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Nutrient Retention in Shallow Reservoirs Using Selected Aquatic Macrophytes

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NUTRIENT RETENTION IN SHALLOW RESERVOIRS USING SELECTED AQUATIC MACROPHYTES

BY

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B.S., Florida Southern College, 1971

THESIS

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ABSTRACT

A field experiment was conducted to evaluate the possibility of using shallow reservoirs containing aquatic plants to reduce excess nutrient levels of agricultural drainage effluent from organic soils. The reservoir systems consisted of three small reservoirs in series, containing separate stands of Eichhornia crassipes, Egeria densa and Typha sp., and a single large reservoir containing equal areas of all three aquatic plants. A control reservoir without plants was included. Drainage water from organic soils was pumped through each reservoir at 39.6 l/sec., 6 hours per day, 6 days per week. The major nutrients monitored in these flow-through systems included nitrate-N, ammonium-N, total-N, ortho-P (soluble reactive phosphorus) and total-P. Temperature, pH, alkalinity, dissolved oxygen, carbon dioxide and turbidity were also monitored at the inflow and outflow of each reservoir system. Standing crop measurements and plant tissue analysis for nitrogen and phosphorus were conducted every 21 days.

When a single large reservoir was used, effluent nitrate-N, ammonium-N, ortho-P and total-P concentrations decreased by 65%, 57.9% 70.3% and 51% respectively, while organic-N concentrations increased by 7.2%. In the a series

of small reservoirs the concentration of nutrients decreased by 80%, 73%, 33%, 74%, and 70% for nitrate-N, ammonium-N organic-N, ortho-P and total-P respectively. The dissolved oxygen increased and turbidity was reduced in both reservoir systems. The bicarbonate and carbonate equilibrium in the series of reservoirs and control reservoir shifted to the carbonate side as carbon dioxide was reduced. The carbon dioxide in the large reservoir remained at the same concentration throughout the study.

The standing crop in both reservoir systems was similar with an average of 11.6 mt/ha grown in R-1 and 11.2 mt/ha grown in the series of reservoirs. The nitrogen retained during the study was 1017 kg/ha and 750 kg/ha in the series and the large reservoir respectively. Phosphorus retained in the series was 249 kg/ha while the large reservoir retained 211 kg/ha of phosphorus.

The series of reservoirs was more effective in reducing the nutrient levels of the drainage effluent than the large single reservoir. The results obtained from this study indicated that reservoirs in series can be used to reduce excess nutrient levels of agricultural drainage waters. However, further studies are necessary to increase the efficiency of the system and to accelerate plant removal. The physical, chemical, and biological processes involved in removal of the nitrogen and phosphate should be optimized in future applications.

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INTRODUCTION

The exponential growth of the human population and the byproducts produced by modern technological development have accelerated the pollution of our environment. The addition of large quantities of inorganic nutrients, particularly nitrogen (N) and phosphate (P) to lakes and streams has been one of the most widespread types of pollution. This artificial increase of nutrients has greatly accelerated the natural process of eutrophication in some lakes.

The major source of N and P has been the primary and secondary waste water treatment plant effluents. The N and P from nonpoint sources such as agricultural effluent also has contributed heavily to the nutrient loading of many drainage basins. This excess nutrient loading has caused much damage to fresh water systems. For example, lakes and rivers have been choked with water weeds so they are no longer navigable and commercial and public fishing has often been eliminated when algal blooms have caused fish kills by toxin release or by oxygen depletion.

The overall destruction of recreational areas and the ecological imbalance imposed on fresh water systems have recently directed public and scientific interests to the problems of eutrophication and the solutions employed to handle nutrient overloads. The techniques used for lake restoration include the following two major categories: 1) the limitation of fertility and sedimentation and 2) the management of the consequences of lake aging (e.g., sedimentation, nuisance vegetation, dissolved oxygen depletion, and deterioration of fisheries). Two principal approaches have been suggested for limiting fertility and controlling sedimentation. One consisted of curbing inputs by collecting, diverting and treating pollution flow. The other consisted of "in-lake" schemes to accelerate nutrient outflows or prevent nutrient recycling (Boyter and Wanielista 1972). The approach presented here was to limit fertility by treating pollution flows to remove N and P from consolidated agricultural effluent drained from organic soils.

The objective of this research was two fold: first to explore the potential of aquatic plants in shallow reservoirs as a possible instrument for lake restoration and water quality management, and second to determine if shallow reservoirs connected in series containing selected aquatic macrophytes are more effective as a nutrient sink than a single reservoir containing the same aquatic plants. This concept was evaluated by monitoring the nutrient levels for N and P in inflowing and outflowing agricultural drainage water and by comparing nutrient concentrations and production of the aquatic angiosperms in two flow-through reservoir systems.

The use of aquatic plants as an in-lake method to remove nutrients, particularly N and P, has been explored by various authors. One study involved the use of algae as a nutrient sink for N and P. Neel et al. (1961) showed that 90% of the total N in ponds was removed by the algae present, and studies by Rigler (1956) indicated that algae could reduce the soluble P by 50% in some lakes. Although these studies indicated that nutrients can be removed by the algae, the problem of high turnover rates still was not eliminated. For example, soluble P was shown to be recycled into the water column of a lake in 3.7 days (Rigler 1956). Cropping experiments have also been attempted to improve the technique of nutrient removal by algae (Fitzgerald 1969; Dugdale and Dugdale 1965). A relatively high nutrient reduction was achieved by this method; however, filtering equipment to harvest algae is expensive and somewhat inadequate for in-lake applications.

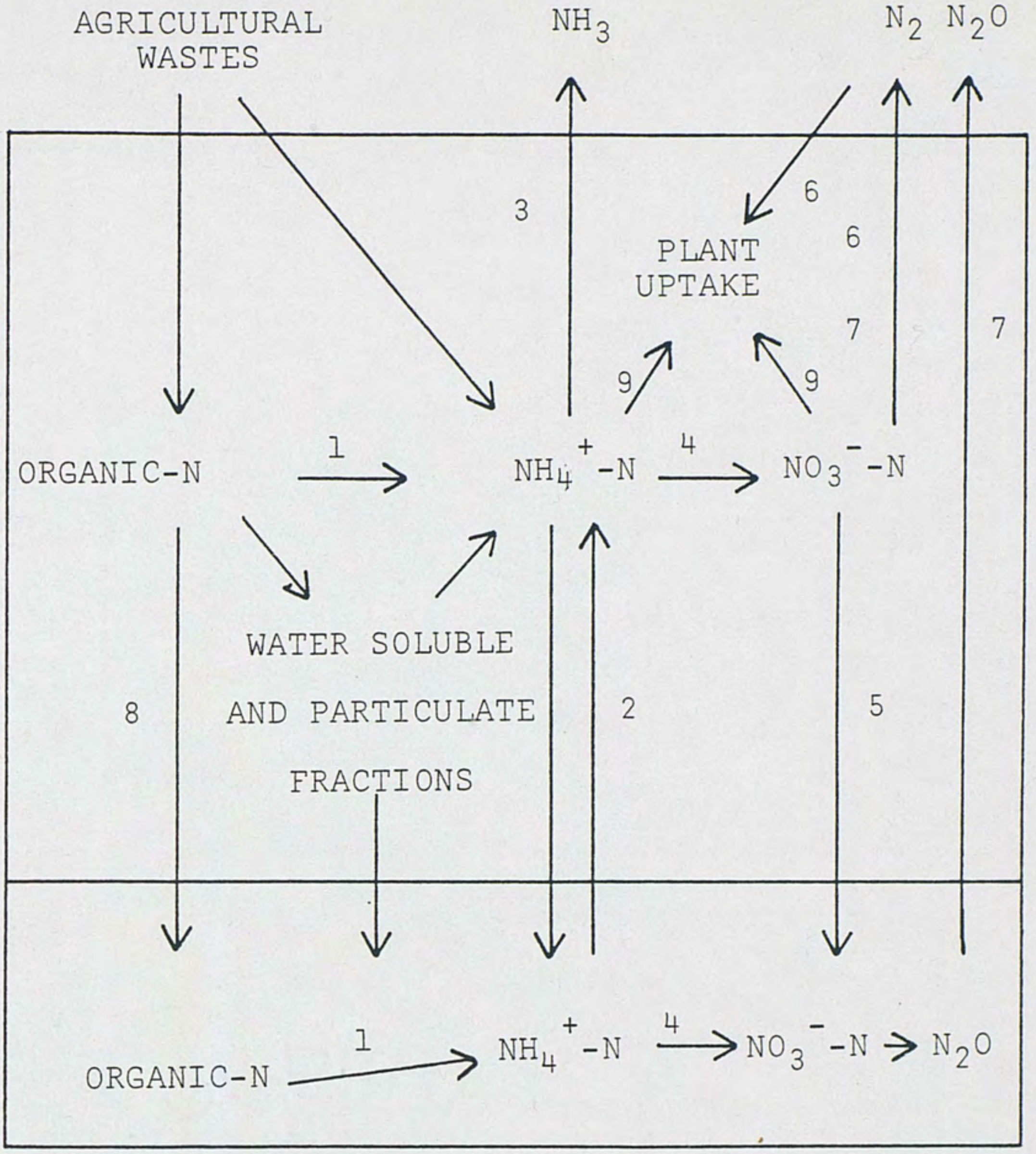
The use of aquatic macrophytes as a nutrient sink for in-lake restoration has also been evaluated. Brezonik and Lee (1968) indicated that 454 kg of plant material accounted for 1.3% of the total-N removed from Lake Mendota. Aquatic plant material used in other attempts to remove nutrients from lake systems accounted for only 20% to 25% of the ammonium-N and nitrate-N removed (Dunigan et al. 1975; Lance 1972; Yount and Crossman 1970). The value of water hyacinths for P removal has been reported in some instances to be negligible for in-lake management (Dunigan et al. 1975).

The potential for nutrient removal by aquatic macrophytes in systems other than lakes, i.e. sewage treatment polishing ponds, has been studied and more favorable results were obtained. Steward (1970), postulated that water hyacinths, with a theoretical productivity of 67 tons of dry matter per acre per year in subtropical Florida, could effectively remove the yearly contribution of nitrogen in waste water from 595 people per acre per year. Water hyacinths grown in sewage treatment plant polishing ponds reduced ammonium-N by 25%, nitrate-N by 9% and soluble phosphorus by 66% (Cornwell et al. 1977). Soluble phosphorus was reduced by 14% in sewage effluent in a five week study using water hyacinths (Ornes and Sutton 1975). Scarsbrook and Davis (1971) using five vascular species for nutrient removal showed that water hyacinths had the greatest potential of the five to reduce nutrients in sewage effluent. Most of these studies used a single aquatic plant species, water hyacinths, for nutrient removal from waste water. Boyd (1969b) suggested that the efficiency of these pond systems for waste water treatment might be improved by using a combination of two or three reservoirs connected in series containing selected aquatic plants.

The forms and sources of N and P in aquatic systems are varied and undergo numerous reactions. Nitrogen occurs in fresh water as organic nitrogen (i.e. amino acids, amines and proteins), ammonium (NH_4^+) nitrate (NO_3^-), and nitrite (NO_2^-). Sources of nitrogen include: a) precipitation, b) nitrogen fixation, and c) inputs from surface and ground water originating as municipal, industrial and agricultural effluents. Losses of nitrogen occur by: a) effluent outflow from a basin, b) by reduction of nitrate-N to molecular-N (N_2) during bacterial denitrification, and c) plant assimilation (Fig. 1) (Porter 1975).

Precipitation and fallout from atmospheric sources has generally been considered to be a minor source of N to lakes (Wetzel 1975). However the atmospheric sources of N from precipitation and fallout are highly variable and are related to the meteorological conditions and locations of water bodies with respect to technological development and pollution sources. Nitrogen may enter a lake from the atmosphere in the forms of molecular-N, ammonium-N, dissolved organic nitrogen (DON) and particulate organic nitrogen (PON).

The ability of plants to assimilate these various forms of nitrogen varies with species. The dissolved molecular nitrogen is accessible only to certain blue-green algae and bacteria. Both groups of organisms oxidize nitrogen gas



1 = AMMONIFICATION
2 = AMMONIUM-N EXCHANGE SOIL AND WATER
3 = VOLATILIZATION
4 = NITRIFICATION
5 = NITRATE-N DIFFUSION
6 = NITROGEN FIXATION
7 = DENITRIFICATION
8 = MINERALIZATION
9 = PLANT UPTAKE

Figure 1. The fate of nitrogen for agricultural waste in an aquatic system.

into organic molecules in a process called nitrogen fixation.

The major ammonium-N contributions to the aquatic environment are through discharge of effluents from agricultural, municipal and industrial sources, and mineralization of organic N. In an aquatic environment ammonium ions present in the water exist in equilibrium with the aqueous ammonia (NH_3), which in turn exists in equilibrium with gaseous (NH_3). The equilibrium reaction is shown by the following equations:

$$NH_3 + H_2O \rightleftarrows NH_4{}^+ + OH^-$$

$$NH_3(g) = NH_3(aq)$$

The above reactions are dependent upon the pH of the system. An alkaline pH favors the presence of the aqueous form of NH_3 while acidic or neutral pH favors the presence of the ionic form (Stratton 1969).

Nitrification is the biological conversion of ammonium-N (reduced state) to nitrate-N (oxidized state)

$$NH_4{}^+ + 2O_2 \rightleftarrows NO_3{}^- + H_2O + 2H^+$$

The nitrate-N produced by this reaction may be assimilated by algae and larger hydrophytes. Under anoxic conditions many faculative aerobic bacteria in the water and sediment can also utilize nitrate-N as the terminal electron acceptor during the oxidation of organic substances. The reduction of nitrate-N in biological metabolism is the process called denitrification. The general sequence of denitrification is

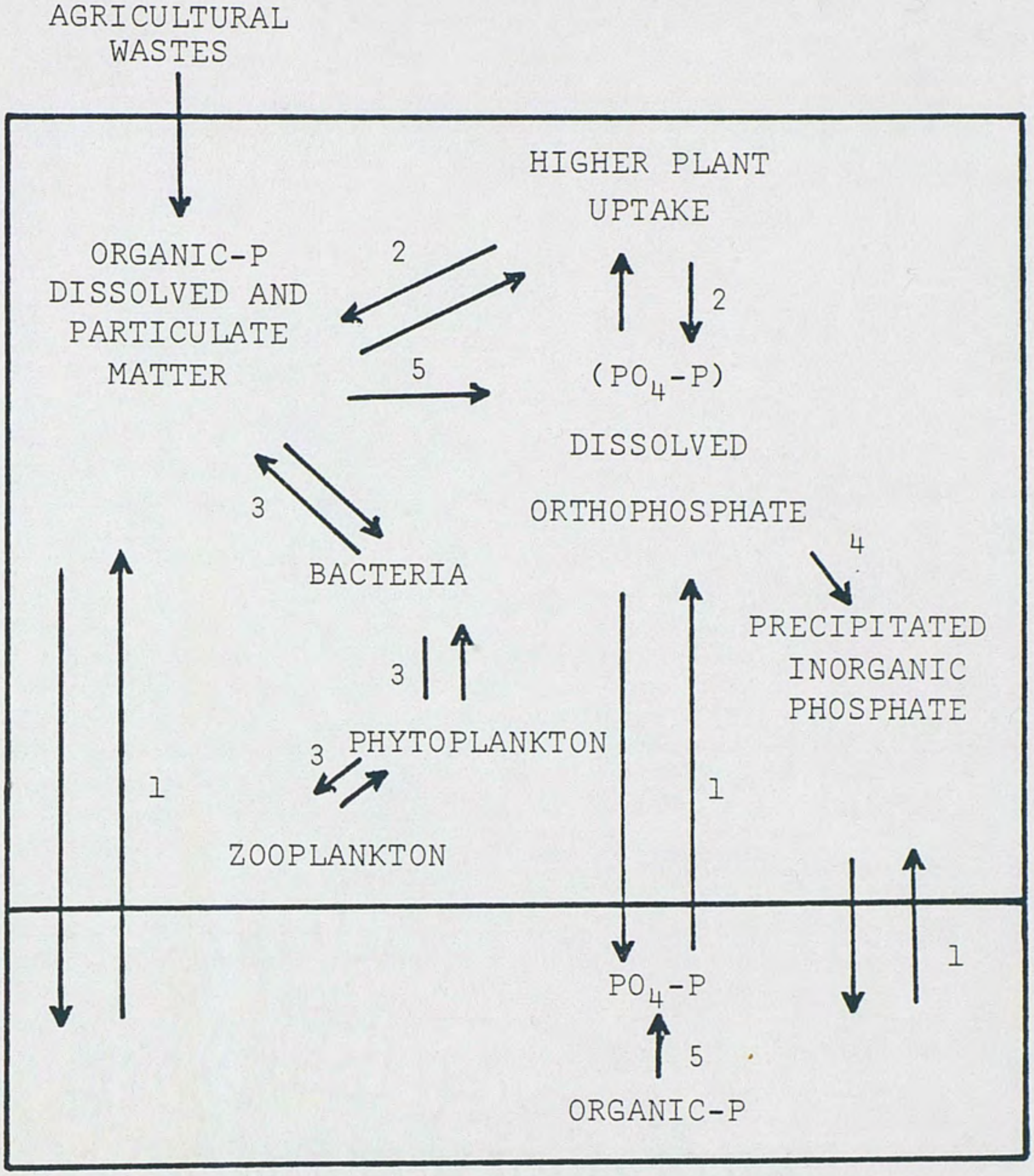
$$NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$$

This reaction can result in a significant reduction of nitrate-N from the aquatic system (Wetzel 1975). Nitrification and denitrification can occur simultaneously and are dependent upon changes in oxygen concentrations, pH, and available energy sources.

Total organic N is made up of two components, particulate organic nitrogen (PON) and dissolved organic nitrogen (DON). Over one-half of the DON is in the form of amino nitrogen compounds, of which about two-thirds are in the form of polypeptides and complex organic compounds and less than one-third occurs as free amino nitrogen. The PON is contained in the plankton and seston which make up the biota of the water (Wetzel 1975). The majority of DON and the PON enters an aquatic system via runoff. However, algae and aquatic plants excrete soluble polypeptides and similar nitrogenous compounds (Vallentyne 1975). Organic compounds are also solubilized in the aquatic environment when plants decay (Wetzel and Manny 1972). The DON and PON are not readily available for assimilation by aquatic plants and the major reduction of organic N in this form is due to ammonification (Wetzel 1975).

In contrast to the rich natural supply of the nutritional and structural components that make up the biosphere (oxygen, carbon, hydrogen, and nitrogen), P is the least abundant and is often the limiting factor in biological productivity (Delwich 1970). The rate of biological productivity in aquatic systems is governed by the rate of P cycling in relation to the input loading of P from external sources (Fig. 2). In general, the quantities of P entering an aquatic system via surface and subsurface drainage are related to the amount of available P in the soils, topography, vegetative cover, rainfall, amount of runoff and the land use patterns.

The total phosphorus (total-P) content of water consists mainly of suspended particulate matter or refractory compounds which are not accessible to the biota and the soluble reactive portion or labile compounds which are easily assimilated by the biota. The particulate P includes the P in nucleic acids, enzymes, vitamins, and nucleotides or organisms and the P adsorbed onto clays, carbonates and ferric hydroxides. The soluble reactive portion or inorganic P is composed of orthophosphates (ortho-P) and polyphosphates of low molecular weight. The polyphosphates hydrolyze at a slow rate in aqueous solution and are converted to the ortho form. The rate of reversion is increased with increasing temperature and/or lowered pH.



1 = MINERALIZATION AND PHOSPHORUS EXCHANGE BETWEEN SOIL AND WATER
2 = HIGHER PLANT UPTAKE
3 = ASSIMILATION BY AQUATIC BIOTA
4 = PRECIPITATION
5 = ORGANIC DECOMPOSITION

Figure 2. The fate of phosphate for agricultural waste in an aquatic system.

In order to evaluate the P cycle, several investigators have added radioactive orthophosphorus to lakes (Hutchinson and Bowen 1950; Rigler 1956; Hayes et al. 1952; Chamberlain 1968; Confer 1972). The studies clearly indicated that ortho-P was rapidly assimilated by the phytoplankton and littoral vegetation. It was also observed that dissolved P was released slowly from the algae into the water column. The studies indicated that movement of the P after initial uptake by the biota was to the sediment via settling and adsorption onto clay and inorganic material. The sediment was considered to be a P sink in most cases; however P release to the overlying water column can occur if the P concentration of the interstitial water exceeds that of the overlying water, or if anaerobic conditions exist in the sediments (Wetzel 1975).

Exchange of P across the sediment-water interface is regulated by mechanisms associated with mineral-water equilibrium; adsorption and desorption, redox potential, pH, chemical precipitation, and the status of the organic P and chemical fractions in the sediment (Wetzel 1975). The removal or adsorption of P from solution under acidic conditions is related to the presence of amorphous oxides and hydrous oxides of iron and aluminum. Under alkaline soil conditions adsorption of P with calcium carbonate results in the formation of calcium phosphate (Sawhney and Hill 1975).

At low redox potential the release of ortho-P, iron, and manganese into the overlying water was increased markedly (Mortimer 1941; 1942). With the reduction of ferric hydroxides and ferric iron, the adsorbed ortho-P was released and appeared in the water. Oxygenation of the sediment reversed the adsorption process and decreased the P concentration in solution.

The organic compounds of P in the sediment originate from decaying plant and animal material and microbial synthesis from inorganic P compounds. The organic P in the sediments is not readily available for assimilation by the biota and is broken down by mineralization and subsequently released by desorption and dissolution reactions.

Some of the advantages of a flow-through, lake restoration technique using selected aquatic macrophytes include: a) It expedites restoration of the homeostatic capacity of the sediments; b) It may reduce phytoplankton productivity not only by removing nutrients but by not reducing flushing rates that are inherent in the containment facilities; and c) It employs resource recovery which reduces total cost through sale of the plant material harvested.

MATERIALS AND METHODS

Description of Study Area

The area chosen for study is located on the north end of Lake Apopka 3.6 miles south of the city of Zellwood in District Two of Orange County, Florida. This area is part of a muck farming district of 7,300 ha (Fig. 3). The soils of this area are of the everglades series and have been formed chiefly from the remains of sawgrass and other sedges. The virgin soils typically are covered with water for several months of the year and have a large amount of N but are low in other essential nutrients for plant growth.

Water remains on or near the surface of the soil during most of the year unless it is removed through artificial drainage. If the soils are dry the organic material is rapidly oxidized and subsidence occurs (Terry 1980). This area, once a lake bottom, was reclaimed by constructing dikes, drainage canals and ditches. The drainage in this area is now controlled by the farming industry. The soil is flooded for cover and irrigation.

The drainage water monitored was agricultural effluent from the organic soils and is one of the many sources of pollution to Lake Apopka, a 12,000 ha lake located south of the muck farming district. The lake is highly eutrophic and

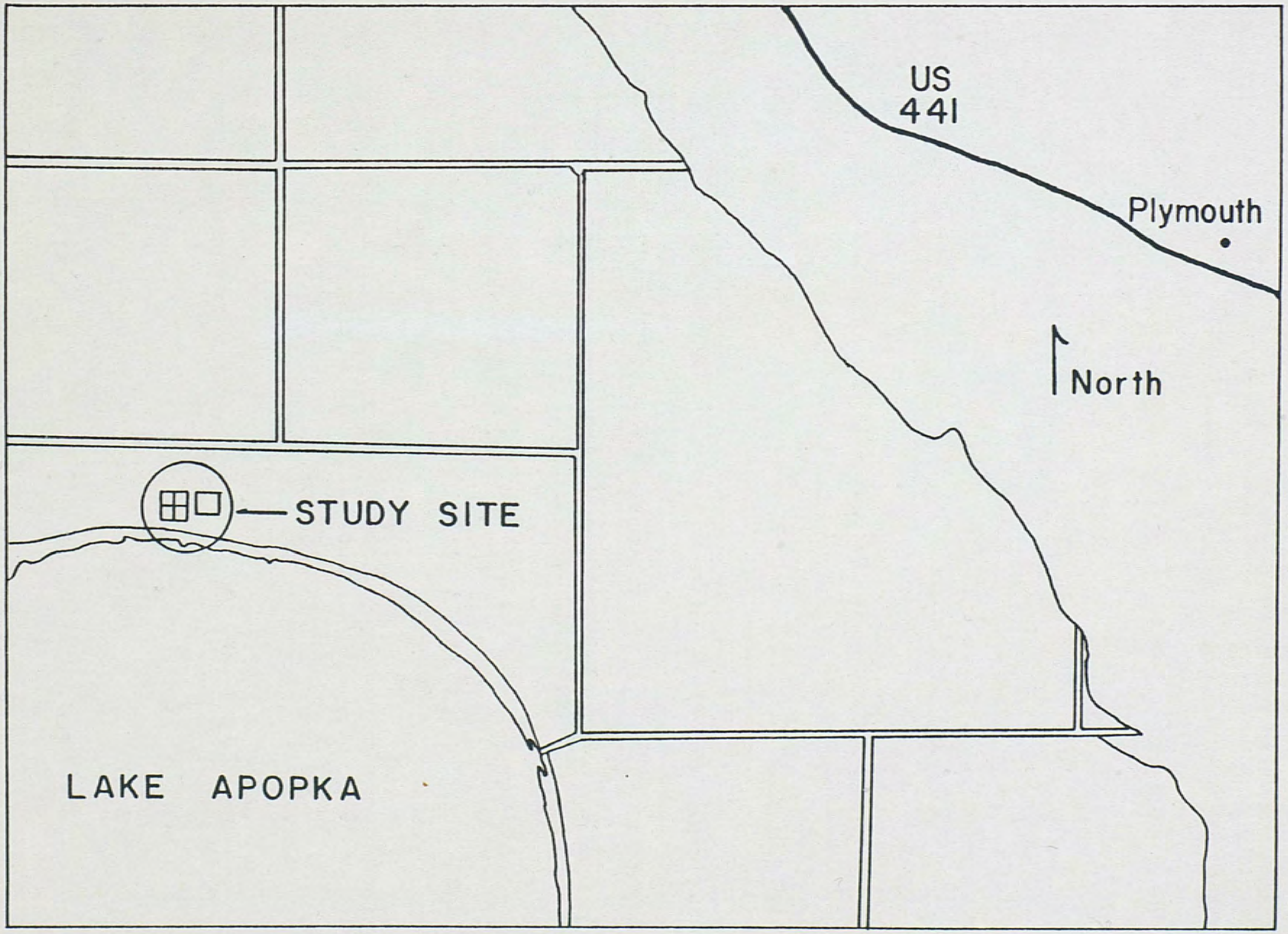


Figure 3. Location of study site in district two of Orange County Florida.

is choked with nuisance blue green algae (Pollman et al. 1980).

The experimental ponds were located at the University of Florida's 9.3 ha branch farm on a shallow phase of everglades muck peat. The thickness of the organic soil at the site ranged from 20 cm to 60 cm and is underlaid by 25 cm of calcarious rock and unconsolidated calcarious marl (United States Department of Agriculture 1960).

Description of the Reservoirs

The species of macrophytes selected for this study included Eichhornia crassipes, Egeria densa, and Typha sp. They were chosen because of their ability to produce a large standing crop, their ability to accumulate large quantities of mineral nutrients (i.e. N and P) and their ease of harvest (Boyd 1969a; Fitzgerald 1969). By taking advantage of these properties one could increase the nutrient retention in the holding ponds. These qualities were taken into consideration in the design of the retention ponds.

By taking advantage of the biological properties of these plants a suitable retention system could be designed. A dense stand of E. crassipes (free-floating) was established to produce anaerobic conditions which should enhance additional nitrogen reduction through denitrification. The effluent from this pond would, however, be low in dissolved oxygen (DO) and have a high biological oxygen demand.

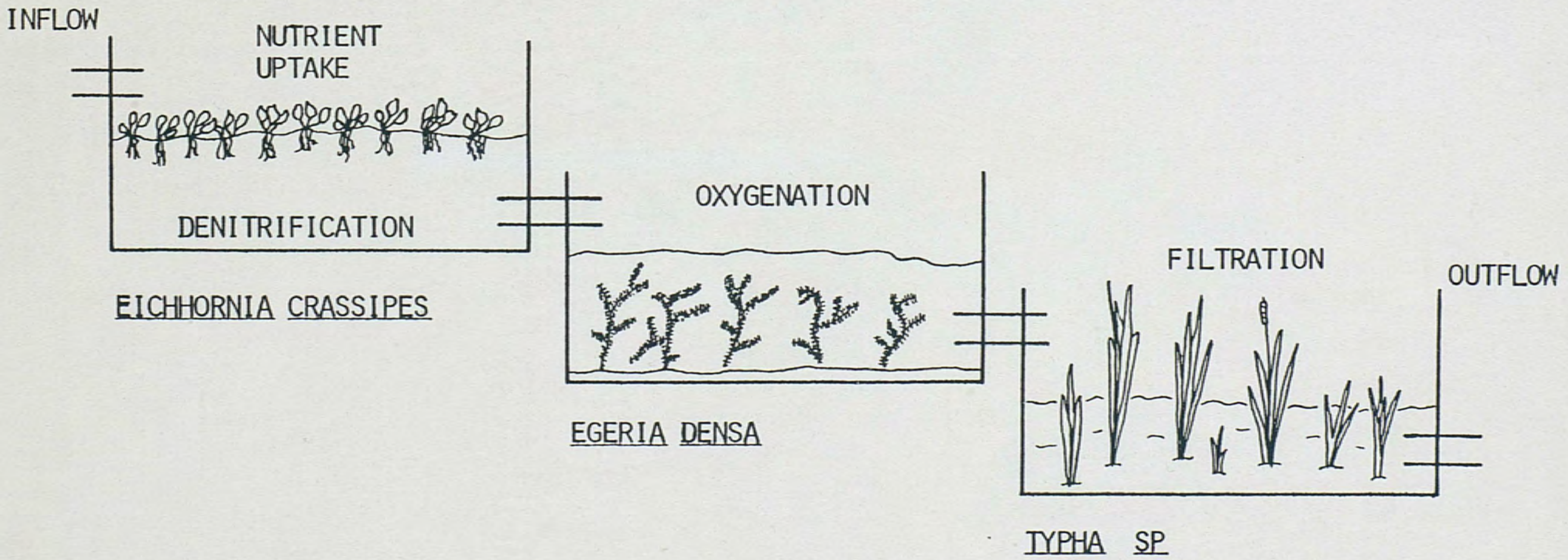


Figure 4. The processes involved in nutrient removal from agricultural effluents in the reservoir systems.

Therefore the dumping of effluent from this system into a lake or aquatic environment could be pernicious to the environment. A successive plant stand was established in a manner that would replenish oxygen without expensive mechanical equipment and increase the efficiency of the system as a nutrient sink. The second plant stand was the submergent *E. densa*. This species has a high photosynthetic carbon dioxide fixation rate and oxygen production rate. *E. densa* has also been shown to assimilate critical concentrations of all essential elements for plant growth from the water and the sediment except for chlorine and copper (Gerloff 1973; Bristown and Whitcombe 1971; Carignan and Kalff 1980). A third plant stand containing the emergent *Typha* sp. was established to remove nutrients from the sediments. Nutrient removal from the sediment by the *Typha* sp. could create a gradient from the water to the sediment and thus increase the adsorption of nutrients by the sediment (Fig. 4).

Five flow-through reservoirs were constructed with two meter high levees of organic soils and with bottoms composed of calcarious rock and Everglades peat. The first of the five reservoirs was designated R-1 and was a square of 61 m per side with a surface area of 3721 square meters. This reservoir was partitioned into three equal areas by two chevron shaped chicken-wire fences. Each section contained a different plant species: *E. crassipes*, *E. densa*, and

Typha sp. Agricultural drainage water was pumped diagonally through the plant stands at a rate of 39.6 l/sec (Fig. 5).

Four additional flow-through reservoirs were constructed, each a square of 33 m length and with a surface area of 1240 square meters. These four small reservoirs were designated R-2, R-3, R-4 and R-5. Reservoirs R-2, R-3, and R-4 were connected in series by flumes and contained *E. crassipes*, *E. densa* and *Typha* sp., respectively. Agricultural drainage water was pumped diagonally through these reservoirs at a rate of 39.6 l/sec. Reservoir R-5 was constructed as a control and contained no aquatic macrophytes. Agricultural drainage water was pumped diagonally through R-5 at a rate of 13.2 l/sec. Table (1) presents a summary of the sizes, volumes and pumping rates of the five reservoirs used in the study.

Soil profiles, before plants were stocked, for organic nitrogen in the upper 15.2 cm of the soil in the 5 reservoirs are presented in Table (2). The four small reservoirs (R-2, R-3, R-4, and R-5) had more organic nitrogen in the top 3.8 cm portion of the column than did the large reservoir.

Sampling Design for Water Analysis

Water samples were collected twice weekly at five sampling stations for 14 months. Untreated drainage water was collected from the south ditch and the center ditch.

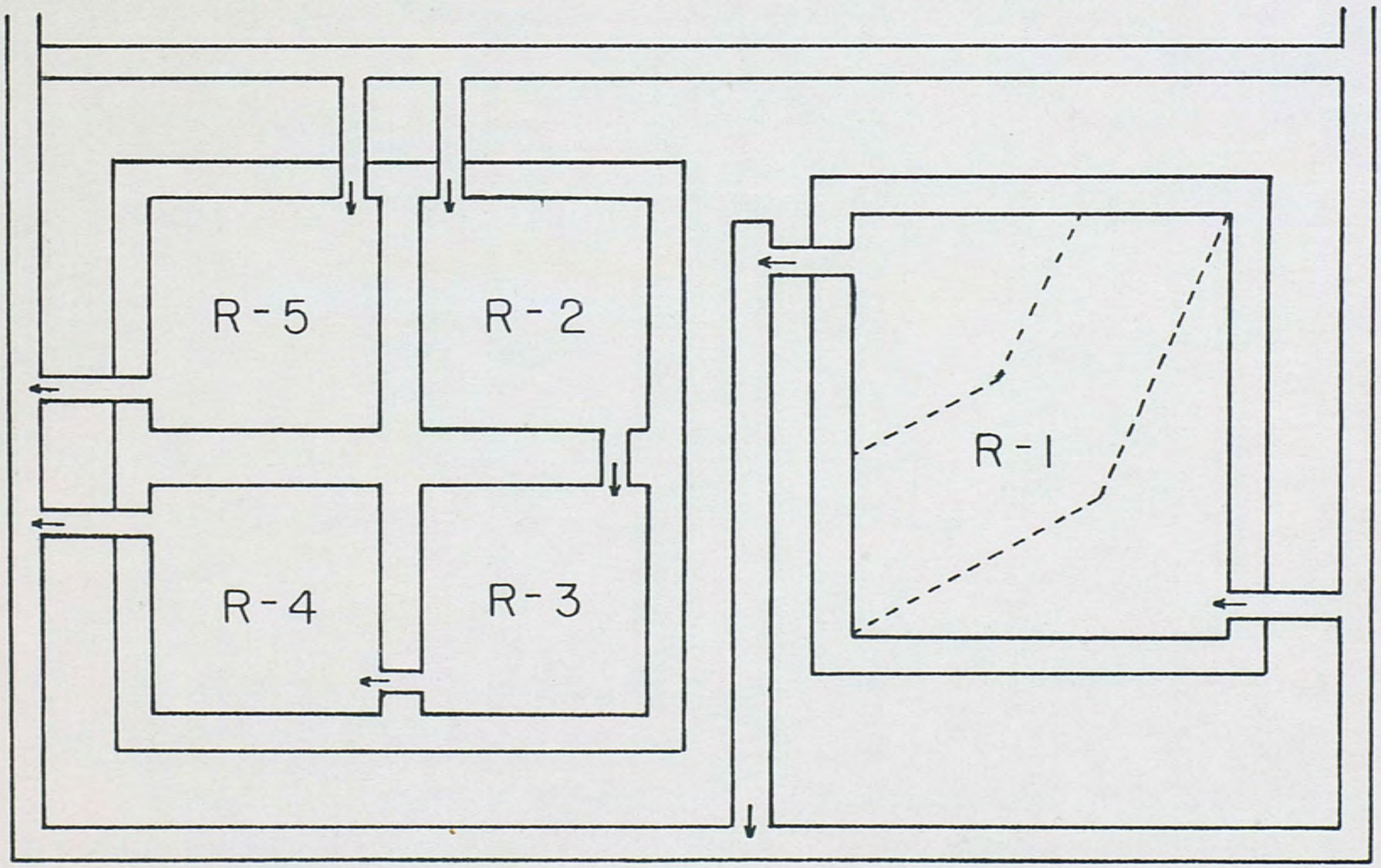


Figure 5. Design, flow patterns and sampling stations (*) of the reservoir systems.

Table 1. The volume, sizes and pumping rates of the reservoirs for the 14 month study period.

Reservoir	Surface Area	Depth	Volumne	Pumping	Pumping	Weekly Vol.**
	m^2	m	m^3	m^3/hr	l/sec	m^3
R-1	3721	1.0	3721	142.6	39.6	5132.2
R-2	1240	1.0	1240			
R-3	1240	1.0	1240	142.6*	39.6*	5132.2*
R-4	1240	1.0	1240			
R-5	1240	1.0	1240	47.5	13.2	1710.7

*The calculated volumes and pumping rates are the totals for the reservoirs in series.

**The weekly volumes were based on six hours pumping per day six days a week.

Table 2. The total organic nitrogen of the sediment in the reservoir systems before macrophyte introduction.

Depth	Location				
cm	R-1	R-2	R-3	R-4	R-5
	mg/cm^3	mg/cm^3	mg/cm^3	mg/cm^3	mg/cm^3
0.0- 3.8	5.49	14.18	13.57	10.96	9.72
3.8- 7.6	3.19	2.50	4.45	1.76	1.85
7.6-11.4	2.79	1.35	1.99	1.33	1.19
11.4-15.2	2.74	0.91	0.64	0.62	0.75

Treated drainage water was collected from the outflows of the large reservoir, the series of reservoirs and the control (Fig. 5). The pumps were maintained six hours per day six days per week. Water samples were transported directly to the laboratory and analyzed. The water samples were refrigerated at 10° C if they were stored for 24 hours and chemically treated if stored for longer periods (Environmental Protection Agency 1974).

Chemical and Physical Measurements

Total Kjeldahl nitrogen (TKN) was measured by a modified micro digestion procedure described by Jirke, et al. (1976). After digestion, the TKN was measured potentiometrically with an Orian selective ion electrode for ammonia, (Environmental Protection Agency 1974). Ammonium-N was also measured potentiometrically with an Orian selective ion electrode. Nitrate-N was measured by the Brucine method (Environmental Protection Agency 1974).

Total-P was measured by the persulfate digestion procedure and read by the ammonium molybdate and antimony potassium tartrate colorimetric method. Ortho-P was measured directly by the ammonium molybdate and antimony potassium tartrate colorimetric method (Environmental Protection Agency 1974).

Dissolved oxygen (DO) concentrations and temperature were measured twice weekly in the water at a depth of 0.5 m at outflow and ditch stations with a YSI model 57 DO meter and a YSI model 5739 DO and temperature probe. The meter was standardized against the Winkler method (Environmental Protection Agency 1974).

Specific conductance was measured twice weekly with a YSI model 33 conductivity meter at a depth of 0.5 m below the surface at each sampling station.

Total, carbonate, and bicarbonate alkalinity were measured on site and were determined by colorimetric titration (American Public Health Association 1965).

All colorimetric measurements were made with a Bausch and Lomb Spectronic 88 spectrophotometer at prescribed wavelengths (Environmental Protection Agency 1974).

Sampling Design for Plant Analysis

Four stations in each plant stand of the ponds were randomly selected at 28 day intervals from a grid map. All the plant material in each station was collected from a 0.25 m^2 quadrat. The plant material in each quadrat was identified to genus and a composite of each group was made. Composite samples were dried in a controlled greenhouse at approximately 40° C for 48 to 96 hr, oven dried at 100° C for 24 hr, and ground using a #40 mesh screen in a Wiley Mill (Allenby 1968). Standing crop was calculated as dry wt in grams per m^2.

Nutrient Analysis of the Plant Tissue

The total-N and total-P content of the ground plant matter was determined by the methods of Schuman et al. (1973), Gallaher et al. (1976) and Jackson (1958). Tissue analysis was based on dry weight.

Plant Harvesting

Periodic harvests of water hyacinths and cattails were conducted to enhance rapid growth of plant material and to remove nutrients (ie. N & P) which would have been recycled to the system. The harvests were conducted by hand and 50 to 75% of the two plant species covering the surface of the reservoirs were removed. The area containing the plant material to be harvested was determined subjectively by size and healthy appearance. Harvested cattails and water hyacinths were usually large healthy plants and those that appeared to be brown or yellow in color. The purpose of this harvest method was to leave enough young healthy plants in the reservoirs to rapidly replace the harvested plant material. Only the above ground portion of the cattail was removed.

The harvest times were based upon the effectiveness of the reservoirs as a nutrient sink and the production of the biomass measured. If the nutrient reduction at the outflow was less than 50% or the production fell below that of the previous 28 day sampling period a harvest was considered. A harvest was conducted after the first hard freeze regardless of the nutrient retention or production measurements.

Statistical Methods

The drainage water samples were taken bi-weekly and measurements were then compiled on a monthly basis. Since the samples were taken from fixed sampling stations (Fig. 6), the criteria for random sampling were violated. The variability created from external sources such as rain events, flooding from adjacent farm land, fertilization practices and the inherent effects in the biological treatments need to be blocked out. In order to meet the objectives of the experiment and to lower the variances a randomized block design was used to compare the means of the untreated drainage analyzed and treated drainage water analyzed. The number of blocks was the number of samples taken during the month and two treatments per block (untreated and treated drainage water).

The test procedure for the paired difference test was as follows:

$$H_o: \; U_d = U_1 - U_2 = 0$$

$$H_o: \; U_d > 0$$

$$TS: \; T = \frac{\bar{d}}{sd\sqrt{n}}$$

R.R. for df = n - 1, reject if $t > t_{.05}$

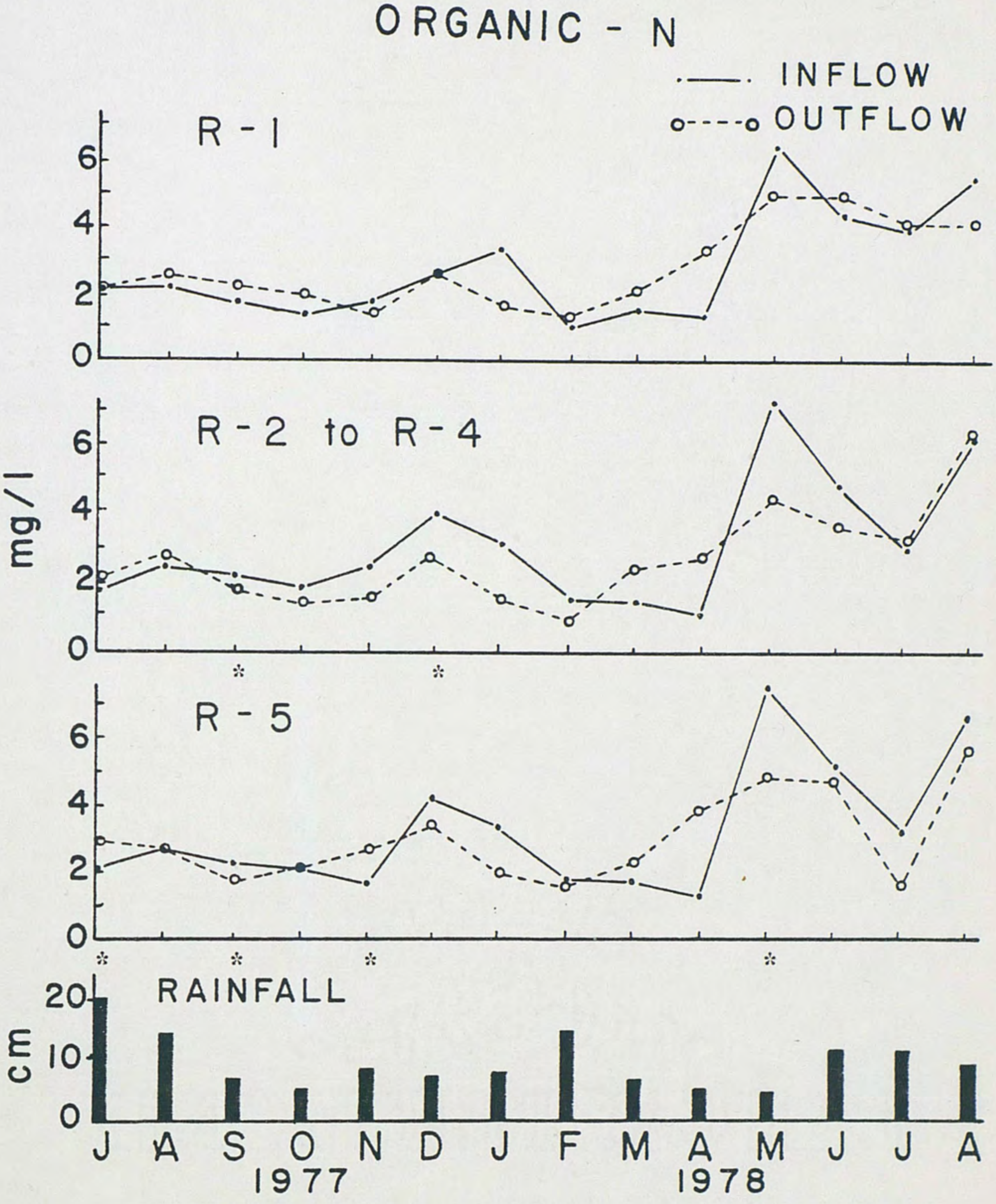
RESULTS AND DISCUSSION

Primary Nutrients

Total Organic Nitrogen

The organic N concentrations for untreated agricultural drainage water had a maximum monthly average of 6.25 mg/l and were never below 1.0 mg/l. The maximum concentrations of organic N for untreated drainage inflow during July and August 1977 had a peak value of 2.53 mg/l; during May, June, July and August of 1978 they had a peak value of 7.48 mg/l; and during December and January of 1977-78 they had a peak value of 4.60 mg/l (Fig. 6). The maximum concentration of organic N measured for the untreated drainage water was associated with rain events that occurred during the same period.

The organic N concentrations for treated drainage ranged from 0.96 mg/l to 6.52 mg/l. The concentrations for treated drainage water during periods of low rainfall intensities were greater than untreated drainage concentrations (Fig. 6). The increased values of total organic N measured in the untreated water from R-1 were probably the result of plant decay and excreted nitrogenous compounds because values were high during winter months when decay of plant



*Indicates significance at the 0.05 level.

Figure 6. Rainfall and total-N concentrations in the reservoir systems.

material, including the aquatic plants in the drainage canals, was maximal and rainfall was lowest. These data were consistent with the speculations of Vallentyne (1975), Manny (1972) and Wetzel and Manny (1972).

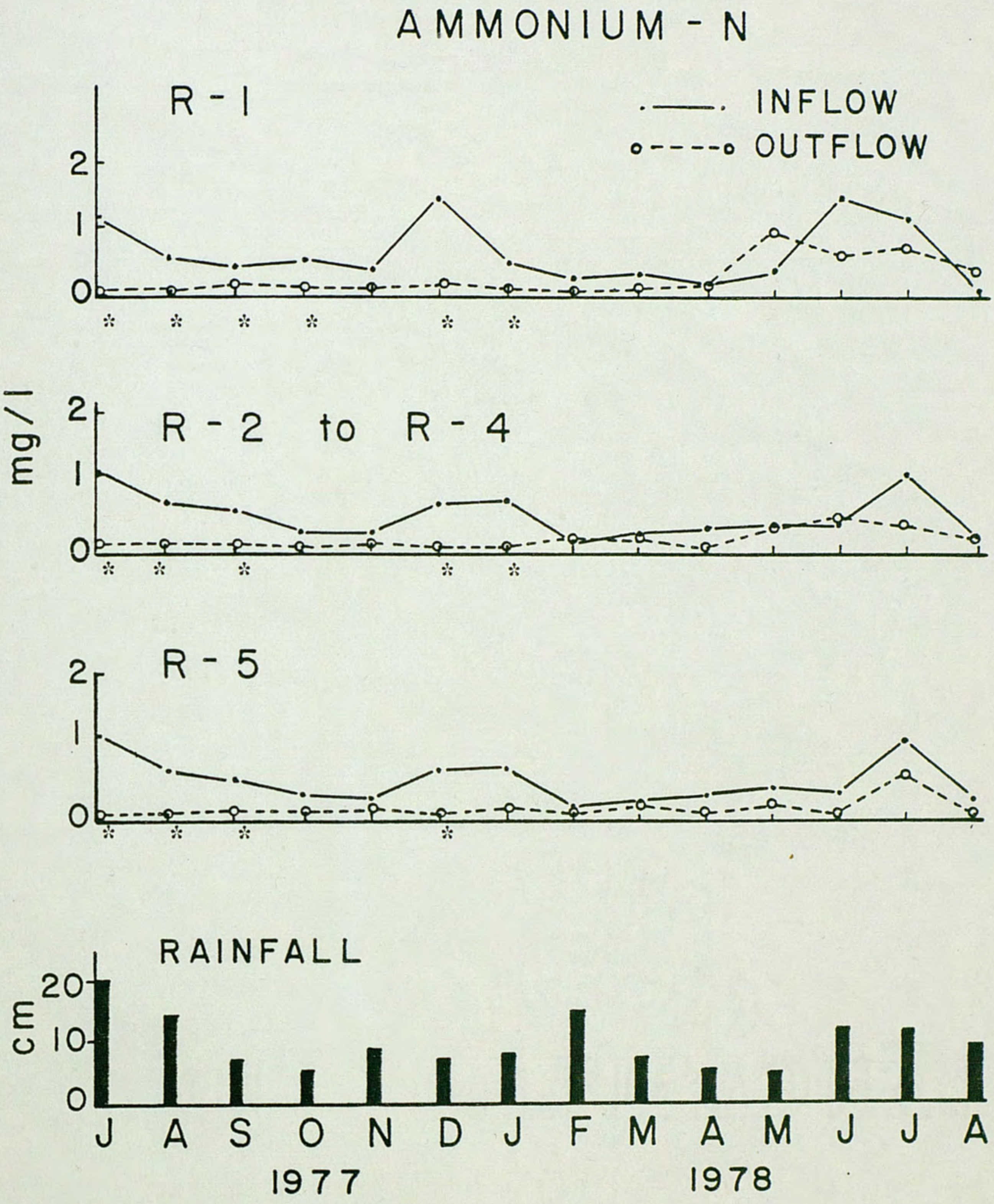
The release of DON and PON from these sources which may be utilized by the biota of the lake, is relatively slow and the cycles of the dissolved and biota-bound PON are often overlooked as a major source of pollution. Concentrations of PON and DON generally follow the dynamics of the biomass of the plankton in most aquatic systems, and autochthonous sources of organic N influence the biota and trophic status of a lake (Wetzel 1975).

The DON and PON are not readily available for assimilation by aquatic plants and the major reduction of organic N was due to ammonification.

The series of reservoirs reduced the organic N by 33.1% and the control reduced organic N by 8.2%. The large reservoir, however, increased the organic N components by 7.2%. The monthly averages for inflow and outflow of organic-N concentrations did not differ significantly at the 0.05 level during December and September of 1977 and March of 1978 and in the control during July, September and November of 1977 and March of 1978. The variability of the measurements was high with concentrations ranging from 1 mg/l to 7 mg/l (Fig. 6). This variance was probably the result of rain events, plant decomposition, fertilization practices in the area and the differences in organic material contained in the reservoirs at the start of the experiment.

Ammonium Nitrogen

Ammonium-N concentrations of drainage water did not exceed 1.5 mg/l at inflow stations and were no less than 0.01 mg/l for treated drainage water during the 14 month period of study (Fig. 7). Maximum concentrations for untreated drainage water occurred during July, August, and September of 1977, with a peak value of 1.1 mg/l at both untreated drainage water sampling stations. The peak ammonium-N concentration of 1.1 mg/l was also observed in July and August of 1978, at untreated drainage water sampling stations. Maximum concentrations for untreated drainage were also observed during the months of November, December, and January of 1977-78 (Fig. 7). The maximum concentrations measured for both winter and summer months in untreated drainage water coincided with rain events that occurred during these time periods. Treated drainage water measurements were low throughout the study in all reservoirs, with concentrations ranging from 0.01 to 0.04 mg/l. However, during the months of May, June and July of 1978 ammonium-N concentrations for treated drainage from R-1 and the series of reservoirs were greater than those measured for untreated drainage water. The outflow concentration



*Indicates significance at the 0.05 level.

Figure 7. Rainfall and ammonium-N concentrations in the reservoir systems.

during May was 0.97 mg/l while untreated drainage concentrations measured 0.31 mg/l. The source of the organic matter was probably due to dead plant material deposited during winter die back.

The loss of ammonium-N in the reservoirs differed, with 73.7% removed by the series of reservoirs, 57.9% removed by the large reservoir, and 75.5% removed by the control. The amount of ammonium ion that can be assimilated by plant material may be minimal because of the toxicity of ammonium hydroxide, the formation of which is a function of pH (Trussell 1972). However, there is considerable evidence that ammonium is the preferred form for plankton assimilation, since it is already at the reduction level of organic nitrogen. Organisms using nitrate as their nitrogen source must reduce it to the level of ammonia before incorporating it into organic forms (Allen and Kramer 1972).

Ammonium-N was reduced by 20% to 25% under experimental conditions using water hyacinths grown in clay pots (Dunigan et al. 1975). Similar results were demonstrated in field studies when 20% of the ammonium-N was removed by water hyacinths in a 10 month study of waste water in polishing ponds (Cornwell et al. 1977). These results and the results obtained in this study indicated that ammonium-N in the reservoir systems was reduced not only by plant assimilation but by environmental factors which affect the N cycle and nutrient exchange.

The distribution of ammonium-N in the reservoirs varied seasonally and in relationship to the extent of organic matter from allochthonous and autochthonous sources. Ammonium-N tends to accumulate when organic matter enters the reservoirs and this accumulation is accelerated under anoxic conditions. If anaerobic conditions were established in the water column under the water hyacinths in R-1 and R-2, ammonium-N concentrations should have been high. This is especially true at the sediment-water interface in which ammonium-N would be released from the sediments under anaerobic conditions (Trussell 1972). As the drainage water flowed through the remaining two plant stands in the reservoirs, the ammonium-N concentrations should have been affected by biochemical and chemical reactions. The drainage water was oxygenated by the _E_. _densa_ stands. The oxygen produced would allow the following oxidation reaction to proceed:

$$NH_4^+ + 2O_2 \rightleftarrows NO_3^- + H_2O + 2H^+$$

The overall nitrification reaction requires two moles of oxygen for the oxidation of each mole of ammonium-N, and is controlled by dissolved oxygen concentrations (at least 0.3 mg/l) inorganic carbon, pH and the temperature of the drainage water (Beckman 1972). Ammonium-N concentrations decreased in columns of drainage water overlying sediments from the reservoirs under aerobic conditions (Reddy et al.

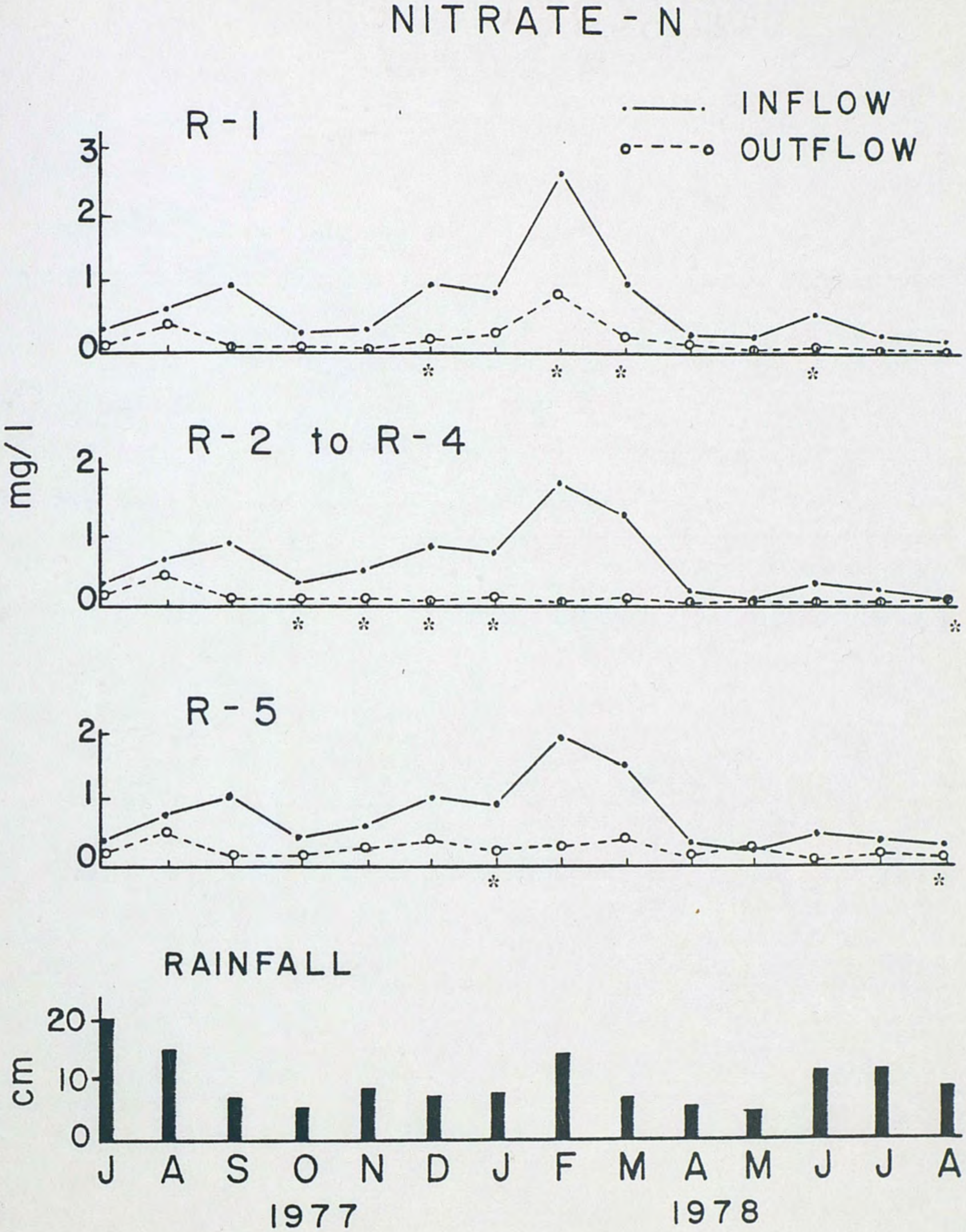
1980). The conditions that existed in the reservoirs (high concentrations of dissolved oxygen, an inorganic carbon source, a neutral pH and a mean water temperature of 23° C) were such that nitrification could proceed and if nitrification took place at a high rate it would be expected that a drop in dissolved oxygen for the treated drainage water would occur. Dissolved oxygen levels did not decrease in the control or the series of reservoirs. However dissolved oxygen concentrations in R-1 were measured and found at times to be lower in the treated drainage than untreated drainage. Nitrification rates may have been high enough in R-1 to utilize the oxygen produced by photosynthetic activity of the flora present in the reservoir. The oxygen produced by the plant species in the series of reservoirs and the control may have been enough that nitrification did not deplete this oxygen source by any appreciable amount. It was difficult to determine the extent of ammonium-N by nitrification without further studies but it was assumed to be an integral part of the processes involved in ammonium-N reduction in the reservoirs under study.

The reservoirs in series and the control reservoir were both slightly alkaline with pH in the outflow ranging from 7.7 to 8.3 and 7.9 to 8.7 respectively. This alkaline condition would shift the ammonium equilibrium to favor the formation of the gaseous NH_3 resulting in a loss of ammonium-N via volatilization (Stratton 1969). The pH of the treated and untreated drainage in R-1 was close to neutral, ranging from 6.8 to 7.7 in the outflow, and could have resulted in less ammonium-N liberated by the gaseous form in this reservoir. No direct measurements of ammonium volatilization were made in this study; however, Stratton (1969) observed a 5.8% reduction by volatilization of ammonium-N in lakes. Ammonium-N may have also been assimilated by algae but the majority of ammonium-N is adsorbed to particulate and colloidal inorganic particles (Keeney 1973). The adsorption process is especially prevalent under alkaline conditions and in waters containing high concentrations of humic dissolved organic matter. The particles settle on the bottom and are adsorbed to the sediments. Ammonium-N can then be oxidized by nitrifying bacteria in the interstitial zone or diffuse into the water when mixing occurs. The extent of oxidation of ammonium-N in the surface sediments and the adsorption properties of the sediments for ammonium-N was not measured in this study, but may have been as important as volatilization and nitrification in the water column of the reservoirs in reducing ammonium-N concentrations of drainage water.

The mean yearly reduction of 73.7% by the series of reservoirs, 57.9% reduction by R-1 and 75.5% reduction by the control were not significant at the 0.05 level. Only four of the 14 monthly averages for treated and untreated drainage water were significantly different in the control and the series of reservoirs. Six of the 14 monthly inflow and outflow averages for the large reservoir were significantly different at the 0.05 level (Fig. 7). The variance that was encountered in the field flow measurements probably reduced the differences between inflow and outflow. The high variance was associated with rain events, fertilizer practices in the area, and possibly the conditions of the reservoirs at the start of the experiment (i.e. soil high in organic nitrogen) (Table 2). Regardless of the variance encountered, the ammonium-N concentrations decreased in the drainage water after treatment.

Nitrate Nitrogen

Maximum peak concentrations of nitrate-N were observed during January, February, and March of 1978 when values of 1.88 mg/l were measured in the untreated drainage water for the series of reservoirs and 2.76 mg/l in untreated drainage water for R-1. Other peak concentrations of nitrate-N observed for untreated drainage water occurred during July and August of 1977 (Fig. 8). The winter and summer peak concentrations of drainage water coincided with the rain events which may have leached nitrate-N from the adjacent farm fields. The concentrations of nitrate-N for the treated drainage water from each reservoir were low, ranging



*Indicates significance at the 0.05 level.

Figure 8. Rainfall and nitrate-N concentrations in the reservoir systems.

from 0.01 mg/l to 1.0 mg/l. The lowest values of nitrate-N for treated drainage water were measured during the summer, with an average concentration of 0.05 mg/l. The average winter concentration for treated drainage water was 0.20 mg/l. The difference in average concentrations for summer and winter from treated drainage water for both reservoir treatments was probably the result of slow assimilation by aquatic plants and lower activity of denitrifiers during the winter season.

Nitrate-N was reduced in all reservoirs, including the control throughout the 14 month period. The smaller reservoirs in series functioned most efficiently with an average removal of 80.2% nitrate-N. The large reservoir removed 65.6% of the nitrate-N and the control reservoir removed 74.6% of the nitrate-N.

The DO concentration in the water column beneath _E. crassipes_ was less than 1 mg/l which favored conditions for dentrification. The activity by the denitrifiers and other microbes in the sediment-water interface as well as the assimilation by the hyacinths may explain the large proportion (61%) of nitrate-N removed in R-2. Allowing the water to flow through the remaining reservoirs (R-3 and R-4) reduced the nitrate-N concentrations by an additional 22%, through denitrification and plant assimilation. The latter two reservoirs increased the DO in the drainage water to values ranging from 6 mg/l to 12 mg/l.

The chemical reactions that took place in the plant stands in the series of reservoirs should have also occurred in R-1, with similar results. However R-1 was less effective in the removal of nitrate-N (65.6% reduction) than the series of reservoirs (82.0% reduction). The hyacinth stand in R-1 probably created anaerobic conditions as in R-2 which increased denitrification in both the water column and the sediment-water interface. As the drainage water passed through the stands of E. densa and Typha sp., nitrate-N concentrations probably increased, thus reducing the overall nitrate-N reduction from this reservoir. The increase in nitrate-N that may have occurred in the E. densa and Typha stands of R-1 was probably the result of the increased ammonium-N produced from decomposition of plant material left in the reservoir prior to this study and from runoff.

The reduction of nitrate-N in the control reservoir was probably the result of denitrification in the sediment-water interface and uptake by algae and aquatic plants. Denitrification in the water column was probably minimal since anaerobic conditions were not established in this reservoir as in the water column under the hyacinth stands.

The process of denitrification is the reduction of nitrate-N to gaseous end products such as N_2O, NH_3, and N_2. There are three basic requirements necessary for dentrification to proceed in the lentic environment: an organic carbon source, a dissolved oxygen concentration of less than 0.5 mg/l and a pH near neutrality (Reeves 1972). These conditions existed in the sediment-water interface in the reservoir systems and especially for those sediments under water hyacinth stands (Reddy et al. 1980).

Denitrification may also occur in the water column of lakes when the proper conditions are present. An 11.1% reduction of nitrate-N by denitrification took place in the hypolimnion of Lake Mendota (Brezonik and Lee 1968). The critical condition in the water column necessary for the reduction of nitrate-N was anoxia, in which dissolved oxygen concentrations were below 1.0 mg/l. The anoxic condition established in Lake Mendota was the result of summer stratification, and respiration in the deep water zone. Deep water conditions and stratification did not exist in the reservoirs; however, low DO concentrations (1 mg/l) were established in the water column under the hyacinths.

A reduction of nitrate-N by 6.0% and 8.4% was attributed to macrophytes in lakes and sewage treatment plants respectively (Dunigan et al. 1975; Cornwell et al. 1977). The high nitrate-N reductions measured in the reservoir systems in this study, when compared to removal of nitrate-N by aquatic plants in these studies indicated that denitrification and assimilation by other biota may have been actively involved in the nitrate-N removal.

Removal of nitrate-N by algae is also important, but was not studied in this project. Neel et al. (1961) demonstrated a 90% removal of N in pond studies via algal assimilation. In studies with domestic waste water effluents, a 98% reduction of the total inorganic N took place also using algae (Gates and Brochardt 1964).

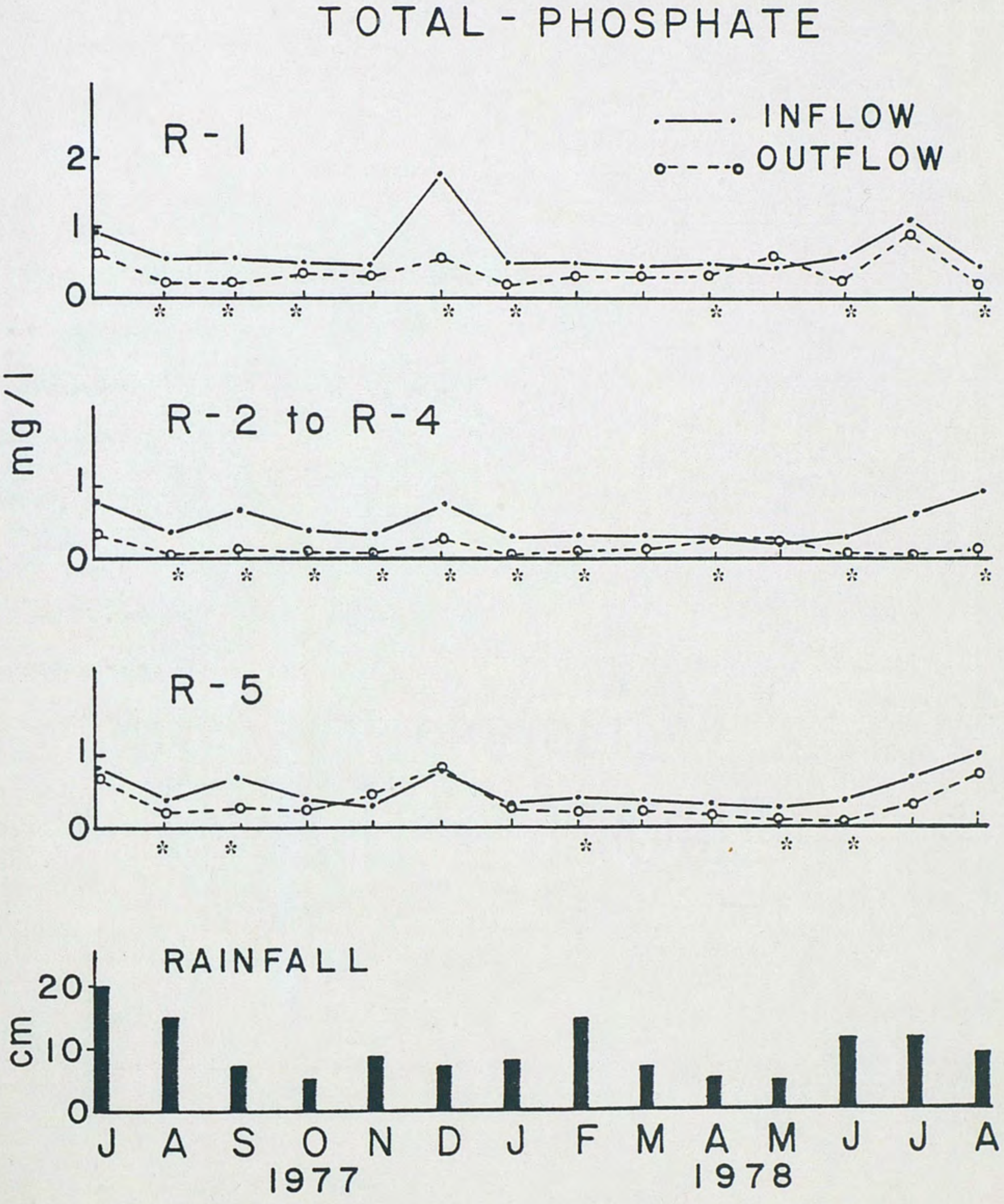
The catabolism of the littoral flora, including the vascular macrophytes was a dominate source of organic N to the water and sediment. Bacterial metabolism in the sediment can significantly influence the flux of N from the water to sediments and vice versa. Release of N from sediments also varies greatly with sediment composition. For example, release of N from sediments of the Rybinsk Reservoir was greatest in silts high in organic matter. Much loss occurred in the form of N_2 produced during anaerobic decomposition of sediment organic matter (Kunznestov 1968). The process of denitrification in the sediment and nitrogen flux between sediment and water was not measured but may have accounted for the large reduction of nitrate-N observed in the reservoirs.

Monthly averages for inflow and outflow differed significantly at the 0.05 level (Fig. 8). The variance that was encountered in the field study may have resulted in small differences between the treated and untreated drainage water. This variance was related to rain events and other uncontrollable variables. Regardless of the variance, the nitrate-N concentrations decreased in the drainage water after treatment.

Total Phosphorus

Phosphorus values for untreated drainage water ranged from 0.2 mg/l to 1.69 mg/l. Maximum concentrations for total-P were observed during the months of peak rainfall. Two exceptions were observed in which total P concentrations of untreated drainage water were lower than that of treated drainage water. The first exception took place in August of 1978 where the source for R-1 was contaminated by lake water from nearby Lake Apopka. Lake water was used to flood farm land located adjacent to the drainage ditch containing the untreated drainage water. Run-off and seepage from the flooded fields occurred at the pumping station for R-1 and may have diluted the total-P concentrations during this period. The second deviation took place during the month of February of 1978, when high rainfall was not accompanied by an increase in the total-P for the untreated drainage water (Fig. 9).

The annual mean reduction for total-P was calculated to be 70.8% in the series of reservoirs, 51.0% for the large reservoir and 33.3% in the control reservoir. These results indicated that R-1 was not as efficient in the removal of the total-P as the series of reservoirs.



*Indicates significance at the 0.05 level.

Figure 9. Rainfall and total-P concentrations in the reservoir systems.

The reduction of the total-P observed in the reservoirs was probably the result of adsorption of ortho-P in the sediment, precipitation by calcium carbonate and assimilation by aquatic plants.

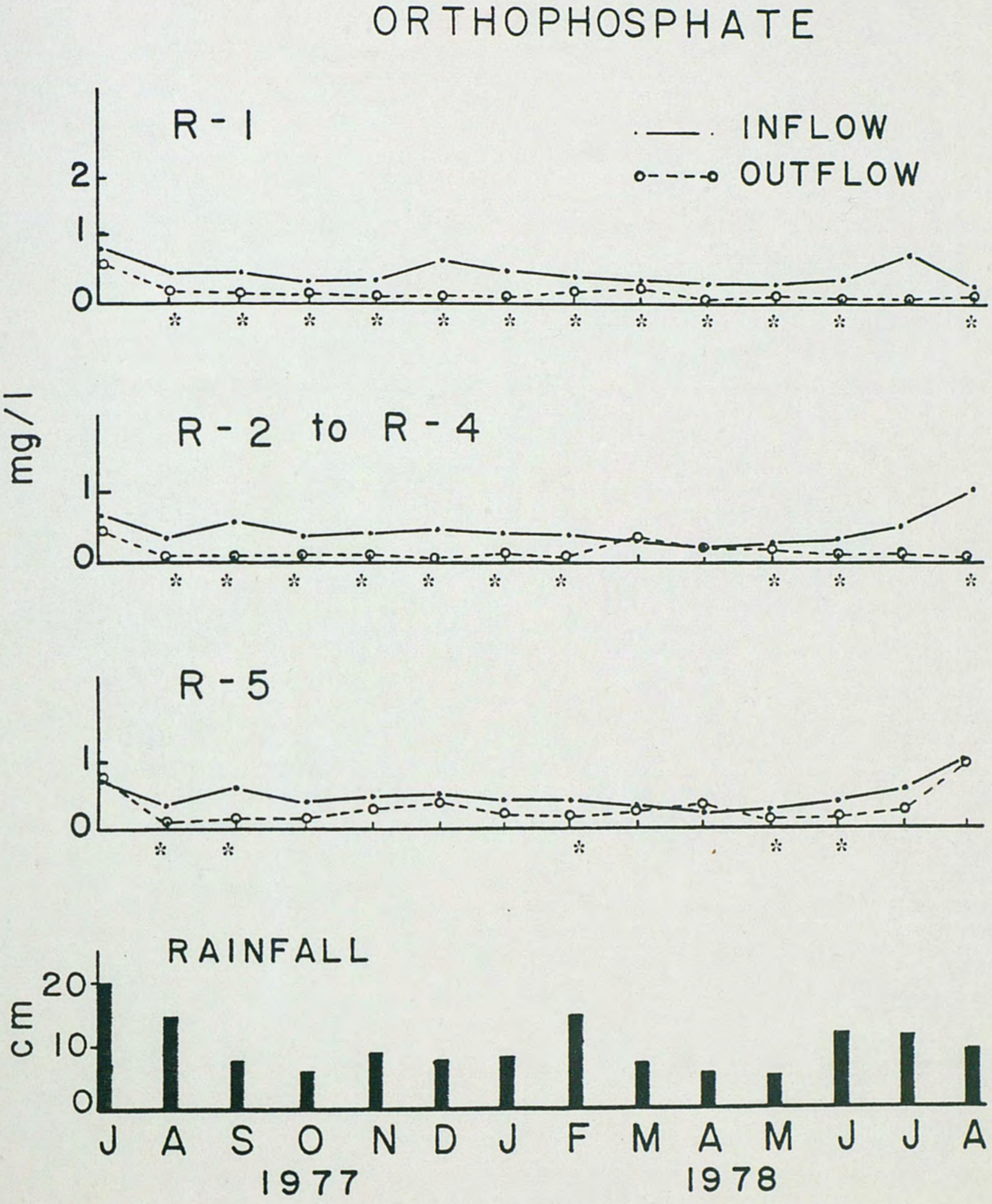
The reduction of the total-P was highly significant at the 0.05 level with 10 of the 14 calculated 'T' test values indicating a significant decrease of total-P in the series of reservoirs. Eight out of the 14 monthly mean values measured for treated and untreated drainage water from R-1 were significantly different at the 0.05 level and five of the 14 calculated mean values indicated a significant decrease at the 0.05 level of total-P by the control reservoir (Fig. 9).

Orthophosphate

The ortho-P never exceeded a mean value of 1.0 mg/l in the three reservoirs monitored for the 14 month period. Untreated drainage water measurements ranged from 0.01 mg/l to 0.09 mg/l. These levels exceeded the 0.01 to 0.03 mg/l range believed to be sufficient to produce several algal blooms (Porter 1975). The inflow concentrations of ortho-P were greatest during the months of highest rainfall, with maximum values occurring during July, August, and September of 1977, June, July, and August of 1978 and again in November, December, and January of 1977-78. There were two months in which maximum ortho-P concentrations did not coincide with maximum rainfall values. The first exception took place in August of 1978 in which the source for R-1 (untreated drainage water) was contaminated by water from nearby Lake Apopka. Lake water was used to flood farm land located adjacent to the drainage ditch containing the untreated drainage water. Run off and seepage from the flooded fields occurred at the pumping station for R-1 and may have diluted the ortho-P concentration during this period. The second deviation took place during February of 1978, where high rainfall was not accompanied by an increase in ortho-P for the untreated drainage water (Fig. 10).

Substantial reduction of ortho-P concentrations were observed in all reservoir treatments during the 14 month study. The series of reservoirs reduced ortho-P by a yearly mean of 74.3%, while the large reservoir reduced ortho-P by a mean value of 70.3%. The control reservoir, however, reduced ortho-P by only 32.9%.

The potential of the plant material to remove ortho-P from the effluent would depend upon the retention time of the effluent, the concentration of the nutrient, the assimilative capacity and the productivity of the plant species. Water hyacinths in particular have been reported to have a great potential for removing nutrients from waste water polishing ponds because of a high productivity rate (Steward 1970). Data collected by other investigators has been both



*Indicates significance at the 0.05 level.

Figure 10. Rainfall and orthophosphate concentrations in the reservoir systems.

in conflict with and supportive of this concept (Cornwell et al. 1977; Ornes and Sutton 1975; and Dunigan et al. 1975).

Rooted and submergent aquatic plants are not as effective in removing ortho-P from water as free-floating plants (Steward 1970). However, these rooted species may be important in removing the P tied up in the sediments via the root system. Studies conducted with _E_. _densa_ concluded that 74% of the ortho-P contained in shoots was absorbed from the rooted portion of the plant and not the ambient medium (Bristow and Whitcombe 1971). _Chara_, rooted in polishing ponds containing treated waste water, reduced ortho-P concentrations by 78% (Ryther et al. 1977). The cattails in the reservoirs, with their extensive root system can contain up to 42% of the total-P making up the plant (Davis 1978).

The fate of P contained in the drainage water other than assimilated by the biota was precipitation, adsorption, desorption or dissolution. The adsorption of P from solution under acidic conditions is related to the presence of amorphous oxides and hydrous oxides of iron and aluminum. Under alkaline soil conditions adsorption of inorganic P is by calcium carbonate. Adsorption via this route may have occurred in the reservoirs since the sediments were composed of calcarious rock and unconsolidated marl (Wetzel 1975).

Precipitation reactions of P with calcium carbonate may have also taken place in the reservoirs. Carbon dioxide in the drainage water hydrates at a pH of less than eight, forming carbonic acid. The carbonic acid that is formed solubilizes the limestone of the calcium enriched rock underlying the reservoirs forming calcium carbonate which precipitates phosphate as calcium phosphate. Calcium carbonate is also formed when carbon dioxide is removed from the drainage water by photosynthetic metabolism (Wetzel 1975). These precipitation reactions may have caused P removal in the reservoirs since carbon dioxide was reduced by 84% in the series of reservoirs, 22.6% in the large reservoir and 98.3% in the control. One final means of P removal in the soil solution is the reaction with silicate minerals (Sawhney and Hill 1975). The fate of the P not removed by adsorption or precipitation was the assimilation by algae, aquatic macrophytes and other biota.

One approach to distinguish the movement of P in the reservoirs is to divide the flux into three distinct compartments similar to those described by Hutchinsen and Bowen (1950), Rigler (1956), Hayes et al. (1952), Chamberlain (1968) and Confer (1972). The compartment theory would divide the reservoirs into a) the open water organisms, mainly algae, b) the littoral organisms, mainly rooted macrophytes and epiphytes and c) the sediment. The shallow reservoir units with the extensive macrophyte material exemplify the littoral region of most lakes. Therefore the movement of P is confined mainly to this littoral zone and sediments.

An important result of the tracer studies conducted by the above authors was the initial rapid loss of tracer from the open water. Each study followed the movement of P from the open water zone to the littoral region with a turnover rate from 0.1 to 4 days, depending upon the physical and biological conditions. The initial rapid loss of P in each study was attributed to the planktonic and epiphytic algae, which were not analyzed in this study. The net movement of P from this point was not clear; in one case the sediments were viewed as a continual source of P while the littoral region was viewed as a dead end trap for P (Confer, 1972). Most of these tracer studies were undertaken in lakes which stratified during the summer. This resulted in limited mixing of the epilimnion with the hypolimnion and sediments. The reservoirs on the other hand were mixed by inflowing effluent. No stratification or deep hypolimnion existed and interactions with sediments may have played a major role in nutrient abatement as well as uptake by plant material.

Although algal measurements were not undertaken in this field study, the possibility existed that the initial flux of P in the reservoirs was also reduced by the algae. Upon death algal cells release P which will be absorbed by the sediments or removed by the macrophytes and other algae. A direct relationship of P concentration to algae growth was shown by Srinath and Pillae (1972) who studied the relationship of algal populations in waste water effluents. Rigler (1956) showed a P reduction of 50% in 3.7 days for tracer experiments conducted on Toussaint Lake. This reduction was also attributed to the algae present. These reduction rates by algae and the deposition into sediments may have also been involved in the high rates of P removal observed in the reservoirs.

The overall reduction of ortho-P in the reservoirs was due to a combination of chemical and biological reactions as well as algal and angiosperm removal. The reduction of ortho-P that occurred in the series of reservoirs was highly significant ($p<0.05$) for the averaged monthly values. Ten of the 14 calculated values measured for treated drainage water and untreated drainage water were significantly different for the series of reservoirs. Eleven of the monthly mean values for ortho-P were significantly different between the inflow and the outflow, while the control had only five mean values that were significantly different (Fig. 10).

Overview: Primary Nutrients

The major nutrient fractions (ie. nitrate-N, ammonium-N, organic-N, ortho-P and total-P) of the agricultural drainage water from the organic soils were closely associated with the agricultural practices, rainfall and biochemical reactions in the organic soil. For example the increased nitrate-N concentration of the drainage water during winter months coincided with fertilization practices conducted during this period and increased rain events which probably resulted in leaching of nitrogen. During the summer months when the soils were kept fallow by flooding, nitrate-N concentrations were generally low in the untreated drainage water. Under the fallow conditions, the initial nitrate-N was probably denitrified and ammonium-N accumulated in the soil. During winter months, fertilizer applications and death of plant material (i.e., _Eichhornia_, _Typha_, _Hydrocotile_ and various grasses) in the drainage canals probably increased the ammonium-N accumulated during the flooding of the fields and leached into the drainage canals during heavy rain events. Ortho-P concentrations of the drainage water was also correlated with rain events. During the summer, high ortho-P concentrations were probably a result of leaching from flooded organic soils. Ortho-P concentrations pulsed during the summer when the _Eichhornia_ in the main drainage canals was killed by herbicide applications. During the winter months, soluble P increased due to 1) plant decay in the canals as a result of freezing and 2) fertilizer application for winter vegetable crops (Reddy et al. 1980).

Use of aquatic plants in the reservoirs created environments which differed in their physical and chemical makeup. Presence of E. crassipes, in the reservoirs decreased the DO concentration of the water column, thus creating an anaerobic environment. The E. densa replenished the oxygen in the system. The presence of Typha in the reservoirs functioned as an additional nutrient sink by depleting the interstitial nutrient concentration of the underlying sediments. The E. crassipes and E. densa in the reservoirs prevented the extensive growth of algal populations. The control reservoir initially with no cultivated aquatic plants became infested by Chara and other algae which functioned as nutrient sinks for the drainage water flowing through this system.

The use of a series of reservoirs containing separate stands of aquatic plants functioned more effectively in the removal of the various fractions of N and P from agricultural drainage water, compared to a single large reservoir (Table 3). By treating the agricultural drainage water from organic soils using these reservoir systems, nutrient loading into Lake Apopka can be reduced by at least 70 to 80% for the inorganic fractions of N and P in the series of reservoirs and 60 to 70% for the single large reservoir.

Table 3. Efficiency of the reservoir systems evaluated as a nutrient sink, expressed as percent reduction/increase in concentration.*

Reservoir System	Percent Reduction/Increase in Concentration				
	NO_3-N	NH_4-N	Organic-N	PO_4P	TP
Series of reservoirs	80.2	73.7	33.1	74.3	70.8
Large reservoir	65.6	57.9	- 7.2	70.3	51.0
Control reservoir	74.6	75.5	8.2	32.9	33.2

Percent reduction/increase in concentration = (I - O/I) 100
where:

I = inflow concentration of the drainage water
O = outflow concentration of the drainage water

Positive sign indicates the reduction in the nutrient content and negative sign indicates the increase in the nutrient content of the drainage water.

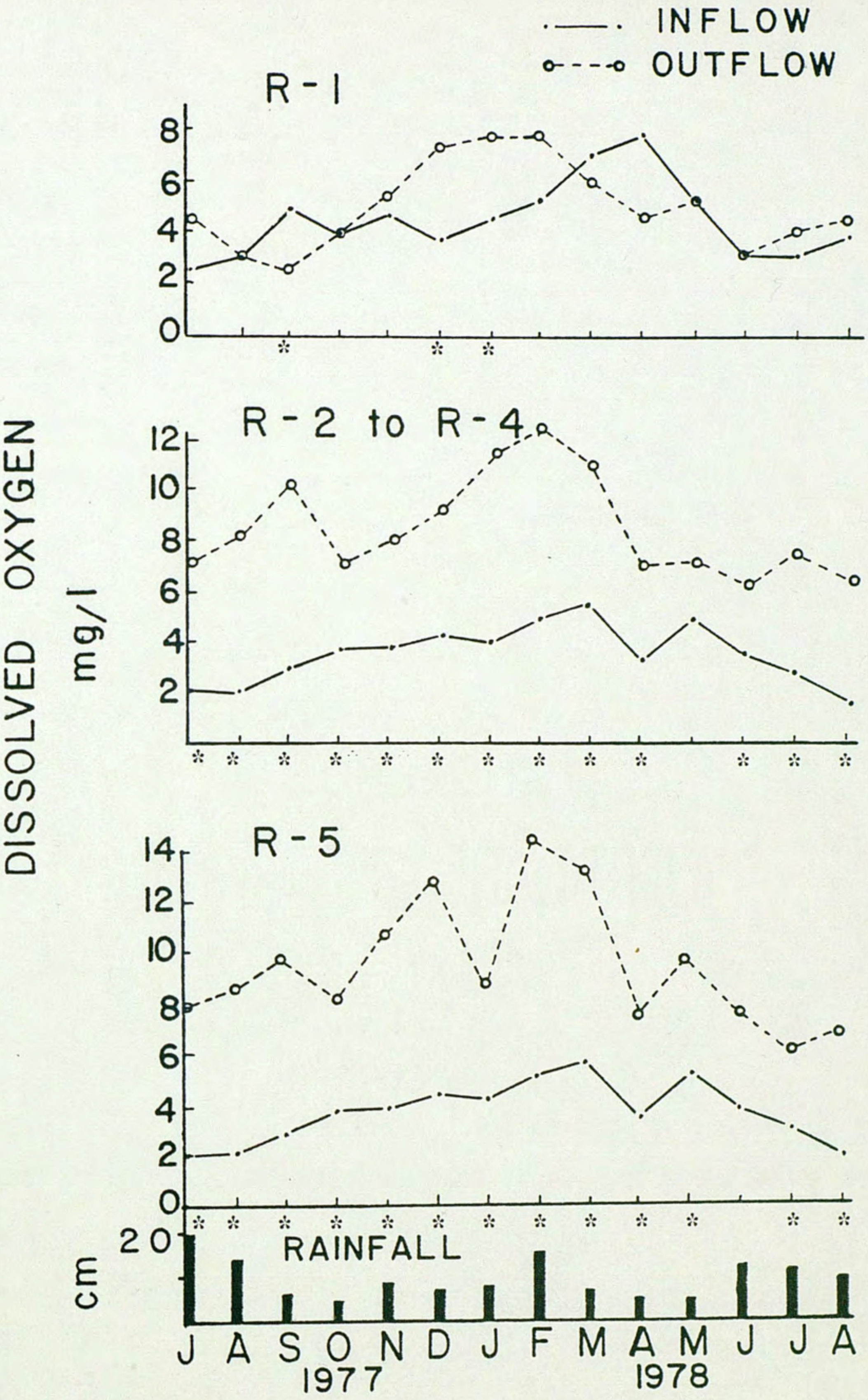
Secondary Nutrients and Physical Parameters

Dissolved Oxygen

Oxygen concentrations in R-5 and the series of reservoirs for treated drainage water were greater than twice those observed for the untreated drainage water throughout the 14 month period. Maximum mean outflow concentrations for R-4 and R-5 were observed during winter months. Reservoir R-5 attained a maximum concentration of 14.7 mg O_2/l in treated drainage water, while R-4 attained a maximum concentration of 12.5 mg O_2/l. Both of these values were observed during the month of February 1978 (Fig. 11). The DO concentrations in R-1 did not respond in this manner. The only period that DO concentrations of treated drainage water exceeded untreated drainage water by any appreciable amount was during December 1977 and January 1978 (Fig. 11). Maximum DO concentrations for treated drainage water in R-1 were observed in December, January, and February with mean concentrations of 7.47, 7.95, and 7.80 mg/l respectively.

The control reservoir increased oxygen levels as effectively as the series. This was probably the result of photosynthetic activity of the algal blooms that were observed and the submergent algae *Chara* that contaminated this reservoir.

Photosynthetic activity of macrophytes along with epiphytic algae generate large amounts of oxygen. Luxuriant



*Indicates significance at the 0.05 level

Figure 11. Rainfall and dissolved oxygen concentrations in the reservoir system.

stands of *E. densa* have increased DO concentrations to greater than 9.0 mg/l (Buscemi 1958). The *E. densa* was utilized in an effort to increase the oxygen concentration of the effluent after treatment with water hyacinths.

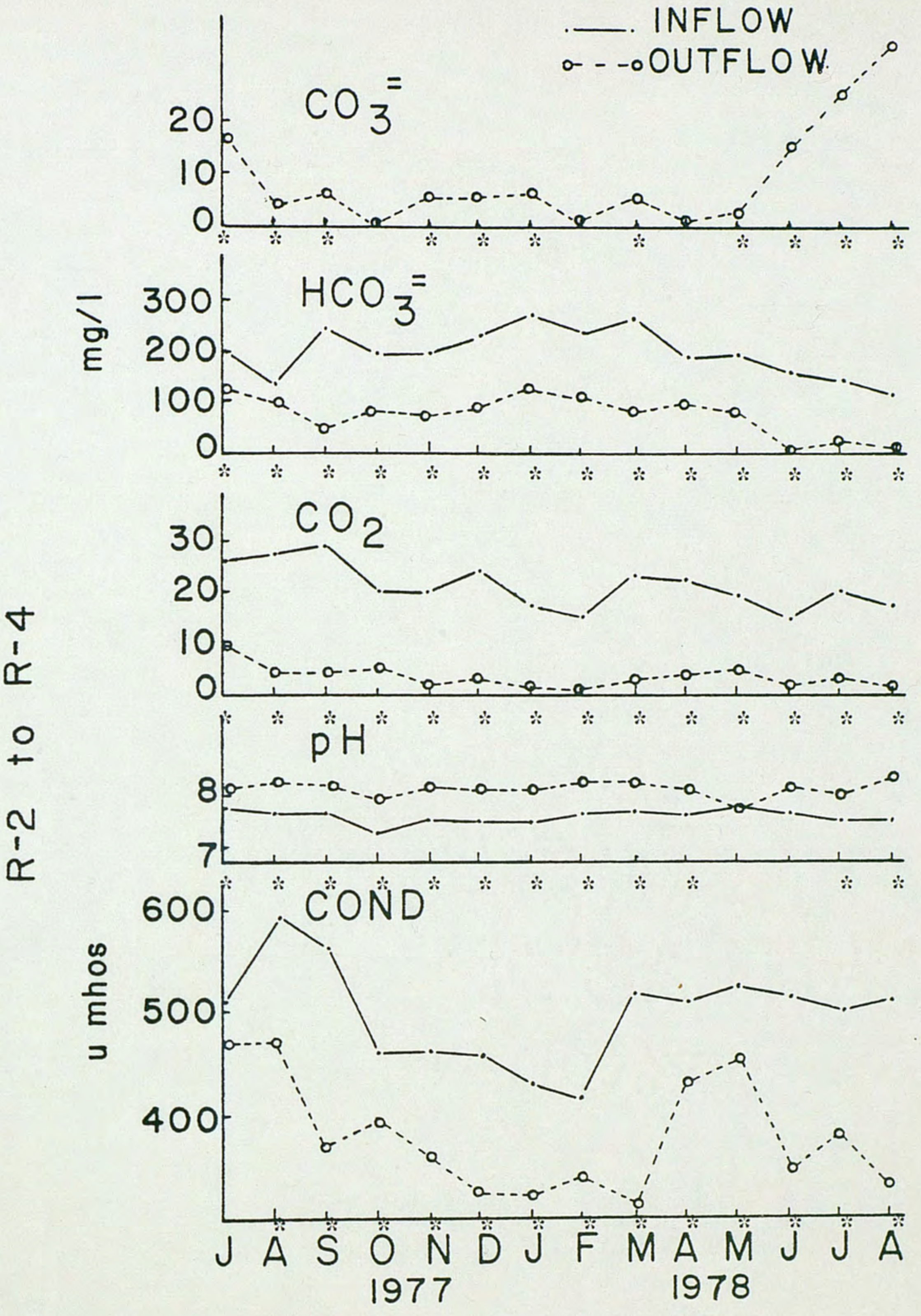
Even though similar aquatic plant species were used in both reservoir systems and production was greater in R-1, the DO concentration was greater in the series of reservoirs. This may have been a result of decayed organic material present in this reservoir at the start of this experiment.

The increased dissolved oxygen of treated drainage water in the series of reservoirs during the 14 month period was significant at the 0.05 level. Thirteen calculated t values indicated that the change (increase) in dissolved oxygen concentrations for treated drainage was significantly different from the untreated drainage. The only month that dissolved oxygen did not increase in the treated drainage from the series of reservoirs was during April 1978 which was a period of lower productivity for *E. densa*. The increase in dissolved oxygen concentration in the treated drainage water from R-1 was significant only twice, and occurred during December and January (Fig. 11). However, the solubility of oxygen would be greatest during these months because it is inversely related to temperature (Wetzel 1975).

The increase in dissolved oxygen observed in treated drainage from the control reservoir was also significant, in 12 of the paired t tests (Fig. 11). The increase of DO in this reservoir was probably the result of the photosynthetic production of oxygen by algae observed growing at the start of the experiment and later by the submergent plants that contaminated this reservoir.

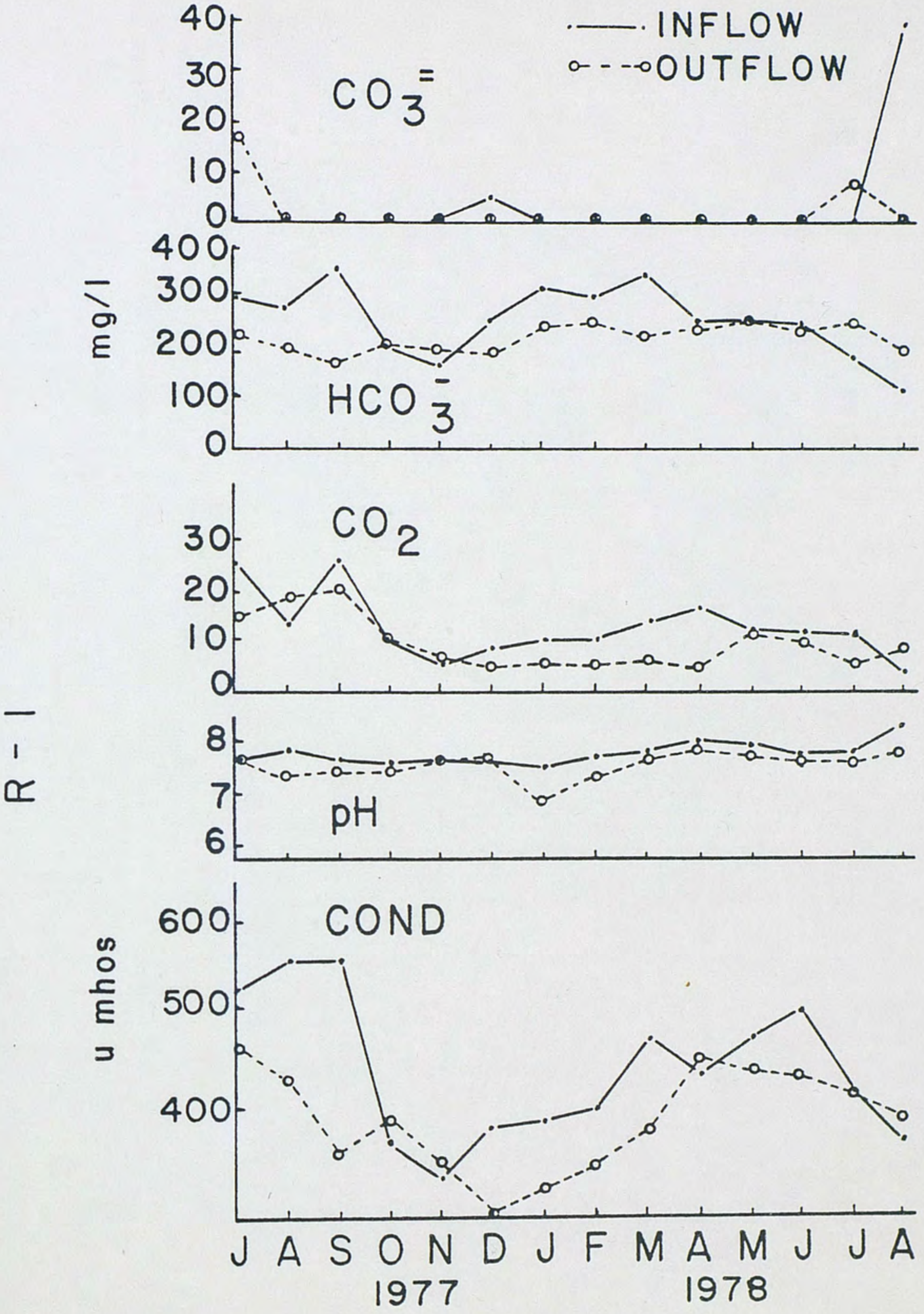
Specific Conductance, pH, Carbon Dioxide, Bicarbonates, and Carbonates

Measurements were made of specific conductance (EC), pH, carbon dioxide, bicarbonate and carbonate concentration of untreated drainage water. During the summer the EC for untreated drainage reached a maximum mean value of 552 µmhos in R-1 and 595 µmhos in the series of reservoirs. These maximum values corresponded to peak rainfall. During winter when rainfall was heavy, the EC values for untreated drainage water were at a minimum with 336 µmhos measured in the untreated drainage from the center ditch. The EC values did not increase in response to rain events during the winter as was observed in the summer (Figures 12 through 14). This seasonal difference in EC values observed for untreated drainage may have been due to farming practices conducted in the area. For example, during March through May the farm lands were being cultivated, planted with corn, fertilized and sprayed with various insecticides and fungicides. After



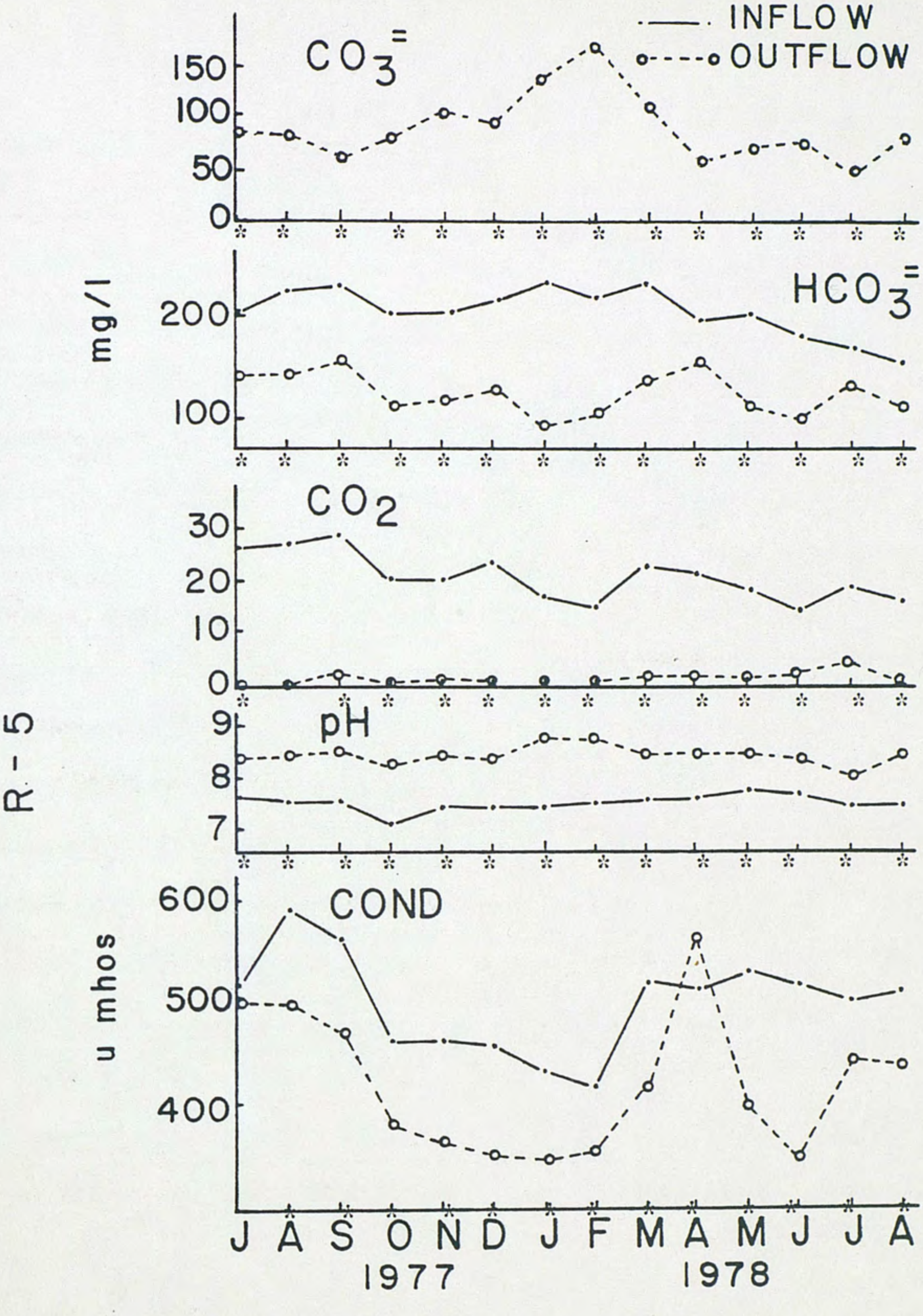
*Indicates significance at the 0.05 level.

Figure 12. Conductance, pH, carbon dioxide, bicarbonate and carbonate data in the series of reservoirs.



*Indicates significance at the 0.05 level.

Figure 13. Conductance, pH, carbon dioxide, bicarbonate and carbonate data in the large reservoir.



*Indicates significance at the 0.05 level.

Figure 14. Conductance, pH, carbon dioxide, bicarbonate and carbonate data in the control reservoir.

the harvest in June the soils were flooded with water from nearby Lake Apopka. The flooded conditions were maintained through August. During late August and September the fields were dried and cultivated for winter crops of carrots, various lettuces, radishes and other leafy plants. In February and March the fields were prepared for the annual corn crop.

Conductivity of the treated drainage water was reduced by 10.3, 24.8, and 15.8% in the large, the series, and the control reservoirs, respectively. The mechanisms involved in the reductions in EC were not studied in detail but may be attributed to precipitation, runoff, dilution, or plant uptake of ions. The reduction of EC was significant at the 0.05 level for the control and both treatment reservoir systems (Figures 12 through 14).

The EC of water is a measure of the resistance of a solution to electric flow. This resistance to electron flow is reduced with an increase of ionized salts. Therefore pure water has a greater resistance than water that is higher in salinity. The seven major cations and anions that are expressed as the salinity of water and directly influence the EC are; Ca^{++}, Mg^{++}, Na^{++}, K^{+}, CO_3^{--} SO^{--}, and Cl^{-} (Wetzel 1975).

In R-5, the average pH of the treated drainage water was 8.4 and for untreated drainage water, 7.5, an increase of 0.8 pH units. The pH in the series of reservoirs increased by 0.5 pH units, with an average of 7.5 in the untreated drainage water and an average value of 8.0 in the treated drainage water. The pH of treated drainage water in R-1 decreased from an average of 7.7 to 8.5 (Figures 12 through 14). The increase in pH for treated drainage water in R-5 and the series of reservoirs was closely associated with a decrease in conductivity, carbon dioxide and bicarbonates and an increase in carbonates (Figure 12 through 14). Almost no change was observed in the above parameters for the treated drainage water in R-1.

The carbon dioxide concentrations for untreated drainage water ranged from 3.2 mg/l to 25.7 mg/l for R-1 and 14.3 mg/l to 29.3 mg/l for R-5 and the series of reservoirs respectively. Carbon dioxide was reduced by 84.4% in the series of reservoirs by 22.6% in the large reservoir and by 98.3% in the control. The equilibrium concentration of dissolved carbon dioxide in water should range from about 0.4 mg/l to 1.1 mg/l (Hutchinson 1975). The high carbon dioxide concentrations measured in the inflow may have been attributed to bacterial activity. It has been reported that bacteria can supersaturate natural water with more than 20 mg/l of free carbon dioxide provided there is a high inorganic carbon source (Kuentzel 1969). Accompanying this decrease in carbon dioxide was an increase in dissolved oxygen to a maximum value of 12 mg/l in the outflowing water of the series of reservoirs. The high DO values were probably the result of a high photosynthetic production rate of the aquatic macrophytes and algae which utilized the carbon dioxide as a carbon source (Wetzel 1975). The low carbon dioxide reduction and high primary productivity in R-1 indicated that the aquatic macrophytes and algae may have utilized a carbon source other than carbon dioxide, or more carbon dioxide was being generated by microbial activity. Microbial activity might also have accounted for the low DO production observed in R-1. Part of the carbon dioxide may react with the drainage water by the following formula:

$$CO_2 + H_2O \rightleftarrows H_2CO_3$$

This reaction predominates at a pH of less than eight (Wetzel 1975). The carbonic acid that is formed solubilizes the exposed limestone ($CaCO_3$) of the calcium enriched rock underlying the drainage ditches and reservoirs, forming calcium bicarbonate ($Ca(HCO_3)_2$). The formation of the calcium bicarbonate was probably the predominant reaction in the ditch water as the untreated drainage water flowing over the marl was between a pH of seven to eight (Figures 12 through 14). The excess carbon dioxide maintained the stability of calcium bicarbonate in solution according to the following reaction:

$$Ca^{++} + 2HCO_3^{-} \rightleftarrows CaCO_3 + H_2O + CO_2$$

As the drainage water was depleted of its carbon dioxide, the above reaction was shifted to the right. This shift was observed as calcium carbonate ($CaCO_3$) precipitated on the *Chara* and *E. densa*. Accompanying this loss of excess carbon dioxide by photosynthesis was a shift in the balance of bicarbonates to carbonates and of a pH to greater than eight (Figures 12 through 14). Reservoir R-1 did not respond in the same manner as R-5 and the series of reservoirs. The carbon dioxide remained high and was probably the result of the increased microbial respiration.

The loss in carbon dioxide and the shift from bicarbonates to carbonates was significant at the 0.05 level in the series and the control reservoirs throughout the 14 month period. The loss of carbon dioxide and the decrease in bicarbonates for the large reservoir were significant only during December, January, February, and March (Figures 12 through 14).

Turbidity

Turbidity in the outflow was significantly reduced ($p<0.05$) in the reservoirs containing aquatic macrophytes. The single large reservoir reduced the turbidity by 35.8% for the 14 month study period, while the series of reservoirs reduced the turbidity by 31.3% (Table 4). The control pond on the other hand reduced turbidity by only 0.5% during the 14 month period. However, during the last six months,

Table 4. Monthly and yearly mean turbidity measurements for the 14 month study period for the reservation systems. Included are calculated (t) values for the paired difference test.

	Reservoirs								
	Series			Large			Control		
Date	In	Out	t	In	Out	t	In	Out	t
Jul	2.27	4.33	-2.38*	3.37	4.87	-1.11	2.67	4.42	-1.88
Aug	2.50	5.99	-5.05*	1.97	2.61	-1.77	2.50	2.99	-3.65*
Sep	2.62	3.19	-2.54*	2.47	2.75	-0.55	2.62	2.27	1.36
Oct	2.50	2.07	1.84	3.92	2.54	2.47*	2.50	2.89	1.84
Nov	2.56	2.21	1.85	5.61	2.03	3.53*	2.56	-1.63	-1.63
Dec	2.70	1.92	2.79*	3.81	2.26	3.66*	2.70	3.46	-2.16
Jan	3.61	2.01	4.41*	3.69	2.00	2.38*	3.62	4.44	-3.27
Feb	4.33	2.37	1.64	4.65	3.35	1.95	4.33	6.28	-2.06
Mar	4.65	2.69	2.71*	3.80	2.50	2.87*	4.65	4.60	0.04
Apr	5.65	1.78	4.63*	6.35	3.03	5.22*	5.65	3.13	4.46*
May	5.51	2.19	4.64*	6.59	3.60	4.89*	5.51	4.00	1.17
Jun	3.47	1.60	2.35*	4.20	2.38	4.93*	3.47	2.20	1.81
Jul	6.36	2.90	2.30	6.85	3.00	3.05*	6.36	4.66	1.12
Aug	4.98	1.93	3.77*	3.33	3.22	0.08	4.98	3.58	1.81
Mean	3.84	2.66		4.35	2.79		3.86	3.85	
sd	1.39	1.20		1.50	0.75		1.36	1.16	
		30.7%**			35.8%**			0.3%**	

*Indicates significance at the 0.05 level
**Percent reduction

the turbidity in the control was reduced by 15.2%, essentially due to the presence of the aquatic macrophyte *Chara*.

In R-1 and the series of reservoirs, turbidity of the treated drainage water was increased during the first three months of the study. However, this increase was only significant ($p<0.05$) for the series of reservoirs. After the plant material became fully established in the reservoirs, turbidity measurements were reduced in the treated drainage. There was a significant decrease ($p<0.05$) in turbidity in the series of reservoirs for eight of the last nine months of the study. The decrease in turbidity for the large reservoir was also significant during nine months of the study indicating a significant decrease in the treated drainage (Table 4). There was an increase in turbidity during the first eight months in the control but only one measurement was significant ($p<0.05$). The decrease in turbidity in R-5 after the plant species became established was significant only once during the last six months (Table 4).

The reduction in turbidity was probably the result of the presence of the macrophytes which reduced mixing that would suspend particulate organic material and reduce algae by shading and competiting for nutrients.

Overview: Secondary Nutrients and Physical Parameters

Inorganic carbon fractions, carbon dioxide, bicarbonate, and carbonates were monitored in the two reservoir systems and control. The results indicated that the series of reservoirs were more efficient in reducing carbon dioxide and bicarbonates than the large reservoir. Accompanying the loss of carbon dioxide in the small reservoirs was a shift in the carbonate equilibrium to the carbonate side and an increase in pH (Table 5). The reduction of the carbon dioxide may have been important since it is considered to be a major source of inorganic carbon for algal blooms (Kuentzel 1969). This, however, may be dependent upon the type of algae present. Species that are characteristic of oligotrophic waters may utilize only the free carbon dioxide and do not grow at pH values above 8.6 to 8.8, whereas species characteristic of eutrophic waters may grow above pH of 9.0, either using bicarbonates directly or using carbon dioxide in very low concentrations (Moss 1973). In lieu of these data, it may be more advantageous to dump the effluent from R-1 into a natural system, rather than from the series of reservoirs.

As the carbon dioxide concentrations dropped in the reservoirs, DO increased. The mean DO value in the outflow of R-1 was 5.1 mg/l while that of the reservoirs in series was 8.5 mg/l. The series of reservoirs produced over 90%

more oxygen than R-1. This increase in DO and loss of carbon dioxide was consistent with the photosynthetic formula and was probably a result of the greater production of the submergent macrophytes _E_. _densa_ and _Chara_ (Table 5).

The EC decreased in all reservoirs and may have been a result of plant uptake of the cations and anions which make up the conductivity.

Both reservoir systems were effective in reducing turbidity. This was considered to be partially a physical effect of the macrophytes which reduced mixing and suspension of particulate material as well as shading which reduced algal growth. The macrophytes may have also reduced biogenic turbidity by outcompeting algae for nutrients (Table 5).

The series of reservoirs were more effective in reducing carbon dioxide and increasing DO (Table 5). Whether or not the changes in concentrations of these chemicals, resulting from treatment by the small reservoirs, are beneficial depends on one's point of view. Followers of Shapiro (1973) and King (1970) would suggest that a decrease in carbon dioxide and an increase in pH would lead to a species change where blue-green algae would probably dominate. In this case effluent water from the series of reservoirs could enhance the growth of certain blue-greens that may become a nuisance. On the other hand, Goldman (1973) suggests that

Table 5. Percent change in the chemical and physical parameters from the 14 month study period.

	Percent Reduction (-), Increase (+) in Concentration					
Reservoir System	Dissolved Oxygen	Specific Conductivity	Carbon Dioxide	Bicarbonate	Carbonate	Turbidity
Series of Reservoirs	+142.8	-24.9	-84.4	-39.0	+100.0	-30.7
Large Reservoir	+ 8.5	-11.3	-22.6	-11.2	+ 60.0	-35.8
Control Reservoir	+163.8	-15.9	-98.1	-51.3	+100.0	- 0.3

the total carbon concentration ($C_t = CO_2 + H_2CO_3 + HCO_3^- + CO_3^{-2}$) is of importance to algal growth and that the relative affinities for C_t of green and blue-green algae determines what type will dominate. From this point of view, effluent from the series of reservoirs could, by dilution, inhibit some algal species respective to their half saturation coefficients (K_s) for total-carbon-limited growth.

Standing Crop and Tissue Analysis

The standing crop data were used to compare the amount of plant material contained in each reservoir system. Theoretically the system containing the most plant tissue would have the potential to remove the greatest amount of nutrients via plant assimilation (Stewart 1970).

The tissue analyzed in this study was used to measure the percent composition of the nutrients contained in the various species grown in this study. The data generated by this analysis were utilized to determine the potential nutrient assimilative capacity of these macrophytes and is discussed in the section on nutrient budgets.

Standing Crop: Typha and Chara

The terminal shoot standing crop of Typha, was first measured on 7/4/77, approximately 70 days after initial shoot growth. Standing crop was first determined for Typha stands in R-1 on 12/8/77 with a value of 844 g/m^2. Peak standing crop values in R-4 for Typha occurred on 9/15/77 with a measured value of 795 g/m^2. A major drop in standing crop values which was probably a result of cold weather, was observed in both reservoirs, R-1 and R-4, after the sampling period on 12/29/77. The lowest standing crop values for Typha occurred on 3/3/78 with a measured value of 386 g/m^2 in R-1 and 140 g/m^2 in R-4 (Table 6). Cattails in the reservoirs were not damaged severely by frost during the winter of 1977-78 and since there was little observed death and decay, a harvest was not undertaken.

The greatest values attained for cattail standing crop were measured on 4/25/78, with a value of 1406 g/m^2 in R-1 and 1091 g/m^2 in R-4 (Table 6). These maximum values for Typha corresponded to data reported by Boyd (1970a) and Penfound (1956).

A drop in Typha standing crop was noted during the sampling period of 6/14/78, as the bulk of the cattails in both stands neared the end of their growth cycle (Table 6). The total above ground plant material in R-1 and R-4 was harvested at this time. Small amounts of Chara were observed in both cattail stands in October of 1977 and were also measured for standing crop, with a maximum value of 58 g/m^2 in R-1 (Table 6). The Chara in this reservoir died back after sampling on 4/14/78 and was no longer observed growing in the large reservoir. The disappearance of Chara in this stand was probably the result of its inability to

Table 6. Standing crop data for *Typha* and *Chara* in reservoirs R-1 and R-4.

	Reservoirs			
	R-1		R-4	
Date	Typha	Chara	Typha	Chara
	g/m^2	g/m^2	g/m^2	g/m^2
8/ 4/77	279.0	---	213.3	---
8/25/77	300.4	---	222.8	---
9.15/77	462.8	---	795.5	---
10/ 6/77	---	---	---	---
10/27/77	587.6	---	622.0	---
11/17/77	393.2	---	610.2	68.4
12/ 8/77	843.9	32.4	505.7	98.6
12/29/77	485.1	46.4	504.2	110.4
1/19/78	---	---	---	---
2/ 9/78	394.7	58.0	183.7	115.6
3/ 3/78	386.0	50.3	193.4	140.3
3/23/78	---	---	---	---
4/14/78	698.2	56.4	752.4	177.2
5/ 5/78	872.0	---	1025.3	182.6
5/25/78	1406.4	---	1091.0	84.2
6/14/78	1190.7	---	930	87.5
7/ 5/78	H*	H*	H*	H*
8/ 2/78	171.8	---	220.7	208.7
8/23/78	272.4	---	224.5	249.4
Mean	582.9	48.7	540.5	138.2
sd	375.0	10.2	293.8	58.6

*H indicates harvest: no samples were taken.

compete for nutrients with the Typha. The Chara in R-4, however, remained throughout the study period and reached a maximum standing crop of 241 g/m^2 (Table 6).

Tissue Content: Typha and Chara

Total-N values for Typha ranged from 1400 μg/g to 25000 μg/g and for Chara from 1300 μg/g to 26000 μg/g. Total-P values for Typha ranged from 76 μg/g to 4600 μg/g and for Chara from 84 μg/g to 2167 μg/g (Table 7). These variations may be the result of certain environmental factors such as changes in nutrient concentrations entering the stand from one sampling period to the next or the channeling of nutrients through the center of the stand. Typha may have also grown faster and assimilated more nutrients near the edges of the reservoirs which contained high concentrations of organic material. Channeling of nutrients and the organic material making up the levees might be responsible for the different nutrient concentrations in the plant material analyzed in these zones.

Correlation coefficients between total-N and total-P levels for Typha and Chara standing crop in R-1 and R-4 during the time periods from 8/4/77 to 9/15/77 and 4/14/78 to 5/25/78 are shown in Table (8). The correlation values for total-P and total-N in R-1 were -.99, for both time periods. The correlation values calculated in R-4 were -.68 for total-N and -.81 for total-P during the first

Table 7. Tissue analysis for total-N and total-P of *Typha* and *Chara* in reservoirs R-1 and R-4. All values are μg/g x 1000.

	R-1 Typha		R-1 Chara		R-4 Typha		R-4 Chara	
Date	N	P	N	P	N	P	N	P
	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g
8/ 4/77	15.1	3.9	--	--	13.8	2.1	--	--
8/25/77	14.5	1.7	--	--	12.6	1.6	--	--
9/15/77	8.6	1.6	--	--	13.0	1.2	--	--
10/ 6/77	--	--	--	--	--	--	--	--
10/27/77	17.6	2.5	--	--	15.1	1.3	--	--
11/17/77	18.9	1.5	--	--	13.2	2.5	19.4	2.0
12/ 8/77	6.5	1.8	10.3	2.0	3.3	1.2	4.3	1.2
12/29/77	9.9	0.7	15.1	0.9	16.0	1.4	10.1	0.9
1/19/78	--	--	--	--	--	--	--	--
2/ 9/78	14.5	1.5	20.1	2.1	11.4	1.9	12.6	0.1
3/ 3/78	7/9	1.1	15.1	1.9	1.4	4.5	1.4	4.5
3/23/78	--	--	--	--	--	--	--	--
4/14/78	23.9	0.9	13.6	0.7	25.2	1.7	12.0	0.5
5/ 5/78	13.8	0.8	--	--	9.1	1.2	16.0	0.9
5/25/78	10.0	0.1	--	--	1.4	0.7	25.8	0.1
6/14/78	12.9	1.2	--	--	15.7	1.1	8.9	1.0
7/ 5/78	H*	H*	H*	H*	H*	H*	H*	H*
8/ 2/78	1.4	0.4	--	--	14.1	0.7	15.1	0.5
8/23/78	15.1	0.5	--	--	13.9	0.5	14.7	0.5
Mean	12.7	1.4	14.8	1.5	11.9	1.6	12.7	1.1
sd	5.5	.9	3.5	.7	6.2	1.0	6.8	1.2

*H indicates a harvest: no samples were taken.

Table 8. Correlation coefficients between tissue content of total-N and total-P and standing crop for the 14 month period and two growing seasons.

Location	Tissue Analysis vs. Standing Crop	
	N	P
14 Month Period		
R-1	-.12	+.23
R-4	-.38	-.32
8/4/77 to 9/15/77		
R-1	-.99*	-.99*
R-4	-.81	-.68
4/14/78 to 5/25/78		
R-1	-.99*	-.99*
R-4	-.84	-.99*

*Indicates significance at the 0.05 level.

time period and -.99 for total-N and -.84 for total-P during the second time period. These correlations were consistent with those reported by Boyd (1970b) and supported the finding that nutrients decline as Typha matures. The correlations between nutrient levels and standing crop were found to be very low for the 14 month period in both R-1 and R-4 and were probably the result of differences in stages of growth of the Typha or the nutrient concentrations at the time of sampling (Table 8).

Standing Crop: Egeria densa

The standing crop of Egeria densa was first measured on August 4, 1977, approximately 60 days after introduction. Little seasonal variation in biomass was observed in either reservoir. After eight months of growth the E. densa in R-1 died back and it was necessary to reintroduce this reservoir with about 800 g of fresh plant material. Maximum growth was observed in R-4 during June, July, and August of 1978 with a peak value of 603 g/m^2 (Table 9). Maximum values of standing crop occurred in R-1 on 9/15/77 with a peak value of 459 g/m^2 and again on 4/18/78 with a value of 462 g/m^2. Minimum values of E. densa were recorded in R-1 and R-4 during winter months. Biomass values dropped to a low of 124 g/m^2 in R-1 and 135 g/m^2 in R-4 (Table 9). Small amounts of Chara were observed in R-1 during the first few

Table 9. Standing crop data for *Egeria densa* in reservoirs R-1 and R-3.

Date	Reservoirs	
	R-1	R-3
	g/m^2	g/m^2
8/ 4/77	206.3	364.6
8/25/77	213.8	326.3
9/15/77	459.0	244.7
10/ 6/77	---	---
10/27/77	151.4	214.8
11/17/77	138.8	135.0
12/ 8/77	124.5	218.0
12/29/77	136.0	302.5
1/19/78	---	---
2/ 9/78	252.3	299.1
3/ 3/78	134.9	233.9
3/23/78	---	---
4/14/78	462.6	250.5
5/ 5/78	384.2	283.7
5/25/78	206.1	297.2
6/14/78	76.1	514.8
7/ 5/78	256.0	530.4
8/ 2/78	262.8	603.6
8/23/78	167.7	445.3
Mean	227.0	315.0
sd	116.9	150.3

months of the study but quickly disappeared. The *Chara* observed in R-1 was not measured for standing crop values.

The mean standing crop values of *E. densa* during the 14 month period in R-4 was almost twice that observed in R-1 (Table 9). The difference in growth of *E. densa* in the two reservoirs (R-1 and R-4) may have been the result of a number of environmental variables. The competition with *Chara* in R-1 may have also affected the growth of the *E. densa*. A major variable that may have caused the variance between the two stands of *E. densa* was the difference in sediment type. Reservoir R-3 had slightly more muck (organic material) overlying the marl layer than did R-1 (Table 2). The thicker organic layer may have allowed for the establishment of a larger root system and exposed the plants to more nutrients, which in turn increased their growth (Bristow and Whitcombe 1971).

Tissue Content: *Egeria densa*

Nutrient values for total-N ranged from 7025 µg/g to 26460 µg/g in R-1 and 1348 µg/g to 26460 µg/g in R-3. Total-P values ranged from 68 µg/g to 4080 µg/g in R-1 and from 77 µg/g to 5865 µg/g to R-3 (Table 10). These variations may be the result of certain environmental factors such as changes in nutrient concentrations entering the stand or the channeling of nutrients through the center of the reservoir. The channeling of the effluent through the

Table 10. Tissue analysis for total-N and total-P of *Egeria densa* in reservoirs R-1 and R-3. All values are μg/g x 1000.

	R-1 *E. densa*		R-4 *E. densa*	
Date	N	P	N	P
	μg/g	μg/g	μg/g	μg/g
8/ 4/77	13.8	2.1	16.4	2.2
8/25/77	16.4	1.3	15.2	2.1
9/15/77	13.9	1.6	14.5	1.3
10/ 6/77	---	---	---	---
10/27/77	20.1	0.7	17.6	5.9
11/17/77	17.6	0.8	15.1	0.2
12/ 8/77	21.4	1.9	5.2	1.5
12/29/77	15.7	1.4	17.6	1.4
1/19/78	---	---	---	---
2/ 9/78	12.6	1.5	12.6	2.0
3/ 3/78	21.7	4.1	11.3	0.4
3/23/78	---	---	---	---
4/14/78	7.0	0.3	9.5	0.7
5/ 5/78	9.9	1.0	18.9	1.1
5/25/78	26.4	0.1	25.2	0.1
6/14/78	17.9	1.2	13.6	1.1
7/ 5/78	18.3	0.5	17.1	0.5
8/ 2/78	16.6	0.6	16.9	0.4
8/23/78	11.6	0.5	15.1	0.4
Mean	16.3	1.2	15.1	1.3
sd	4.9	1.0	4.4	1.4

center of the reservoir should enhance the growth of the plant material.

The exposure to a higher concentration of nutrients may also increase the luxury uptake and could result in higher tissue concentrations of the plants in that portion of the stand.

Nutrient level for *E. densa* in R-1 and R-3 and the standing crop in these reservoirs varied considerably and resulted in low correlations between nutrient concentrations and standing crop (Table 11). The correlations for tissue analysis and standing crop indicated both increasing and decreasing trends in total-N and total-P content of *E. densa* for both R-1 and R-4. Similar results in tissue analysis of aquatic plants were demonstrated by Geuloff and Krombholz (1966). The variances were the result of different concentrations of nutrients present in the reservoirs. The general decline in nutrient tissue content over the growing season was not observed (Boyd 1970b).

Standing Crop: *Eichhornia crassipes*

The standing crop of *Eichhornia crassipes* was first measured on 8/14/77 about 60 days after introduction. Maximum biomass was first observed on December 12, 1978 with a value of 4584 g/m^2 in R-2. After this sampling period the biomass covering 50% of the surface area was removed from both reservoirs. The hyacinths were again harvested two

Table 11. Correlation coefficients between tissue content of total-N and total-P and standing crop for the 14 month period and two growing seasons.

	Egeria densa Tissue Analysis vs. Standing Crop	
Location	N	P
14 Month Period		
R-1	-.41	-.66
R-3	-.50	+.25
9/14/77 to 9/15/77		
R-1	-.09	-.48
R-3	+.98*	+.92
6/14/78 to 9/2/78		
R-1	-.99*	-.66
R-3	-.72	+.57

*Indicates significance at the 0.05 level months later when 60% to 70% of the biomass was removed. The second harvest was initiated in order to remove a majority of the plant material killed back by frost. The water hyacinths were allowed to grow until the end of the experiment. The maximum standing crop values at that time were 3603 g/m^2 for R-1 and 4175 g/m^2 for R-2 (Table 12). The values of standing crop were greater than those reported by Penfound (1956). However Penfound emphasized that his values were low, since the number of hyacinth plants per m^2 in his study were much less crowded than observed in natural stands. Westlake (1963), however, recorded values of up to 15018 g/m^2 under optimum conditions in tropical regions. Little difference in average biomass for *E. crassipes* between the two reservoirs was observed (Table 12). These results indicated similar growth responses of the two stands of hyacinths to the environmental conditions and nutrients present.

Tissue Content: *Eichhornia crassipes*

Plant tissue analysis for total-P and total-N varied through time in each stand, but little variance was observed between the two stands at the time of sampling. The variances within the stands may have been the result of changing environmental conditions especially the changes in flux of nutrients entering each reservoir. Tissue analysis for total-N ranged from 3771 µg/g to 25200 µg/g while total-P

Table 12. Standing crop data for <u>Eichhornia crassipes</u> in reservoirs R-1 and R-2.

Date	Reservoirs R-1	Reservoirs R-3
	g/m^2	g/m^2
8/ 4/77	1308.8	1035.0
8/25/77	1361.9	1011.7
9/15/77	2570.6	3544.0
10/ 6/77	---	---
10/27/77	3686.5	3430.3
11/17/77	4200.0	3504.0
12/ 8/77	4421.4	3552.5
12/29/77	4584.0	4004.0
1/19/78	H*	H*
2/ 9/78	1960.0	2820.9
3/ 3/78	2310.2	2460.0
3/23/78	H*	H*
4/14/78	1052.0	609.0
5/ 5/78	1659.3	833.0
5/25/78	1735.3	1375.9
6/14/78	2245.4	1943.8
7/ 5/78	2353.1	1697.6
8/ 2/78	2836.5	2271.8
8/23/78	3603.8	4175.0
Mean	2624.3	2391.8
sd	1153.6	1212.2

*H indicates a harvest: no samples were taken ranged from 73 μg/g to 5100 μg/g for hyacinths in both R-1 and R-2 (Table 13).

Correlation coefficients were calculated between tissue analysis and biomass measurements. Two sets of correlation values were determined. The first set was based on the growing season from 8/4/77 to 12/29/77 and the other after the winter freeze and harvest during 3/23/78. The correlation values for total-P were -.17 and -.31 in R-1 for the two growing seasons and -.12 and -.21 in R-2. Although the correlations between total-P content and biomass were low, there was a trend of decreasing concentrations through time as reported by Boyd (1970b). Nitrogen analysis and nutrient correlation values did not indicate this decreasing trend of tissue concentrations through time (Table 14). The differences in correlation values and tissue analysis were probably a result of the response of the plant material to the changes in environmental conditions through time.

Overview: Standing Crop and Tissue Analysis

Reservoir R-1 had the greatest mean standing crop with a value of 11.6 mt/ha which was 0.4 mt/ha more than the reservoirs in series and 10.5 mt/ha more than the control. The seasonal variance of standing crop was evident in R-1 as standing crop values ranged from 7.4 mt/ha in April 1978 to 17.6 mt/ha in December of 1977. The drop in biomass for R-1 during February, March, and April was due to the cold

Table 13. Tissue analysis for total-N and total-P of *Eichhornia crassipes* in reservoirs R-1 and R-2. All values are µg/g x 1000.

	R-1 *E. crassipes*		R-4 *E. crassipes*	
Date	N	P	N	P
	µg/g	µg/g	µg/g	µg/g
8/ 4/77	15.7	1.7	12.3	1.2
8/25/77	12.6	2.1	11.3	1.2
9/15/77	15.2	1.3	16.3	1.5
10/ 6/77	---	---	---	---
10/27/77	14.5	3.7	15.1	1.1
11/17/77	13.8	0.2	12.6	2.1
12/ 8/77	6.5	2.1	5.6	1.6
12/29/77	15.1	0.8	18.9	0.8
1/19/78	---	---	---	---
2/ 9/78	8.8	1.9	6.9	1.9
3/ 3/78	4.4	5.1	3.7	4.1
3/23/78	---	---	---	---
4/14/78	13.6	0.8	14.2	0.8
5/ 5/78	10.8	1.2	17.3	0.6
5/25/78	22.7	0.1	25.2	0.1
6/14/78	14.4	1.1	15.8	1.2
7/ 5/78	15.9	0.8	19.2	1.0
8/ 2/78	14.2	0.5	13.8	0.5
8/23/78	14.5	0.5	13.8	0.5
Mean	13.9	1.5	13.9	1.3
sd	4.5	1.3	5.4	0.9

Table 14. Correlation coefficients between tissue content of total-N and total-P and standing crop for the 14 month period and two growing seasons.

	Eichhornia crassipes Tissue Analysis vs. Standing Crop	
Location	N	P
14 Month Period		
R-1	+.07	-.16
R-2	+.28	-.18
8/14/77 to 12/8/77		
R-1	-.17	-.14
R-2	-.12	+.59
4/14/78 to 8/23/78		
R-1	-.31	+.03
R-2	-.21	+.34

weather (Table 15). Water hyacinths were harvested during February and April.

The mean standing crop measured in the series of reservoirs was 11.2 mt/ha. The plant species in these reservoirs were subjected to similar conditions as the plant species in the large reservoir. The difference of 0.4 mt/ha in standing crop between the two reservoirs was insignificant ($p<0.05$). Seasonal variations were also observed in this system with values ranging from 5.4 mt/ha in April of 1978 to 15.1 mt/ha in December of 1977. The low range of standing crop was measured during winter months (Table 15). Hyacinths were harvested in the series of reservoirs during February and April.

The control reservoir contained no aquatic macrophytes at the start of the experiment. The plant species, Chara, that invaded R-5 was first measured on 2/9/78 with a mean value of 0.2 mt/ha. The biomass data for R-5 indicated an increase of plant tissue for this species for the remainder of the experiment. A peak standing crop of 2.4 mt/ha was measured on 8/23/78, the last sampling period (Table 15).

The correlations between the total nutrients accumulated by the plant tissue in each reservoir system and the biomass measured in the corresponding system were calculated. The results of this analysis indicated that the plant growth in each system was directly related to the

Table 15. Mean monthly values and yearly averages of the total standing crop in mt/ha for the reservoir systems.

	Locations		
Date	R-1	R-2 thru R-4	R-5
Aug	6.1	5.3	
Sep	11.9	15.0	
Oct	14.7	14.2	
Nov	15.8	14.2	
Dec	17.6	15.1	
Jan			
Feb	8.7	11.0	0.2
Mar	9.4	9.6	0.4
Apr	7.4	5.4	0.7
May	10.0	8.2	0.9
Jun	11.7	11.3	1.5
Jul	13.1	11.1	1.9
Aug	12.2	13.2	2.4
Mean	11.6	11.2	1.1
sd	3.4	3.5	1.1

accrual of N and to a much lesser extent the removal of the P (Table 16). Two possible conclusions can be deduced from this data: 1) either E. crassipes has a greater affinity for N than P, or 2) P was limiting (Dunigan et al. 1975).

The biomass and nutrient content of the aquatic macrophytes varied in response to light, temperature, nutrient content of the water, local habitat, and a number of other associated environmental factors (Boyd 1969a; Boyd and Hess 1970). Where nutrients channeled through the reservoirs, water hyacinths were generally larger, greener, and more succulent than plants growing adjacent to this zone. The Typha and E. densa on the other hand grew more profusely near the levees which had the thickest organic sediment.

Each reservoir system contained about the same amount of plant tissue on a dry weight basis but with some variation in tissue content for total-N and total-P.

Nutrient Budgets and Harvest

The use of aquatic plant harvesting as a nutrient removal technique was based upon a number of assumptions and information from previous studies. It has been shown that aquatic macrophytes do require N and P for growth and they do assimilate these nutrients from water and sediments. Aquatic plants have been shown to also accumulate N and P in levels beyond those required for physiological maintenance (ie. luxury uptake). Furthermore, it is generally agreed

Table 16. Correlation coefficients between tissue content of total-N and total-P in the reservoir systems for the 14 month study period.

	Tissue Analysis vs. Standing Crop	
Location	N	P
R-1	.82*	.26
R-2 thru R-4	.76*	.43
R-5	.97*	.02

*Indicates significance at the 0.05 level that N and P are the elements most likely to be involved in limiting the growth of aquatic plants.

The total amount of N and P removed by a harvest can be calculated by multiplying the average nutrient content calculated for a particular species by the total amount of that plant removed during a harvest. Approximately 75% of the plant biomass was removed for each plant species harvested. The hyacinth material included both root and shoot tissue and was harvested twice during the study from both R-1 and R-2. The biomass from these reservoirs totaled 6417 kg and 6011 kg respectively. The above ground cattail material removed was approximately 1107 kg from R-1 and 867 kg from R-4. The *E. densa* was not harvested.

The N and P removed from the reservoir systems as a result of the harvest was 83 kg of N and 1.1 kg of P from the large reservoir and 84 kg of N and 0.8 kg of P from the series of reservoirs.

The nutrient content of the plant material contained in the reservoirs can also be calculated by the same procedure for determining the nutrients removed by harvest. The percent nutrient content measured for each species was multiplied by the calculated standing crop of that species. The values measured were totaled for both treatment systems and averaged for monthly analysis. The result of these calculations provided the nutrients accumulated by the standing crop in each reservoir system and the potential nutrient removal if all the material was harvested at that time (Table 17).

The plant tissue in R-1 contained a monthly average of 162 kg N/ha and 14.7 kg P/ha. The plants in the series system contained an average of 150 kg N/ha and 13.4 kg P/ha.

Nutrient budgets for N and P entering the system via agricultural drainage was calculated for each month. The total water pumped for a month was multiplied by the average nutrient concentration in mg/l, for both inflow and outflow of that month. The difference between these measurements was the net gain or loss of N and P for both reservoir systems and the control (Appendix A).

The net gain or total retention of N in the series of reservoirs was 1017 kg/ha, as compared to a value of 750 kg/ha for the large reservoir and 704 kg/ha for the control. Phosphate retention was greatest in the series of reservoirs with 249 kg/ha removed. The large reservoir retained 211 kg P/ha and the control retained 116 kg/ha.

The data for the nutrient tissue content were used to calculate monthly net tissue assimilation or release of nutrients. When compared to the net nutrient analysis of the drainage water it was found that during the summer the N budgets were not in steady state in the treatment reservoirs. Essentially there was more N contained in the plant

Table 17. The potential nutrient removal of total-N and total-P by the aquatic macrophytes in the reservoir systems for the 14 month study period.

	Locations					
	R-1		R-2 thru R-4		R-5	
Date	N	P	N	P	N	P
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Aug	89.8	10.8	71.9	9.2	---	---
Sep	150.0	13.0	223.1	20.4	---	---
Oct	257.1	27.7	227.0	8.8	---	---
Nov	265.0	19.6	193.3	3.3	---	---
Dec	221.7	15.6	168.9	19.9	---	---
Jan	---	---	---	---	---	---
Feb	104.0	14.5	113.8	21.6	3.9	0.4
Mar	107.1	32.2	21.0	40.9	4.9	2.1
Apr	109.6	4.9	87.8	5.7	7.2	3.3
May	120.4	10.8	132.5	4.2	9.0	0.6
Jun	176.6	13.9	170.4	11.5	24.2	2.4
Jul	223.9	8.2	202.7	8.4	28.4	1.3
Aug	122.9	5.8	193.5	6.6	10.9	1.5
Mean	162.3	14.7	150.5	13.4	16.9	1.7
sd	63.9	8.3	65.2	10.7	14.9	1.0

material than can be accounted for by the net N retention of the reservoir systems (Fig. 15). However, this N loading from the plant tissue was apparently offset by some other chemical or physical process as the net N removal was greatest during the winter with 161 kg N/ha removed during January from the series and 314 kg N/ha removed during February from the large reservoir.

The N that entered the reservoirs from sources other than the agricultural effluent may have been from oxidized organic matter making up the levees. Neller (1944) reported nitrate-N concentrations as high as 422 μg/g in Everglades peat. The N mineralization rate for Pahokee muck was estimated to be 686 kg N/ha for each centimeter of soil lost to microbial oxidation (Terry 1980). The oxidized organic matter entering the reservoirs from this source could increase production provided no other nutrients were limiting. The extra N could also be taken up in luxury amounts (Fitzgerald 1969). During summer, oxidation rates would increase due to an increase in temperature, and loading would be greater because of increased rainfall (Reddy et al. 1980).

During the first 3 months of 1977 there was more P contained in the plant material than was retained by reservoir R-1. During the remainder of the study the P retained by the plant tissue was less than the P retained by this reservoir (Fig. 16). This indicates that processes other

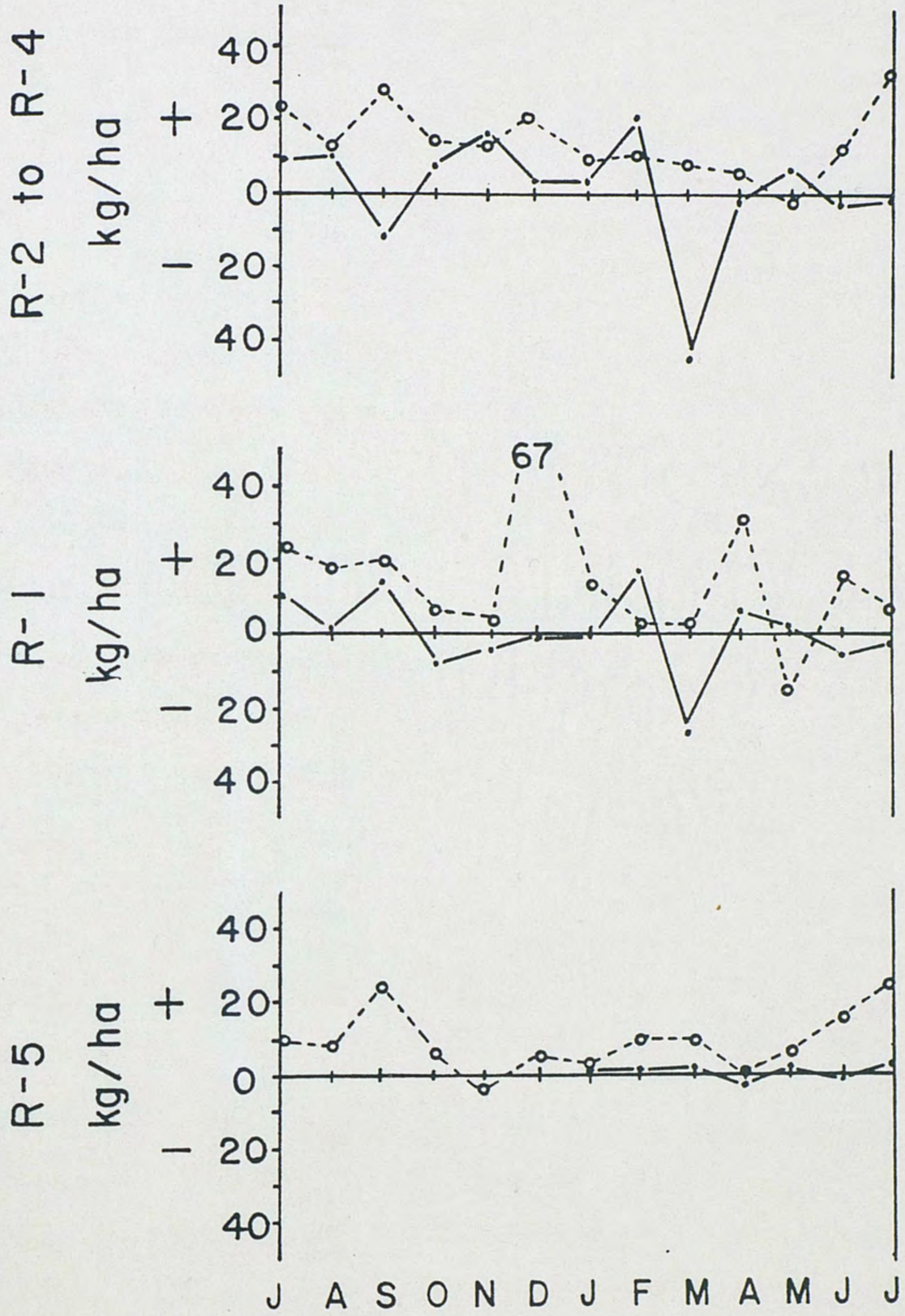


Figure 15. Comparison of monthly nitrogen budgets (∘---∘) in the agricultural effluent with monthly net plant tissue content (•——•) for nitrogen.

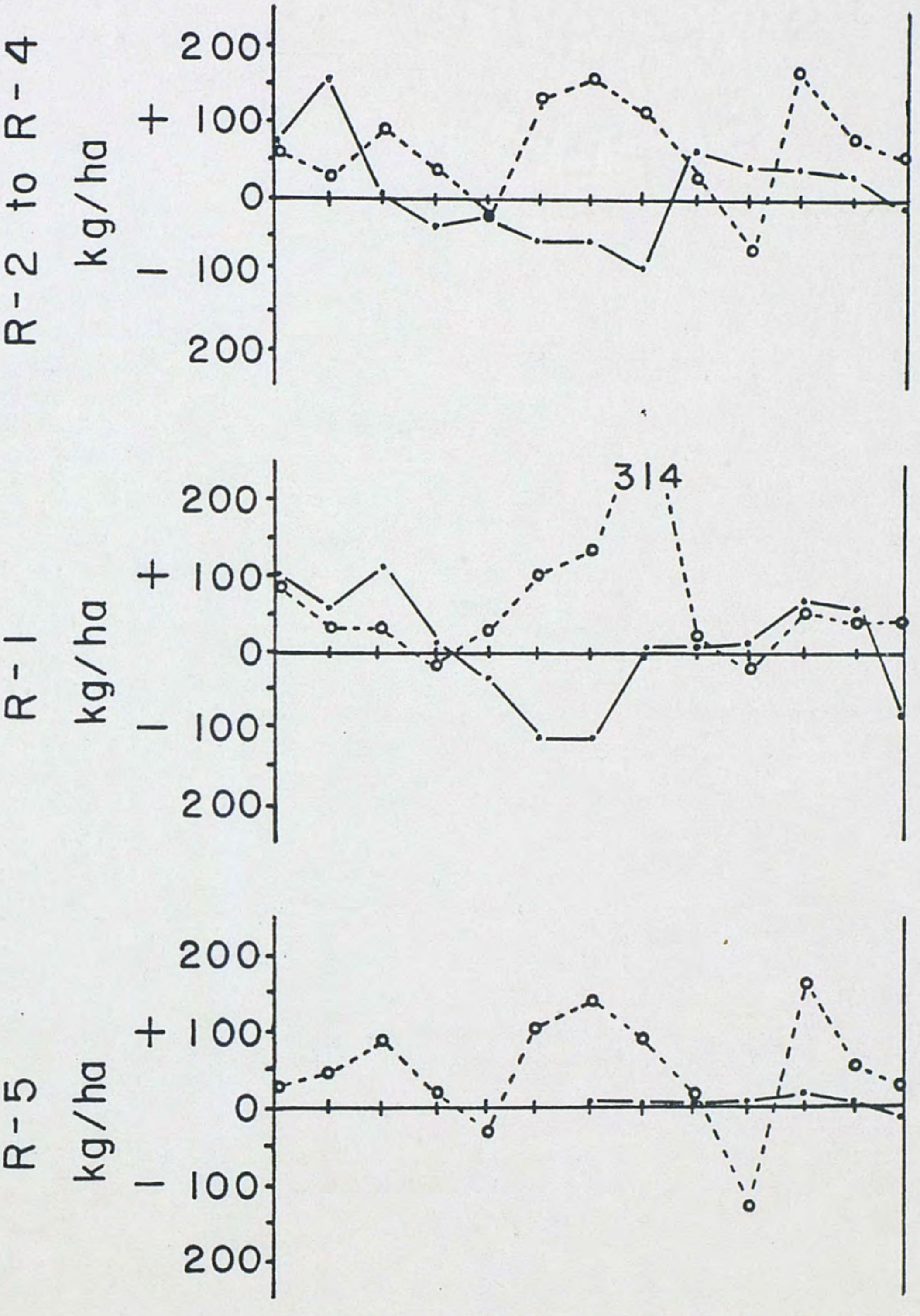


Figure 16. Comparison of monthly phosphate budgets (∘---∘) in the agricultural effluent with monthly net plant tissue content (•——•) for phosphate.

than plant assimilation were involved in reducing P concentrations in the reservoir.

The P content in the plant tissue in the series of reservoirs oscillated through the 14 months. It appeared that the plant tissue would build up P then release it into the reservoir every three months.

SUMMARY AND CONCLUSIONS

Nitrogen and phosphate from agricultural drainage are transported primarily by surface runoff and subsurface flow, resulting in nonpoint source pollution of adjacent water bodies. Measurements were made of N and P concentrations of agricultural drainage water from a muck farming district of 7,300 ha located south of Zellwood, Florida. Data for the physicochemical parameters, nutrient concentrations and standing crop were collected for a 14 month period beginning September 1977.

Samples from agricultural drainage water were taken twice weekly at five sampling stations (two inflow and three outflow). Field analysis consisted of measurements for DO, alkalinity, carbon dioxide, water temperature, pH, and rainfall. Laboratory analysis consisted of measurements for total phosphate, orthophosphate, total-N, ammonium-N, nitrate-N and turbidity. All samples were analyzed in accordance to Environmental Protection Agency (1974) and Standard Methods (American Public Health Association 1971).

Four 0.25 m^2 quadrats in each plant stand were sampled at 21-day intervals for standing crop and tissue analysis. The plant material collected from each stand was sorted to genus and a composite of the four samples was made for analysis. The plant material covering 50% to 60% of the surface area in each cattail and hyacinth stand was removed approximately every six months and after winter kills.

Maximum nitrate-N concentrations for untreated drainage water were greatest during periods of highest precipitation. The reservoir treatments and the control reduced levels of nitrate-N contained in the untreated drainage water. The reductions of 65%, 80%, and 74% by R-1, the series of reservoirs and the control, respectively, were not attributed to the uptake by aquatic macrophytes alone. The biological process of denitrification and accumulation of nitrate-N by algae may have been the additional contributing factor affecting nitrate-N reduction. Overall, the series of reservoirs were more effective in reducing nitrate-N concentrations from agricultural drainage water than a single large reservoir.

The large reservoir reduced ammonium-N in the untreated drainage water by 57%, the series reduced ammonium-N by 73%, and the control reduced the ammonium-N by 75%. The reduction of ammonium-N was not attributed to the aquatic macrophyte assimilation alone. Part of the ammonium-N was also reduced by: 1) ammonia volatilization and 2) nitrification and subsequent denitrification.

The series of reservoirs reduced the organic nitrogen components by 33% and the control reduced organic nitrogen by 8%. The large reservoir treatment increased the organic nitrogen concentration by 7%. The increase measured in R-1 was probably the result of plant decomposition and plant excretion.

Total-P concentrations for untreated drainage water ranged from 0.2 mg/l to 1.68 mg/l, while P concentrations for treated drainage water ranged from 0.02 mg/l to 0.85 mg/l. Total-P concentrations were associated with the rain events as peak concentrations for P were observed during the months of peak rainfall. The annual mean reduction of P was significant ($p<0.05$) and was calculated to be 74% by the series of reservoirs, 70% by the large reservoir, and 33% by the control. The reduction in P observed in the reservoirs was probably the result of adsorption, precipitation and plant assimilation of the P fractions associated with these chemical and biochemical processes.

Ortho-P concentrations in the untreated drainage water exceeded the 0.01 to 0.03 mg/l believed to be sufficient for algae blooms. Concentrations of ortho-P in the untreated drainage water were associated with surface and groundwater runoff caused by rain events, and varied considerably for the 14 month period. The series of reservoirs reduced ortho-P by 74%, the large reservoir reduced ortho-P by 70%, and the control reduced ortho-P by 33%. These reductions were the result of aquatic plant assimilation and precipitation by calcium carbonate.

The photosynthetic activity increased DO concentrations in the series of reservoirs by an average of 5 mg/l, while the control increased DO by an average of 6 mg/l. The increase in DO observed in the large reservoir was 0.5 mg/l. This low oxygen concentration in the treated effluent from R-1 was probably the result of higher respiration rates coupled with lower photosynthetic activity. Although R-1 produced more total standing crop than the series of reservoirs, the series produced more E. densa which functioned as an oxygen pump for both reservoir systems.

The specific conductance was reduced by 24%, 10%, and 15% by the series of reservoirs, R-1, and the control, respectively. The small reservoirs in series were more efficient in reducing the ions associated with specific conductance than was the large reservoir. Specific conductance in the untreated drainage water varied with rain events, agricultural practices and flooding of soils.

The carbon dioxide was reduced in the series of reservoirs and the control mainly by photosynthetic activity of the submergent macrophytes. The large reservoir was not as efficient in the reduction of carbon dioxide, therefore the oxygen produced by photosynthetic activity was almost equal to the carbon dioxide produced by respiration at the time of sampling in R-1. The photosynthetic carbon fixation in the series of reservoirs and the control shifted the alkalinity equilibrium from bicarbonates (HCO_3^-) to carbonates (CO_2^{--}) and increased pH to values of greater than eight.

Turbidity was significantly reduced in the series of reservoirs and R-1 with a reduction of 35% and 31%, respectively. The control, on the other hand, reduced turbidity by 0.3%. The reductions in turbidity were directly related to the plant material present in the reservoir systems.

The mean standing crop of _E_. _densa_ in R-1 was 227 g/m^2 dry wt., while the mean standing crop in the series of reservoirs was 329 g/m^2 dry wt. The total mean standing crop was 3428 g/m^2 in R-1 and 3,398 g/m^2 in the series of reservoirs.

The nutrient concentrations of aquatic macrophytes varied greatly through time but these data were useful for relative comparisons among different aquatic macrophytes and among reservoirs. Phosphate levels were greater in plant tissue measured from the series of reservoirs, while nitrogen levels were greater for the plant species measured in R-1, with the exception of _E_. _crassipes_. The variance in plant tissue analysis within species was probably the result of nutrient channeling through the center of the plant stand and the random sampling procedure.

Although the mean biomass and nutrient uptake by the major aquatic plants were slightly greater in R-1, the reservoirs in series were 63% more efficient in removing N and 89% more efficient in removing P from the untreated drainage water during the 14 month period of study. The series of reservoirs were also more efficient than the large reservoir in improving the physicochemical properties of the treated agricultural drainage water.

Based on the results obtained from this field study the following conclusions can be drawn

1. All reservoir systems, including the control, (with no macrophytes) were efficient in removing N and P from the agricultural drainage water.
2. Presence of aquatic macrophytes removed about 25 to 30% of the N and 20 to 25% of the P from the agricultural drainage water.
3. Nitrogen and P concentration in untreated drainage water were directly associated with rain events that occurred during the study period.
4. Several physical, chemical, and biological reactions such as nitrification, denitrification, ammonification, volatilization, mineralization, precipitation and adsorption were involved in the reduction of N and P from drainage water pumped through the reservoirs.
5. Dissolved oxygen increased in treated drainage water from the control and the series of reservoirs.

6. The bicarbonate and carbonate equilibrium in the series of reservoirs and control reservoir shifted to carbonate as carbon dioxide was reduced.
7. Turbidity values were significantly reduced in R-1 and the series of reservoirs as compared to the control.
8. Standing crop in the series and the large reservoirs were similar with an average of 11.6 mt/ha grown in R-1 and 11.2 mt/ha grown in the series of reservoirs. The average biomass measured from the control was 1.1 mt/ha.
9. Nitrogen retained in the reservoir systems during the study period was 1013 kg/ha, 730 kg/ha and 704 kg/ha in the series of reservoirs, the large reservoir and the control reservoir, respectively. Phosphate retained in the reservoir systems was 249 kg/ha, 211 kg/ha and 116 kg/ha in the series of reservoirs, the large reservoir and the control reservoir, respectively.

In conclusion, the nutrient retention of the reservoir systems was not solely a function of the plant assimilation but the result of several balanced physical, chemical, and biological reactions inherent in both systems. The series of reservoirs was the most effective nutrient sink and the most easily maintained, i.e., containing the macrophytes into separated stands and harvesting.

Although both reservoir systems were effective nutrient sinks, shapes should be changed from square to long, shallow, rectangular plots of about 1.5 meters in depth because the longer reservoir will expose more plant matter to the drainage effluent for a greater length of time.

The economics involved in maintenance and harvesting of aquatic angiosperms of the reservoirs needs to be offset by the conversion of the harvested plants into forage, fertilizers, or biogas production. The development cost for such reservoir systems would include: 1) capital cost of the land, the harvesting equipment, processing equipment and pumps, and 2) operational costs for fuel, labor, and maintenance. The excavation costs of digging ponds would be about \$2.00 per cu. yd. with land cost of about \$20,000 per acre. The harvesting equipment would be about \$10,000 initially (screw pump, or recessed impeller pump) and \$300 per year energy cost. Labor cost could run as high as \$50,000 per year (Stewart 1978).

The harvested plants could be sold for \$25/ton at 15% moisture or used for producing methane on site. According to Wolverton et al. (1975), it can be predicted that 1,604 pounds of methane would be produced weekly, which at \$0.05 per pound amounts to an annual recovery rate of \$4,200. Cost for digesters and storage facilities for handling gas may amount to a \$50,000 initial investment.

If the increased aesthetic value of a lake protected by such an aquatic plant system could significantly stimulate visitation and commercial activity within the watershed, it would prove to be of considerable economic benefit to those who reside there (Stewart 1978).

Aquatic systems containing macrophyte material can turn undesirable nutrient pollution from industrial sources or domestic sources into usable products that can in turn increase food production and at the same time improve the water quality.

APPENDIX A

DATA USED FOR CALCULATING NUTRIENT BUDGETS FOR NITROGEN AND PHOSPHATE

Table A-1. Nitrogen budget for the series of reservoirs.

Date	Water Pumped	Mean Concentration		Total Concentration		Net gain or loss*
		Inflow	Outflow	Inflow	Outflow	
	$1x10^6$	mg/l	mg/l	kg/ha	kg/ha	kg/ha
Jul	22.24	3.23	2.26	177.4	124.1	53.3
Aug	23.09	3.77	3.32	215.0	189.3	25.7
Sep	22.24	3.61	1.95	198.3	107.1	91.2
Oct	22.24	2.36	1.64	129.6	90.0	39.6
Nov	22.24	2.12	2.35	116.5	138.9	22.4
Dec	22.24	5.50	3.07	302.1	168.6	133.5
Jan	22.24	4.54	1.60	249.4	87.9	161.6
Feb	20.51	3.52	1.16	178.3	58.9	119.4
Mar	23.09	3.04	2.48	173.4	141.4	32.0
Apr	21.38	1.36	2.75	71.4	145.2	- 73.8
May	23.09	7.84	4.94	447.1	281.8	165.3
Jun	22.24	5.68	4.09	312.0	224.6	87.4
Jul	21.38	4.26	3.37	237.2	177.9	59.3
Aug	23.09	6.64	3.96	378.7	225.8	152.9
Total gain						1013.1
Average monthly gain						72.4

*A positive value indicates that nutrients were trapped by the impoundment and a negative value indicates nutrients lost from the impoundment.

Table A-2. Nitrogen budget for the large reservoir.

	Water Pumped	Mean Concentration		Total Concentration		Net gain or loss*
		Inflow	Outflow	Inflow	Outflow	
Date	$1x10^6$	mg/l	mg/l	kg/ha	kg/ha	kg/ha
Jul	22.24	3.58	2.34	193.8	126.6	67.2
Aug	23.09	3.45	2.93	193.9	164.6	29.3
Sep	22.24	3.22	2.54	174.3	137.5	36.8
Oct	22.24	2.12	2.34	114.7	126.6	- 11.9
Nov	22.24	2.27	1.73	122.9	93.6	29.3
Dec	22.24	5.07	3.09	274.4	167.2	107.2
Jan	22.24	4.71	2.06	254.9	111.5	143.4
Feb	20.51	8.72	2.44	436.9	121.8	314.8
Mar	23.09	2.81	2.60	157.9	146.0	11.9
Apr	21.38	2.73	3.51	158.7	182.6	- 23.9
May	23.09	7.03	6.05	395.0	339.9	55.1
Jun	22.24	6.39	5.63	345.8	334.7	41.1
Jul	21.30	5.32	4.89	278.1	315.8	37.7
Aug	23.09	4.37	5.93	245.6	333.2	- 87.6
Total gain						750.4
Average monthly gain						53.6

*A positive value indicates that nutrients were trapped by the impoundment and a negative value indicates nutrients lost from the impoundment.

Table A-3. Nitrogen budget for the control reservoir.

Date	Water Pumped	Mean Concentration Inflow	Mean Concentration Outflow	Total Concentration Inflow	Total Concentration Outflow	Net gain or loss*
	$1x10^6$	mg/l	mg/l	kg/ha	kg/ha	kg/ha
Jul	7.41	3.22	2.78	177.8	152.6	25.2
Aug	7.70	3.77	2.90	215.0	164.9	50.1
Sep	7.41	3.61	1.81	198.3	99.4	98.9
Oct	7.41	2.36	2.00	129.6	109.8	19.8
Nov	7.41	2.12	2.73	116.5	149.9	- 33.4
Dec	7.41	5.50	3.64	302.1	199.9	102.2
Jan	7.41	4.54	1.92	249.7	105.4	144.0
Feb	6.84	3.52	1.60	178.3	81.1	97.2
Mar	7.70	3.02	2.68	172.4	152.9	19.5
Apr	7.13	1.36	3.86	71.4	203.9	132.5
May	7.70	7.84	4.86	447.1	277.3	169.8
Jun	7.41	5.68	4.76	312.0	261.4	50.6
Jul	7.13	4.26	3.89	237.2	205.5	31.7
Aug	7.70	6.64	5.56	378.9	317.3	61.6
Total gain						704.7
Average monthly gain						50.3

*A positive value indicates that nutrients were trapped by the impoundment and a negative value indicates nutrients lost from the impoundment.

Table A-4. Phosphate budget for the series of reservoirs.

	Water Pumped	Mean Concentration		Total Concentration		Net gain or loss*
		Inflow	Outflow	Inflow	Outflow	
Date	$1x10^6$	mg/l	mg/l	kg/ha	kg/ha	kg/ha
Jul	22.24	0.80	0.35	43.9	19.2	24.7
Aug	23.09	0.29	0.06	16.5	3.4	13.1
Sep	22.24	0.65	0.12	35.7	6.6	29.1
Oct	22.24	0.31	0.02	17.0	1.1	15.9
Nov	22.24	0.35	0.08	19.2	4.4	14.8
Dec	22.24	0.77	0.36	42.3	19.8	22.5
Jan	22.24	0.26	0.07	14.2	3.8	10.4
Feb	20.51	0.33	0.09	16.7	4.6	12.1
Mar	23.09	0.29	0.16	16.5	9.1	7.4
Apr	21.38	0.22	0.11	11.6	5.8	5.8
May	23.09	0.19	0.23	10.8	13.1	- 2.3
Jun	22.24	0.30	0.03	16.5	1.6	14.8
Jul	21.38	0.65	0.03	34.3	1.6	32.7
Aug	23.09	1.00	0.16	57.0	9.1	47.9
Total gain						249.2
Average monthly gain						17.8

*A positive value indicates that nutrients were trapped by the impoundment and a negative value indicates nutrients lost from the impoundment.

Table A-5. Phosphate budget for the large reservoir.

	Water Pumped	Mean Concentration		Total Concentration		Net gain or loss*
		Inflow	Outflow	Inflow	Outflow	
Date	$1x10^6$	mg/l	mg/l	kg/ha	kg/ha	kg/ha
Jul	22.24	0.83	0.41	45.6	22.5	23.1
Aug	32.09	0.41	0.07	23.4	4.0	19.4
Sep	22.24	0.43	0.07	23.6	3.9	19.7
Oct	22.24	0.30	0.17	16.5	9.3	7.2
Nov	22.24	0.29	0.21	16.0	11.5	4.5
Dec	22.24	1.67	0.44	91.7	24.2	67.5
Jan	22.24	0.34	0.08	18.6	4.4	14.2
Feb	20.51	0.32	0.27	16.2	13.7	2.5
Mar	23.09	0.21	0.17	11.9	9.7	2.2
Apr	21.38	0.30	0.14	38.6	7.4	31.2
May	23.09	0.21	0.46	11.9	26.2	14.3
Jun	22.24	0.38	0.06	20.9	3.3	17.6
Jul	21.30	0.93	0.84	49.1	44.6	4.5
Aug	23.09	0.24	0.03	14.3	1.7	12.6
Total gain						211.9
Average monthly gain						15.1

*A positive value indicates that nutrients were trapped by the impoundment and a negative value indicates nutrients lost from the impoundment.

Table A-6. Phosphate budget for the control reservoir.

	Water Pumped	Mean Concentration		Total Concentration		Net gain or loss*
		Inflow	Outflow	Inflow	Outflow	
Date	$1x10^6$	mg/l	mg/l	kg/ha	kg/ha	kg/ha
Jul	7.41	0.80	0.65	43.9	35.7	8.2
Aug	7.70	0.29	0.12	16.5	6.8	4.7
Sep	7.41	0.65	0.21	35.7	11.5	24.2
Oct	7.41	0.31	0.20	17.0	11.0	6.0
Nov	7.41	0.35	0.42	19.2	23.0	- 3.8
Dec	7.41	0.77	0.87	42.3	47.8	- 5.5
Jan	7.41	0.26	0.21	14.2	11.5	2.7
Feb	6.84	0.33	0.15	16.7	7.6	9.1
Mar	7.70	0.29	0.14	16.5	8.0	8.5
Apr	7.13	0.22	0.18	11.6	9.5	2.1
May	7.70	0.19	0.08	10.8	4.6	6.2
Jun	7.41	0.30	0.05	16.5	2.7	13.8
Jul	7.13	0.65	0.30	34.3	15.9	18.4
Aug	7.70	1.00	0.70	57.0	39.9	17.1
Total gain						116.7
Average monthly gain						8.3

*A positive value indicates that nutrients were trapped by the impoundment and a negative value indicates nutrients lost from the impoundment.

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