and Pathogenic Quality

### Total Organic Carbon

Total organic carbon (TOC) samples were collected from May 1977 to December 1978. TOC was measured rather than biochemical oxygen demand (BOD) because the test was faster, more accurate, and more representative of the actual organic carbon content of the water sample. During the entire period that TOC was measured there were no clear trends observed among the wells, marsh water, and channel stations sampled. In particular, no common trend was seen between any two of the northwest corner wells (W21M, W22M, W23M, and W24M) in the plots. Similarly, no common trend was evident between any two of the wells in the "natural" areas of the marsh (wells W1M, W2M, and W8M). TOC values for sampling stations C-1, C-3, and HIW usually all fell within the 10-30 mg/l range.

Since the Clermont Sewage Treatment Plant achieved very good BOD removal, periodically 98% or better but always above 90%, there was no reason to expect any problem with organic carbon loading in the marsh. Quite often the TOC value for the applied treated wastewater was lower than the TOC value measured in the natural marsh or in the Palatlakaha River. It was therefore concluded that when a good quality secondarily treated wastewater (better than 90% BOD removal) is applied to a marsh similar to the experimental site, no problems associated with organic carbon will be present.

### Suspended Solids

Suspended solids (SS) samples were collected from May 1977 to December 1978. During the entire period of SS collection, there were no trends observed among the wells, marsh water, and channel for lake stations sampled.

SS concentrations in a marsh depend on several factors. Particulate matter enters a marsh as runoff from surrounding upland, litterfall of particulate matter from the emergent vegetation, and transport via channel tide or wave action. In the Clermont marsh the suspended solids in the treated water applied to the test plots consisted largely of algal cells and debris due to the long detention time in the treatment plant chlorination pond and percolation pond (approximately 10 days).

Nute (1977) determined SS in the inflow, standing water, and outflow from a marsh treatement system and concluded that SS were an insufficient test to determine the nature of the particulate matter in the water. The SS in discharge from the marsh consisted of unsettled humus. In some cases the marsh appeared to be a sink for suspended matter, and in other cases it appeared to be a net exporter of SS.

SS values in the wells ranged from 2 mg/l to as high as 158 mg/l. The high variability was probably a function of the way the well was pumped, the age of the well, and the degree of sampling disturbance. In the process of well sampling it was necessary to walk up close to the well. This may have loosened peat surrounding the well screen and caused fine sediment to enter the well through the screen. Although care was taken to minimize this effect, it was impossible to eliminate completely, especially as the project progressed and the peat became more trampled. Generally, the SS values in the wells were in the 20-40 mg/l range. The SS values in the standing water were usually in the 15-30 mg/l range, with the SS values in the Palatlakaha River in the 10-20 mg/l range. At no time in the study were there any problems observed in the test plots that could have been associated with SS in the applied treated wastewater.

Pathogenic Quality

The two paremeters of interest in this category are bacteria and viruses. Historically, fecal coliforms have been an indication of pathogenic contamination of water. Unfortunately, past research has not been definitive concerning coliform concentrations in a wetlands situation. In a marsh study where the coliforms were measured in the water as it passed through the swamp (Kadlec and Kadlec 1978), the total coliforms were found to increase from 1300/100 ml at the input site to 18,000/100 ml at the output. The fecal coliforms decreased from 148/100 ml to 50/100 ml, and the fecal streptococci increased from 145/100 ml to 910/100 ml. Apparently, phenomena were occurring for which there was no simple explanation. The researchers determined an increasing ratio of fecal streptococci to fecal coliform as the water proceeded from input to output. This is surprising, in view of the fact that a high ratio is indicative of human pollution.

Odum et al. (1974) found that the organic soil in a cypress dome effectively filtered out nearly all of the applied coliforms. Similar reductions were observed by Stanlik (1976) in a study of the treatment of secondary effluent using vertical flow through a peat bed. This study showed that 99.99% of the coliform bacteria were prevented from reaching groundwater, and that at no time over a two-year period did any fecal coliform reach groundwater. One can conclude that the soil substrate presents a rather attractive attachment site that effectively removes coliforms which contact it.

Virus contamination is a relatively new concern that has become more heavily researched with the advent of better analytical procedures. Unfortunately, the cost per virus analysis is approximately $500, with no assurance of exactly what is being measured. Reproducible results are very difficult to achieve due to sample collection and concentration techniques. Fortunately, some research has been conducted by virologists that indicates there is only a slight need for concern. Wellings (1975) conducted an extensive study of a cypress wetland receiving treated wastewater and found very few viruses in the input water and no virus contamination in the wetland receiving water body. Bitton et al. (1975) determined from laboratory studies that the sandy clay loam that underlined certain cypress domes adsorbed 99% of added polio virus. Further, adsorbed virus could not significantly be eluted with rain water. Dubois et al. (1976) also determined that clay soils were excellent adsorbers for viruses.

Throughout this study coliforms and viruses were not analyzed due to the high cost involved and the very high quality of the treated wastewater being applied to the test plots. No pathogenic contamination difficulties were reported in the literature for wetland disposal of secondarily treated wastewater, and no health problems were observed in this study even though the researchers came in intimate contact with the applied treated wastewater for over a two-year period.

## ABILITY OF THE MARSH TO ASSIMILATE PHOSPHORUS AND NITROGEN FROM SECONDARILY TREATED WASTEWATER

### Comparison with Other Research

The results of this study verified that the freshwater marsh at Clermont, when managed properly, is capable of removing nitrogen and phosphorus from treated wastewater. These results are consistent with the results of some other experiments in wetlands throughout Florida and other parts of the country. Several of these studies were discussed earlier, in the Overview section of this report. The highly organic substrate of the Clermont marsh may be a key factor in the ability of this wetland to renovate treated wastewater (Whigham and Bayley in press).

Results for surface water phosphorus content in this study were similar to results of a phosphorus assimilation study conducted in the Everglades. In that study, Steward and Ornes (1975a) found eventual enrichment of phosphorus in the surface waters of enclosed plots of sawgrass (*Cladium jamaicense* Crantz) receiving weekly additions of phosphorus. The study in the Clermont marsh also found eventual enrichment of phosphorus in surface waters within experimental plots. However, a marked reduction in the phosphorus content of applied water was evident once such water had been forced through the peat.

Kadlec et al. (1979) recently reported on the results of the full-scale application of 65 million gallons of secondarily treated wastewater at a rate of 1 mgd to a peatland near Houghton Lake, Michigan, in the summer of 1978. The water was distributed evenly across the width of the peatland through small gated openings in a discharge pipe. Each gate discharged approximately 16 gpm. Average water depth was 10-20 cm above the marsh surface. Roughly 90% of both nitrogen and phosphorus applied to the peatland was removed within 100 m of the discharge pipe. Plant growth and chlorophyll content were increased within 30 m of the discharge pipe.

## Model of the Study System

A model of the Clermont experimental marsh system is given for wet and dry years for Plots H (9.6 cm/wk treated wastewater) and C (4.4 cm/wk fresh water) in Figs. 103-106. A description of the symbols used in these models is given in the Appendix. Some of the flows of nitrogen and phosphorus are not directly coupled to one another (e.g., denitrification and adsorption of phosphorus by peat), while others transfer these two nutrients in a relatively constant ratio (e.g., nutrient assimilation by plants). Nutrients bound up in live biomass are deposited as aboveground dead biomass (litter) or belowground dead biomass (included in the "roots" compartment in the diagram). Part of the nitrogen and phosphorus are released to the waters of the marsh as decomposition proceeds. However, a certain fraction of each is so resistant to decomposition that it remains bound up in the newly deposited peat. Eventually, dead biomass may even assimilate additional nitrogen, due to microbial acitivity.

By far the most significant pathways for nutrient removal appeared to be: 1. release of inorganic nitrogen to the atmosphere by nitrification/denitrification, and 2. absorption of phosphorus by the peat soil complex. Deposition of new peat trapped an undetermined but possibly significant quantity of applied nitrogen.

## General Considerations

### Loading Rate

The results of this study indicated that the application of 9.6 cm/wk (3.8 in./wk) of treated wastewater could be applied to

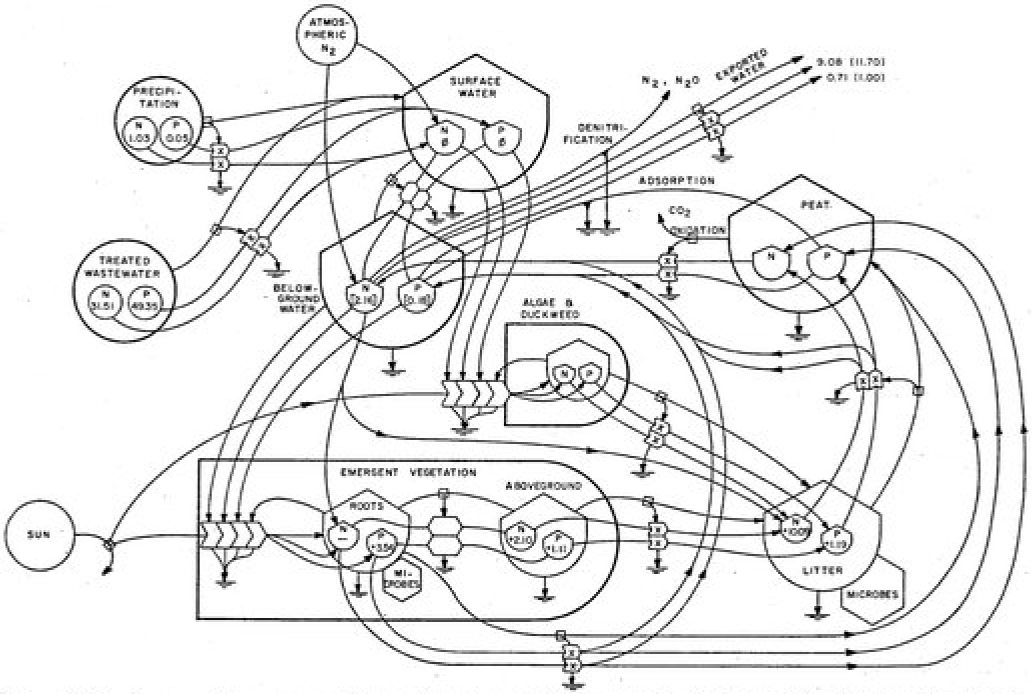



Figure 103. Summary of sources and changes in storage of nitrogen and phosphorus (in g/m$^2$·year) in Plot H (9.6 cm/wk of treated wastewater) during the "dry" year. Bracketed values are average concentrations (in mg/l). Export values in parentheses utilize center well W3M data (assumes vertical outflow); unparenthesized outflow values utilize corner well W23M data (assumes lateral outflow). See Appendix for a description of symbols.

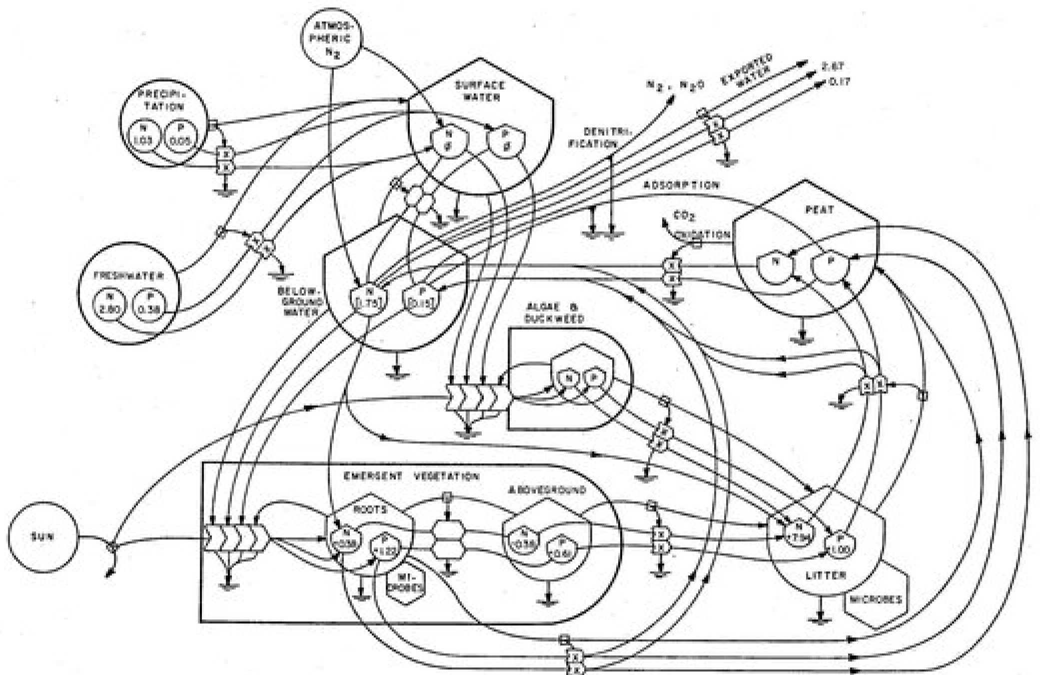



Figure 104. Summary of sources and changes in storage of nitrogen and phosphorus (in g/m$^2$·year) in Plot C (4.4 cm/wk of fresh water) during the "dry" year. Bracketed values are average concentrations (in mg/1). See Appendix for a description of symbols.

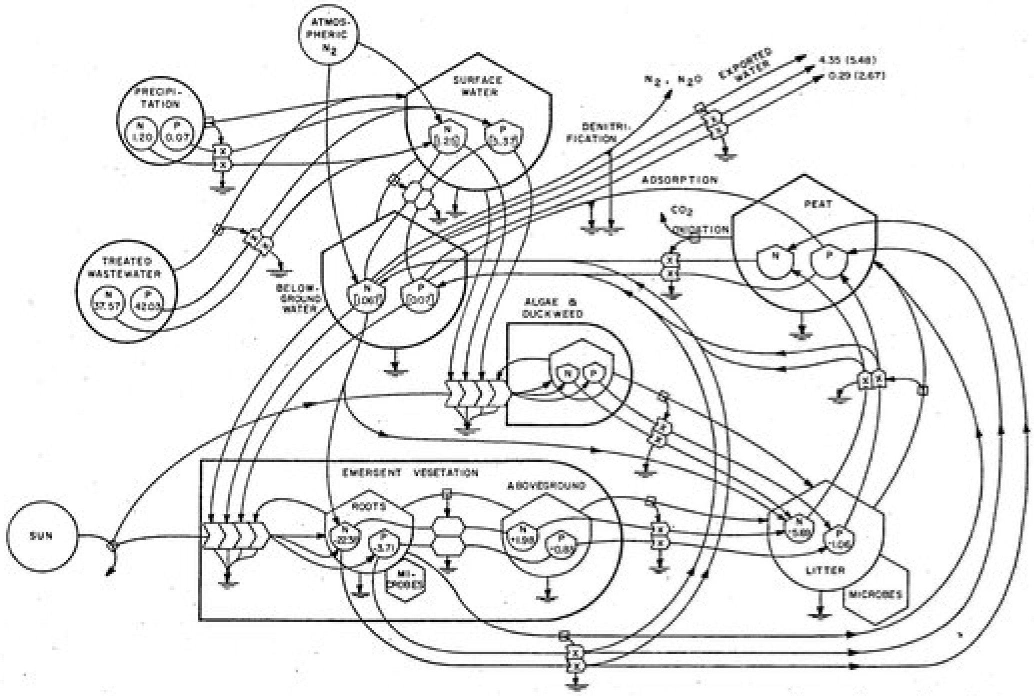



Figure 105. Summary of sources and changes in storage of nitrogen and phosphorus (in g/m$^2$·year) in Plot H (9.6 cm/wk of treated wastewater) during the "wet" year. Bracketed values are average concentrations (in mg/l). Export values in parentheses utilize center well W3M data (assumes vertical outflow); unparenthesized outflow values utilize corner well W23M data (assumes lateral outflow). See Appendix for a description of symbols.

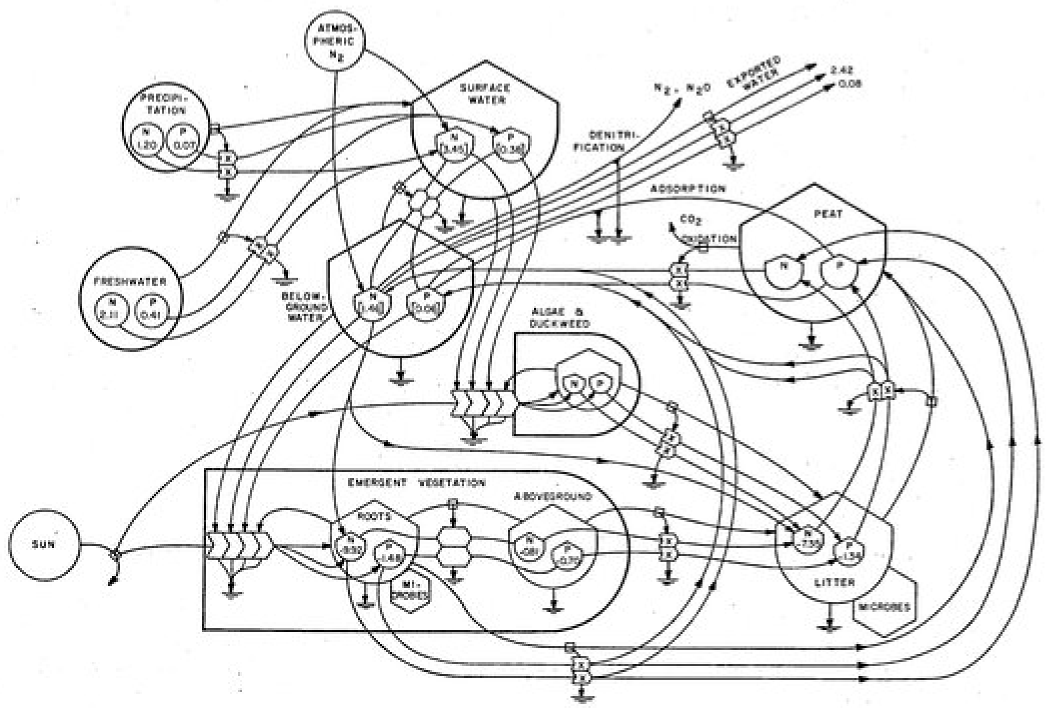



Figure 106. Summary of sources and changes in storage of nitrogen and phosphorus (in g/m$^2$·year) in Plot C (4.4 cm/wk of fresh water) during the "wet" year. Bracketed values are average concentrations (in mg/l). See Appendix for a description of symbols.

the Clermont freshwater marsh with very high removal of phosphorus (97%) and inorganic nitrogen (95%) occurring during the first two years. It has been established by past studies that suspended solids in treated wastewater applied to a marsh were completely removed due to the very large surface area, and therefore good settling characteristic of the wetland. It has also been established that pathogens present no problem when good quality secondarily treated wastewater is applied to a marsh. The TOC in the treated wastewater of this study was approximately equal to the TOC in the standing water of the marsh and therefore had little effect on the marsh itself.

The 9.6 cm/wk loading rate was found to have a slight impact on the marsh ecosystem, particularly during the first (dry) year. Semiwoody plants such as marsh hibiscus were found to grow rapidly near the distribution pipe during the first year, substantially more so than in the rest of the enclosed test plot. Total biomass was also found to be greater near the distribution pipe during the dry year. However, none of these observations indicated that the marsh system was being grossly affected. During the second, wet year there was no significant difference in the biomass found near the application pipe in the high rate loading test plot as compared to the area further away from the pipe in that plot. However, there was an increase in algal biomass near the distribution pipe, with a similar increase in duckweed (Lemna sp.) near the pipe. Less of this effect was noted for the medium-rate loading plot (3.7 cm/wk) or the low-rate loading plot (1.5 cm/wk).

The increased growth of hibiscus during the dry year and of algae and duckweed during the wet year were in fact beneficial changes so far as nutrient removal was concerned. As a semiwoody plant, hibiscus is slower to decompose than herbaceous plants. Thus nutrients tied up in senescent hibiscus will be trapped for a longer period before release to marsh waters. The net effect of slower decomposition would be the increased deposition of nutrients as new peat. Algae and duckweed near treated wastewater distribution pipes served to trap some nutrients present in marsh waters by their continued growth and senescence, followed by sinking to the marsh peat surface as particulate matter. At the marsh peat surface, carbon in such particulate matter could serve as an energy source for denitrification, enhancing the rate of that nitrogen removal mechanism.

Since it is standard engineering practice to design a system with a factor of safety, it is recommended that the prototype treated wastewater treatment system to be adopted by the city of Clermont utilize the loading rate of 3.8 cm/wk (1.5 in./wk). The results of this study indicate that there will be acceptably slight changes in the marsh ecosystem with this loading and that nitrogen and phosphorus removal will be good enough to reduce the nitrogen and phosphorus in the exported groundwater to background levels.

## Application System

It is recommended that the marsh treatment system adopted be designed in such a manner that the applied treated wastewater is forced to pass through the peat soil into the underlying sand aquifer to insure maximal removal of phosphorus. Nitrogen was effectively removed to background levels in the surface water, so it is possible that impoundment is not necessary for effective nitrogen removal.

Many reactions occurring in the marsh are of the first order type, which means that higher applied concentrations of nitrogen and phosphorus could result in faster degradation. There are many different possible modes of treated wastewater effluent application. It might be very beneficial to apply the treated wastewater periodically rather than continuously, which would then result in a faster rate of degradation. A sufficient "rest period" between applications would be necessary to insure that background levels of nutrients were reached. In this study the treated wastewater was applied once per week during a 24-hour period, with the marsh "resting" for six days before the next application. A similar application procedure is recommended for the prototype system, although several other procedures might be effective. Due to the high rate of evapotranspiration in the marsh during daylight hours in the summer, it may be possible to apply the treated wastewater during the daylight hours once per week and have better removal compared to a 24-hour application time with a six-day rest. Evapotranspiration would tend to concentrate the nutrients in applied waters, which could result in faster removal. It is also very possible that a uniform application during the daylight hours of each day would result in effective nutrient removal in an impounded marsh. It is recommended that the ultimate design for the application of the treated wastewater be of such a nature that various application procedures can be attempted in order to determine the one that presents the fewest operational problems and is the most effecient.

In this study the treated wastewater was applied by jetting it through small holes in PVC pipes in a downward direction onto the marsh. This system was adopted in order to minimize evaporation so that a hydraulic mass balance could more easily be constructed. The prototype treatment system need not be designed in the same configuration; nevertheless, it is important that relatively uniform distribution be attained throughout the entire impounded marsh. When there is standing water in the marsh it is easier to attain uniform distribution because the applied treated wastewater will mix with the standing water. The results of the chloride tracer experiment in this study indicated that the applied wastewater did reach the far corners of the test plots, even under dry conditions; however, it was impossible to determine exactly how much flow reached these far corners. It is therefore recommended that every attempt be made to ensure uniform distribution in the area of application, particularly when the marsh is in a dry cycle.

### Fluctuating Water Table

The standing water in the test plots was observed to be primarily a function of the lake water elevation, which in turn was controlled mainly by the elevation of the downstream dam and the amount of rainfall. The natural marsh undergoes structural changes depending on whether or not standing water is present. The relative dominance of different plant species is altered during the dry phase as compared to the wet phase. Long dry periods result in substantial decomposition of peat, with the organic-matter being lost to the atmosphere as carbon dioxide. Denitrification may proceed fastest when the water table is near the surface of the peat. It was fortunate that a relatively dry period was observed during the first year of this study, and a wetter period was observed during the second year of the study. This enabled the comparison of the different phenomena that occurred under wet and dry conditions. Buildup of new peat in wetter years raises the average elevation of the peat surface only slightly over a period of decades. There would be no great change in the proportion of time the marshland was inundated as opposed to being dry due to peat buildup alone. Data presented earlier in this report (see Figs. 15 and 16) showed the water surface was above the present surface of the peat in the experimental marsh roughly 80% of the time over a twenty-year period.

Prototype Marsh Similarities as Compared to the Experimental Marsh

The prototype marsh treatment system proposed by the city of Clermont is tentatively planned in an area south of SR 50. It is important to determine whether this proposed site will have nutrient removal characteristics similar to the marsh used in this study. The similarity of any two marsh systems in their ability to assimilate nutrients from treated wastewater will depend on several factors. The most important of these are: 1. depth of peat; 2. chemical composition of the peat; and 3. plant community. The depth of peat indicates how much substrate is available for chemical adsorption and microbial activity, both important for nutrient removal. The specific plant species present in the marsh during the growing season will influence long-term retention of nutrients assimilated in biomass. Certain species may also be more stimulatory of desirable microbial activity (such as denitrification) in the substrate, their root tissue providing energy or favorably regulating the chemical environment of the peat where such microbes are living. Oxygen content, pH, and redox potential of interstitial peat waters can all be influenced by plant growth and subsequent root decay.

Peat is formed through the long-term interaction of senescent and living plants with the water in which they are submersed. Since similar vegetation is present in the experimental marsh adjacent to the sewage treatment plant and in the marshland south of SR 50, then similar composition of peat would be expected for both marshes. Since both marshes are part of the same wetland area, being artificially divided by SR 50 and the channelized Palatlakaha River, it is expected that nutrient removal characteristics will be very similar if not identical.

Nutrient Export

Nitrogen and phosphorus in applied treated wastewater were found in this study to be reduced nearly to background levels. This has two important ramifications concerning the use of this marsh for tertiary treatment. First, significant removal of total nitrogen and total phosphorus occurred. Second, the ratios of organic nitrogen to total nitrogen and of organic phosphorus to total phosphorus both increased as the applied treated wastewater passed through the marsh system. The export of organic forms of nitrogen and phosphorus to lakes is more desirable than the export of inorganic forms of these nutrients. The organic forms are much less easily assimilated by algae and aquatic weeds (e.g., Hyacinth) than are the inorganic forms. Whether the marsh was dry or wet, the bulk of the nitrogen and phosphorus exported from the high-rate loading plot was bound in organic form. Eighty-three percent of the total nitrogen exported during the dry year from the high-rate loading plot was in organic form, and 61% of the exported phosphorus was in organic form during that year. During the wet year, 79% of the total exported nitrogen and 66% of the total exported phosphorus were in organic form. These values assume that most of the applied treated wastewater flowed out laterally past northwest corner well W23M in Plot H. Percentages of organic to total nitrogen and phosphorus applied to and exported from Plots H and C are summarized in Table 82. While inorganic forms of nitrogen and phosphorus predominate in applied treated wastewater, organic forms predominate in exported waters.

Another parameter reflecting the water quality changes that occurred as the applied treated wastewater passed through the marsh system is the molar nitrogen to phosphorus ratio. The ratio of average total nitrogen to average total phosphorus in applied treated wastewater was 1.41:1 during the dry year and 1.98:1 during the wet year. The values observed for outflowing waters in Plot H were 28.3:1 for the dry year and 33.2:1 for the wet year, using data for the northwest corner well of that plot. These are similar to the values for the adjacent channel. The low N:P ratio of the surface waters of Plot H during wet periods indicated that phosphorus was not limiting to growth in these standing waters. The average natural N:P ratio of surface waters in the marsh was 16.6:1, while in Plot H the average value was 0.33:1 near the distribution pipe and 0.54:1 near the perimeter. Results of N:P ratio calculations are shown in Table 83. Reduction in the phosphorus content of the applied treated wastewater would bring its nitrogen to phosphorus ratio closer to the natural level of marsh waters. This might result in fewer structural changes in the marsh. Specifically, less growth of algae and duckweed in the marsh might result if less phosphorus were present in applied treated wastewater. Such a reduction would probably not affect the efficiency of nitrogen removal by denitrification, since the microbes responsible for denitrification are not generally limited by phosphorus.

## Summary and Conclusions

1. Outflow of water from the experimental plots was usually a large percentage of the applied fresh water or secondarily treated wastewater, depending on the time of year and the accompanying rate of evapotransporation.
2. The application of wastewater had no major effect on the storage of water in the peat soil within the plots. The water

Table 82. Organic N:Total N and Organic P:Total P ratios for applied treated wastewater, freshwater, and exported water from Plots H (9.6 cm/wk treated wastewater) and C (4.4 cm/wk freshwater).

| | Plot C | | Plot H | | |
|---|---|---|---|---|---|
| | Applied[a] Freshwater | Exported[b] W21M | Applied[c] Treated Wastewater | Exported (W3M)[d] | Exported W23M[d] |
| Organic N:Total N (as %) | | | | | |
| Dry year | 72.98 | 84.76 | 26.68 | (74.14) | 83.43 |
| Wet year | 70.18 | 86.60 | 34.09 | (59.92) | 79.27 |
| Organic P:Total P (as %) | | | | | |
| Dry year | 48.00 | 69.87 | 42.05 | (42.17) | 61.38 |
| Wet year | 56.59 | 72.62 | 38.78 | (67.54) | 66.14 |

[a]Derived from values in Tables 36 and 69.

[b]Derived from values in Tables 39 and 76.

[c]Derived from values in Tables 35 and 67.

[d]All numbers in parentheses utilize mass outflow values derived for well W3M, located in the center of Plot H directly beneath the treated wastewater discharge pipe. These values were derived in Tables 38 and 74. All other numbers utilize mass outflow values derived for well W23M, located in the northwest corner of Plot H. These values were derived in Tables 38 and 75.

Table 83. Average molar total N:total P ratios for treated wastewater, exported water from the high rate loading plot (Plot H: 9.6 cm/wk treated wastewater), surface water in the high rate loading plot, natural marsh surface, and adjacent channel waters.

| | N:P ratio (as moles Total N:moles total P) | | | | | | |
|---|---|---|---|---|---|---|---|
| Time Periods | Treated Wastewater[a] | Plot H[b] Export | | Plot H[c] Surface | | Natural[d] Marsh Surface | Adjacent[e] Channel |
| | | (W3M) | W23M | H-I | H-O | | |
| Dry Year | 1.41 | (25.89) | 28.29 | --- | --- | --- | 26.31 |
| Wet Year | 1.98 | (4.54) | 33.19 | 0.33 | 0.54 | 16.59 | 26.20 |

[a]Derived from values given in Tables 35 and 67.

[b]All numbers in parentheses utilize mass outflow values derived for well W3M, located in the center of Plot H directly beneath the treated wastewater discharge pipe. These values were derived in Tables 38 and 74. All other numbers utilize mass outflow values derived for well W23M, located in the northwest corner of Plot H. These values were derived in Tables 38 and 75.

[c]Derived from averages of the concentrations illustrated in Figs. 39 and 89 for the periods of standing water. H-I was a composite of samples collected directly beneath the wastewater discharge pipe in Plot H. H-O was a composite of samples collected near the inside perimeter of Plot H.

[d]Derived from averages of the concentrations illustrated in Figs. 39 and 89 for the periods of standing water. Sampling station N was located north of the experimental plots.

[e]Derived from averages of concentrations for station C-4, illustrated in Figs. 41 and 85 for total nitrogen.

table height in the plots and in the adjacent marsh was controlled by evapotransporation, rain inputs, and adjacent lake levels.

3. Application of treated wastewater did not significantly increase the phosphorus concentration measured in the medium and deep wells within the experimental plots as compared to the levels found in background control wells. All corner medium depth wells within the experimental plots exhibited phosphorus concentrations approximately 97% less than the concentrations in applied treated wastewater.
4. A phosphorus mass balance indicated that only a small amount of the phosphorus applied to Plot H (approximately 3%) was exported by groundwater from the plot during the study. The average two-year loading rate for Plot H was 9.6 cm/wk of treated wastewater. The remainder of the phosphorus appears to have been stored in the peat soil complex.
5. A very small portion of the applied phosphorus (a few percent) was stored in the aboveground live plants and litter during the first year.
6. Harvesting at peak standing crop would remove at best approximately 10% of the phosphorus applied during the growing season. However, harvesting would undoubtedly have a severe impact on the marsh system and is not recommended.
7. Application of treated wastewater did not significantly increase the nitrogen concentration measured in the medium and deep wells within the experimental plots as compared to the levels found in background control wells.
8. A nitrogen mass balance indicated that 98.5% of the nitrate plus nitrite nitrogen applied in the treated wastewater to Plot H was removed by the marsh system during the study; only 1.5% was exported. A mass balance for ammonium indicated 88% removal. A mass balance for organic nitrogen indicated 43% removal.
9. Belowground biomass (live and dead roots) acted as a sink for nitrogen in both Plots H and C during the growing season of the first year (dry year). The average two-year loading rate for

Plot C was 4.4 cm/wk of freshwater. Between the first and second year (wet year) there was a net loss from this component for Plot H. Some of this loss may have been accounted for by production of new peat.

10. Litter (aboveground dead biomass) acted as a sink for nitrogen in Plot M (3.7 cm/wk of treated wastewater) over the two-year study.
11. During the first year, the net annual aboveground production of emergent plants measured in Plot H was significantly higher than Plot L (1.5 cm/wk of treated wastewater) or Plot C. During the first year, there was no significant difference detected between the production of Plot C and Plot L. During the second year, there was no significant difference detected in the biomass production among Plots H, M and C. (Plot L was not sampled for production during the second year.)
12. During the growing season of the first year, there was a significantly higher belowground standing crop (live and dead roots) under the high loading rate (Plot H) as compared to the freshwater control (Plot C). During the second year, there was no significant difference.
13. Plot M had a higher rate of buildup of litter than Plot H. This indicates that the higher rate of treated wastewater application may not result in a higher rate of new peat production. Different rates of decomposition could be the cause of this phenomenon.

In conclusion, three main findings support the view that the marsh system has functioned successfully as a tertiary treatment facility during the two years of treated wastewater application: 1. The phosphorus and nitrogen concentrations in the renovated treated wastewater effluent leaving the low-, medium-, and high-rate plots were within the range of background levels; 2. of the total phosphorus applied to the high-rate plot, 3% of the phosphorus was exported in the groundwater; 3. of the total nitrate plus nitrite nitrogen applied to the high-rate plot, 98.5% of the nitrogen was denitrified or stored in dead biomass and new peat.

APPENDIX

Figure A1. Symbols of the energy circuit language (Odum 1971).

a. A Pathway whose flow is proportional to the quantity in the storage or source upstream.

b. Source: an outside source of energy delivering forces according to a program controlled from outside; a forcing function.

c. Passive Storage: a compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

d. Heat Sink: dispersion of potential energy into heat that accompanies all real processes; lossof potential energy from further use by the system.

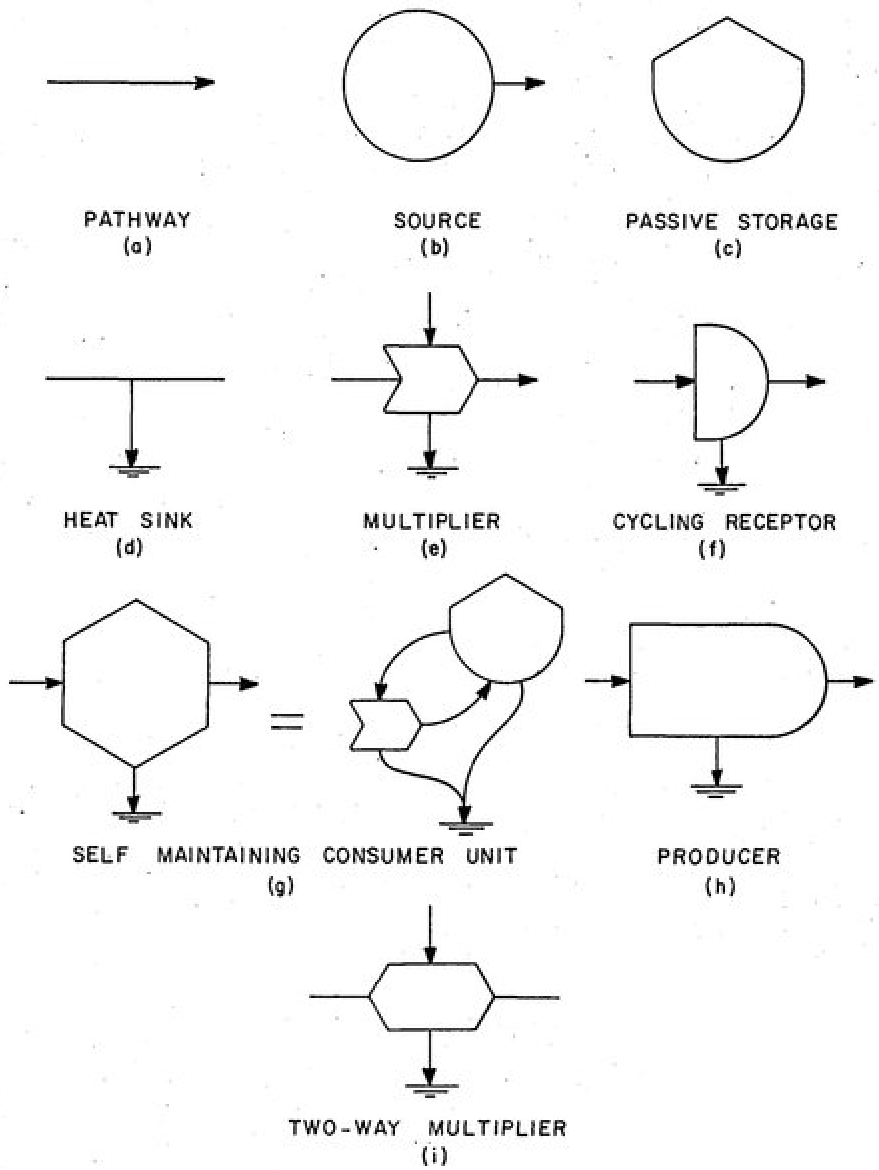
e. Work Gate: interaction of two pathways, which produces an outflow in proportion to some function of both.

f. Self-Limiting Energy Receiver: a unit that has a self-limiting output when input drives are high because there is a limiting constant quantity of material reacting on a circular pathway within; e.g., cycling receptor module of chlorophyll extraction in green plants.

g. Self-Maintaining Consumer Unit: unit in which the storage feeds back some of its energy to enhance its uptake.

h. Producer: green plant or plant community, which combines cycling receptor (f) with self-maintaining consumer unit (g).

i. Two-way Work Gate: similar to e: an interaction of two pathways resulting in flow in either direction, or in both directions simultaneously (as in mixing). Flow is in proportion to some function of both pathways.


PATHWAY
(a)
SOURCE
(b)
PASSIVE STORAGE
(c)
HEAT SINK
(d)
MULTIPLIER
(e)
CYCLING RECEPTOR
(f)
SELF MAINTAINING CONSUMER UNIT
(g)
PRODUCER
(h)
TWO-WAY MULTIPLIER
(i)

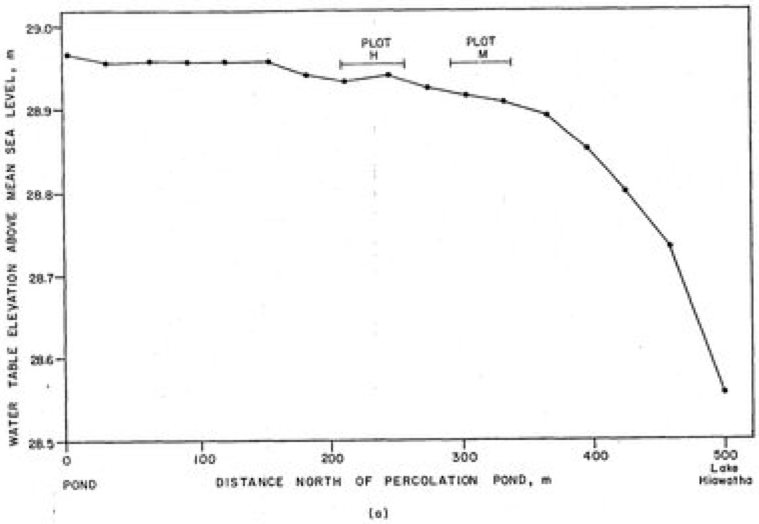



Figure A2. Water table elevations measured along the south-north transect (Transect B). The survey was conducted in December 1977 by Blackburn and Associates, Inc. of Clermont.

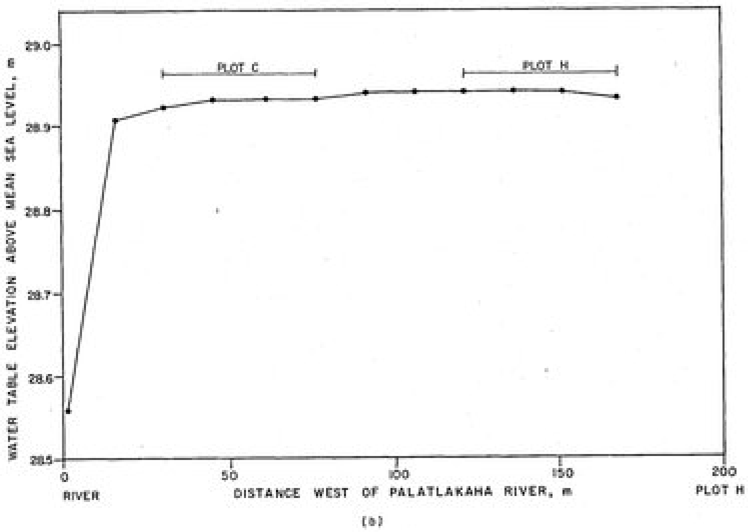



Figure A3. Water table elevations measured along the west-east transect (Transect A). The survey was conducted in December 1977 by Blackburn and Associates, Inc. of Clermont.

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