Water Treatment by Aquatic Ecosystem: Nutrient Removal by Reservoirs and Flooded Fields[1]

K. R. REDDY
P. D. SACCO
University of Florida
Agricultural Research and Education Center
P. O. Box 909
Sanford, Florida 32771

D. A. GRAETZ
University of Florida
Soil Science Department
Gainesville, Florida 32611

K. L. CAMPBELL
University of Florida
Agricultural Engineering Department
Gainesville, Florida 32611

L. R. SINCLAIR[2]
University of Florida
Agricultural Research and Education Center
P. O. Box 909
Sanford, FL 32771

ABSTRACT / Potential use of reservoirs and flooded fields stocked with aquatic plants for reduction of the nutrient levels of organic soil drainage water was evaluated. The treatment systems include 1) a large single reservoir (R1) stocked with waterhyacinth (*Eichhornia crassipes*), elodea (*Egeria densa*), and cattails (*Typha* sp.) in series; 2) three small reservoirs in series with waterhyacinth (R2), elodea (R3), and cattails (R4), grown in independent reservoirs; 3) a control reservoir (R5) with no cultivated plants; 4) a large single flooded field planted to cattails; 5) three small flooded fields in a series planted to cattails; and 6) a flooded field with no cultivated plants. Drainage water was pumped daily (6 hours a day, and 6 days a week) into these systems for a period of 27 months at predetermined constant flow rates. Water samples were collected at the inlet and outlet of each treatment system and analyzed for N and P forms.

The series of reservoirs stocked with aquatic plants functioned effectively in the removal of N and P from agricultural drainage water, compared to a single large reservoir. Allowing the water to flow through the reservoir stocked with waterhyacinth plants with a residence time of 3.6 days was adequate to remove about 50% of the incoming inorganic N. Allowing the water to flow through a series of two small reservoirs, R2 and R3, with a residence time of 7.3 days was necessary to remove about 60% of the incoming ortho-P. Flooded fields were effective in the removal of inorganic N, but showed poor efficiency in the removal of ortho-P.

One of the widespread types of water pollution is the input of large quantities of inorganic nutrients, particularly nitrogen (N) and phosphorus (P), to freshwater lakes and streams, thus enhancing eutrophication. Lake Apopka (12,500 ha), located in central Florida is currently highly eutrophic. Nutrient loading is primarily responsible for the degraded condition of the lake (U.S. EPA 1979). One of the sources of nutrient discharge into the lake has been the drainage water pumped back into the lake from the surrounding muck farms (7,294 ha). Muck (organic) soils have a high natural fertility and contain large amounts of N, P, and soluble C, but are very poorly drained. The water table in such soils is at the surface and water holding capacity is high; therefore, drainage is often necessary before these soils can be utilized for agricultural purposes. During the wet season considerable amounts of water must be pumped off the farms to maintain the desired water table. To reduce nutrient loads into the lake, it was proposed that either the existing swamps be used as nutrient sinks or some recycle reservoirs (with an area ratio of 1:10 of recycle reservoir to the farmland drained) to store water and reduce nutrient levels of drainage water from the farm rather than pumping directly into the lake (Sinclair and Forbes 1980). Four swamp systems and seven recycle reservoirs are presently in operation along the north shore of Lake Apopka. However, the efficiency of these systems in reducing nutrient levels of drainage water is presently not known.

In the past decade, use of aquatic ecosystems for nutrient removal from waste waters has been studied by several workers (Yount and Crossman 1970, Stewart 1970, Scarsbrook and Davis 1971, Harvey and Fox 1973, Cornwell and others 1977, Dinges 1976, Wolverton and McDonald 1979). Most of these studies used monoculture systems for nutrient removal from waste waters, and to increase the efficiency of nutrient removal, a

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combination of two or three aquatic plant systems may prove more effective (Boyd 1969). The present study was designed to evaluate the nutrient removal efficiency of six treatment systems: 1) a large single shallow reservoir with three aquatic plant species; 2) three small shallow reservoirs in series, each containing a different aquatic plant; 3) a control reservoir with no cultivated aquatic plants; 4) a large single flooded field planted to cattails; 5) three small flooded fields in series planted to cattails; and 6) a flooded field with no cultivated plants. Agricultural drainage water from surrounding organic soils planted to vegetable crops was used as the water source.

Materials and Methods

The experimental reservoirs and flooded fields were located at the Agricultural Experiment Station Research Farm in the Zellwood Drainage District near Lake Apopka. The soil type (Monteverde Series) in this area is organic (Lithic Medisaprists, euic, hyperthermic) with a muck layer thickness of 20 to 120 cm underlaid by about 25 cm thick calcareous rock and marl. Selected characteristics of the reservoirs' bottom sediment and flooded field soil are given in Table 1.

Five flow-through reservoirs (Figure 1) were constructed with 2.0-m high levees of organic soil and with bottom composed of calcareous marl. Reservoir R1 (3720 m^2) was partitioned into equal areas by two chevron shaped chicken-wire fences. The first section was stocked with waterhyacinths, followed by elodea and cattails in the second and third sections, respectively. Drainage water was pumped diagonally through the plant stands in the order of waterhyacinth, elodea, and cattails. Three additional reservoirs, R2, R3, and R4 (1240 m^2) were connected in series by riser panels and were stocked with waterhyacinths (R2), elodea (R3), and cattails (R4), respectively. Water was pumped diagonally through R2 and was allowed to flow by gravity through R3 and R4. Control reservoir R5 (1240 m^2) contained no cultivated aquatic macrophytes. The depth of water column was 1.0 m in R1, R2, R3, and R5, and 0.6 m in R4. Selected physico-chemical parameters of the organic soil drainage water used during the study period (expressed as time average) are shown in Table 2. Drainage water was pumped for a period of 6 h/day and 6 days/week at predetermined flow rates (Table 3). Water samples were collected at the inlet and outlet of each reservoir and analyzed for selected chemical parameters.

Similarly, five flow-through flooded fields (with 20-cm floodwater depth) were established to study the efficiency of nutrient removal by these systems (Figure 1). Flooded field, F1 (3720 m^2) was stocked with cattails. A series of flooded fields, F2, F3, and F4 (1240 m^2), were also stocked with cattails. Flood field F5 (3720 m^2) was

Table 1. Selected characteristics of the soils in flooded fields and reservoirs.

Parameters	Flooded fields	Reservoir sediments
pH	6.7	6.8
Bulk density, g/cm^3	0.40	1.10
Total Kjeldahl N, %	3.53	0.62
Total organic C, %	45.10	6.67
Water soluble P. μg/g	19.1	0.25
Double acid extractable P, μg/g	41.8	0.49

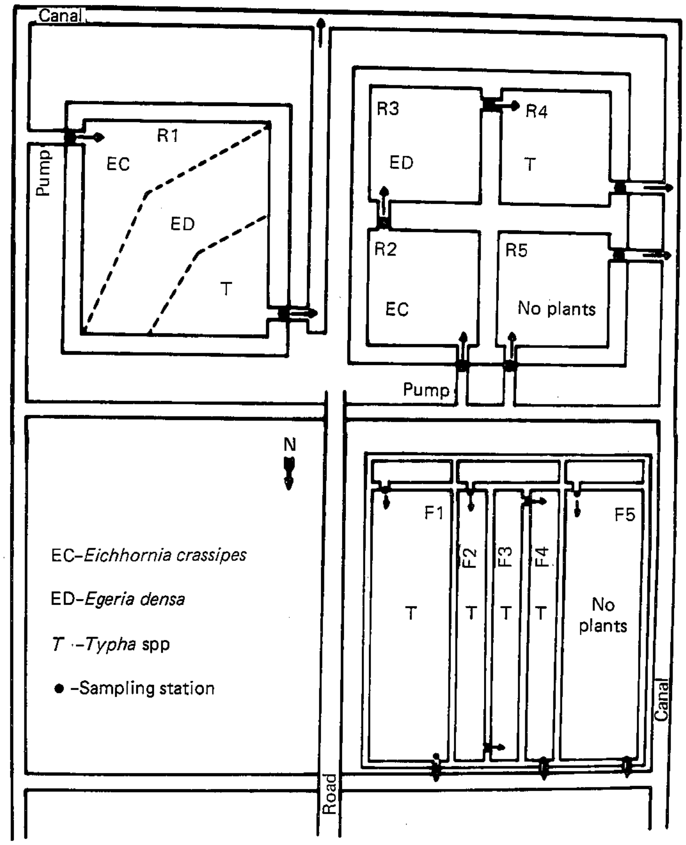

Figure 1. Schematic representation of the field layout of reservoirs and flooded fields.

Table 2. Selected characteristics of the drainage water from organic soils.

Parameter	Units	Mean	SD ±	CV %	No. of samples
NH_4–N	μg/ml	0.57	0.53	92.3	178
NO_3–N	μg/ml	1.04	1.74	167.2	182
TKN	μg/ml	3.76	2.53	67.4	156
Total P	μg/ml	0.66	0.73	111.1	166
DO	μg/ml	5.10	3.60	71.0	168
Alkalinity	μg/ml	280	93	33.2	86
COD	μg/ml	152	102	67.2	20
BOD	μg/ml	22	7	33.2	14
pH	—	7.41	0.25	3.3	184
Conductivity	μMhos/cm	634	146	23.0	182
Turbidity	JTU[a]	4.9	4.3	87.8	180

[a] Jackson turbidity units.

Table 3. Showing the reservoir or flooded field size and pumping rates of drainage water.

Reservoir flooded field	Surface area m^2	Volume of water	Pumping rate m^3/hr	Residence time days
R1	3720	3720	57	10.9
R2	1240	1240	57	3.6
R2 → R3	2480	2480	57	7.2
R2 → R3 → R4	3720	3224	57	9.4
R5	1240	1240	19	10.9
F1	3720	774	26	4.8
F2	1240	248	26	1.6
F2 → F3	2480	496	26	3.2
F2 → F3 → F4	3720	744	26	4.8
F5	3720	744	26	4.8

not stocked with plants. Water was pumped into F1, F2, and F5 at predetermined constant flow rates 6 h/day, 6 days/week (Table 3). The depth of water column in all flooded fields was 0.2 m. Drainage water was allowed to flow by gravity from F2 to F3, and F4. Water samples were collected at the inlet and outlet of each reservoir and analyzed for chemical parameters noted below.

Once every 3 months, 50% of the waterhyacinths were removed from the reservoirs. Cattails were harvested every 4 months. Elodea was not harvested. Productivity of waterhyacinths was in the range of 40 to 52 dry metric tons/ha/yr, while productivity of elodea was in the range of 3 to 5 dry metric tons/ha/yr. Cattail productivity was about 12 and 40 dry metric tons/ha/yr for reservoirs and flooded fields, respectively.

Sampling and Analytical Procedures

Water samples were obtained at the inlet and outlet of each reservoir and flooded field after 3 h of pumping. During the first 14 months of the study (July 1977 to August 1978), water samples were obtained only once a week, whereas during the latter part of the study (September 1978 to September 1979), frequency of water sampling was increased to three times a week. Dissolved oxygen and pH were measured on site. All water samples were analyzed for NO_3^-, NH_4^+, organic N, ortho-P, and total P. From July 1977 to February 1979, water samples were analyzed for NH_4^+ using an Orion ammonia electrode. Organic N was analyzed by digestion followed by the use of an Orion ammonia electrode. Organic N was analyzed by digestion followed by the use of an Orion ammonia electrode. From February 1979 to August 1979, a steam distillation (Bremner 1965a) method was used to analyze water samples for NH_4^+. Total Kjeldahl N (TKN) of the water samples during this period was analyzed by digestion followed by distillation (A.P.H.A. 1971). During the entire experimental period, NO_3^- was determined by the brucine method, ortho-P was determined by a single reagent method (Murphy and Riley 1962), and total P was determined by persulfate digestion and the ascorbic acid method (A.P.H.A. 1971).

Wet reservoir sediments and flooded organic soil were obtained from the 15-cm surface layer, and the pH was measured directly in wet samples. Wet samples were extracted with water at a soil to solution ratio of 1:5 after shaking for 15 minutes. The soil solutions were filtered through 0.2-μm filter paper and analyzed for ortho-P. Remaining soil was dried at 40°C and analyzed for total nitrogen (Bremner 1965b) and for total carbon by wet oxidation (Allison 1965). Five grams of dried soil were extracted with 50 ml of 0.025 N H_2SO_4 + 0.05 N HCl. The filtered solutions were analyzed for ortho-P and reported as acid extractable P.

Statistical Analysis

Data were statistically analyzed using a two way classification model with interaction and with fixed and random effects (Graybill 1961). In this model, month effects were considered to be random effects, while treatment effects were considered to be fixed. Analysis of variance of the data shows that month to month variation

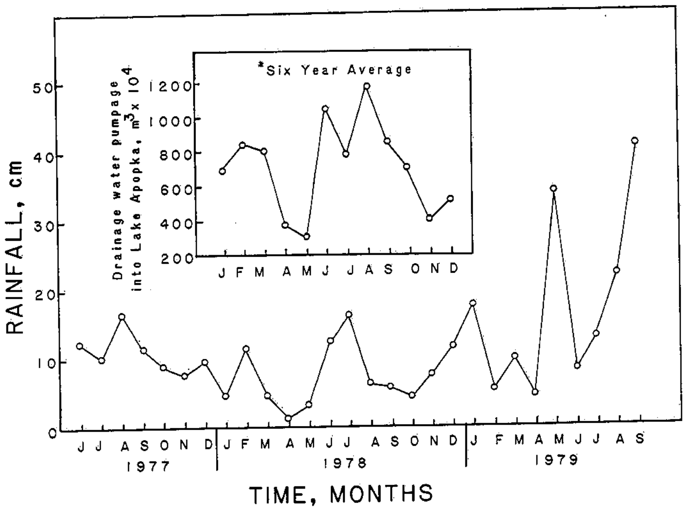

Figure 2. Rainfall distribution and pumpage of drainage water in the Zellwood area.

and treatmental differences were significant. Mean separation by modified Duncan's Multiple Range Test (Chew 1977) was used to test relative significance among treatments.

Results and Discussion

Organic Soil Drainage Water Quality

Monthly rainfall during 1977, 1978, and 1979 for the Zellwood area is shown in Figure 2. Drainage water pump data are not available for the study period of 1977 to 1979. However, data on average monthly pumping rates (Zellwood Drainage District Records, Orange County, FL) for the previous six-year period shown in Figure 2 and the average drainage water composition (Table 2) were used in calculating the annual loading of the nutrients into Lake Apopka. The resulting loading

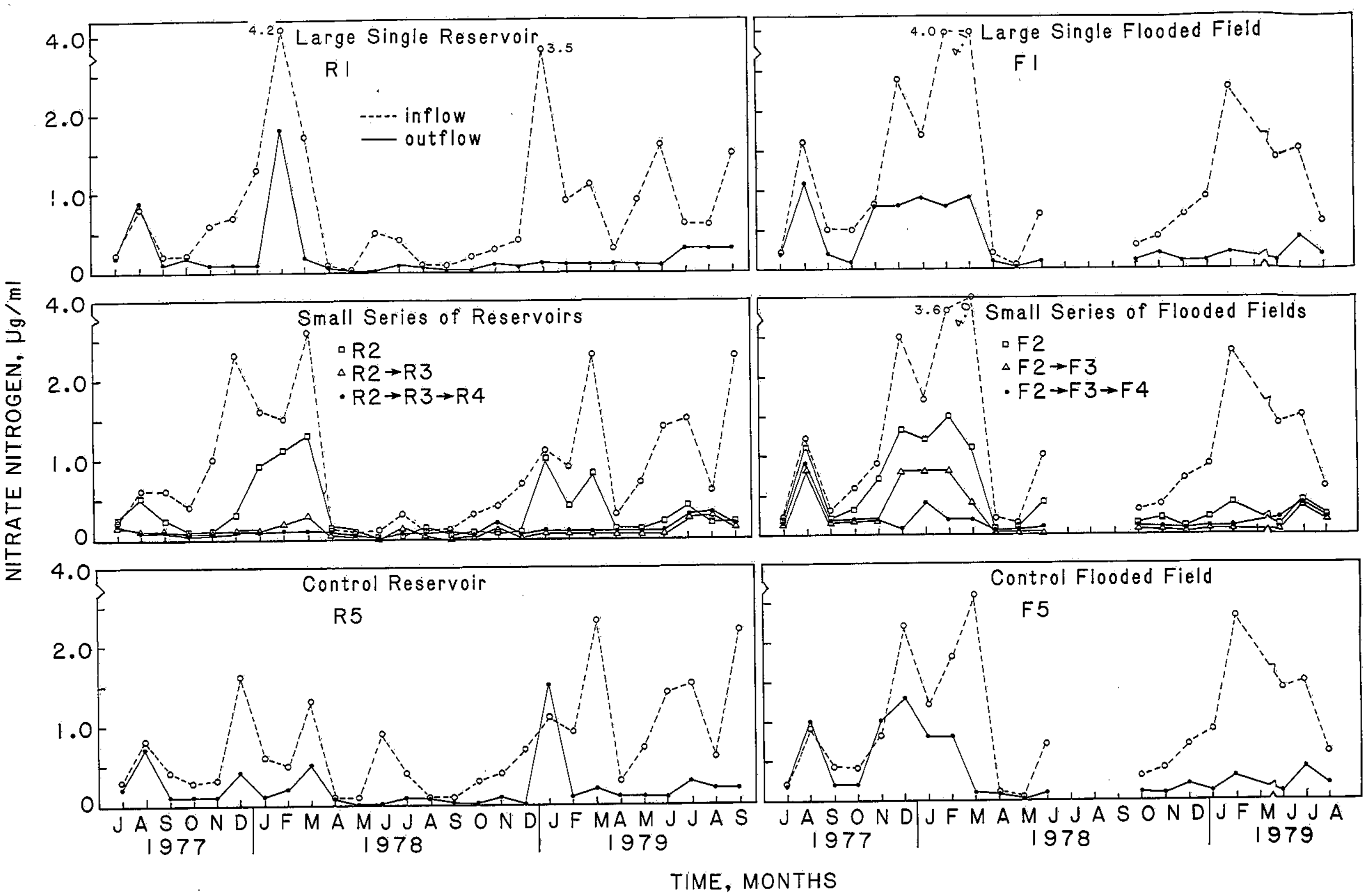

Figure 3. Nitrate N concentration of the drainage water at the inflow and outflow of each treatment system.

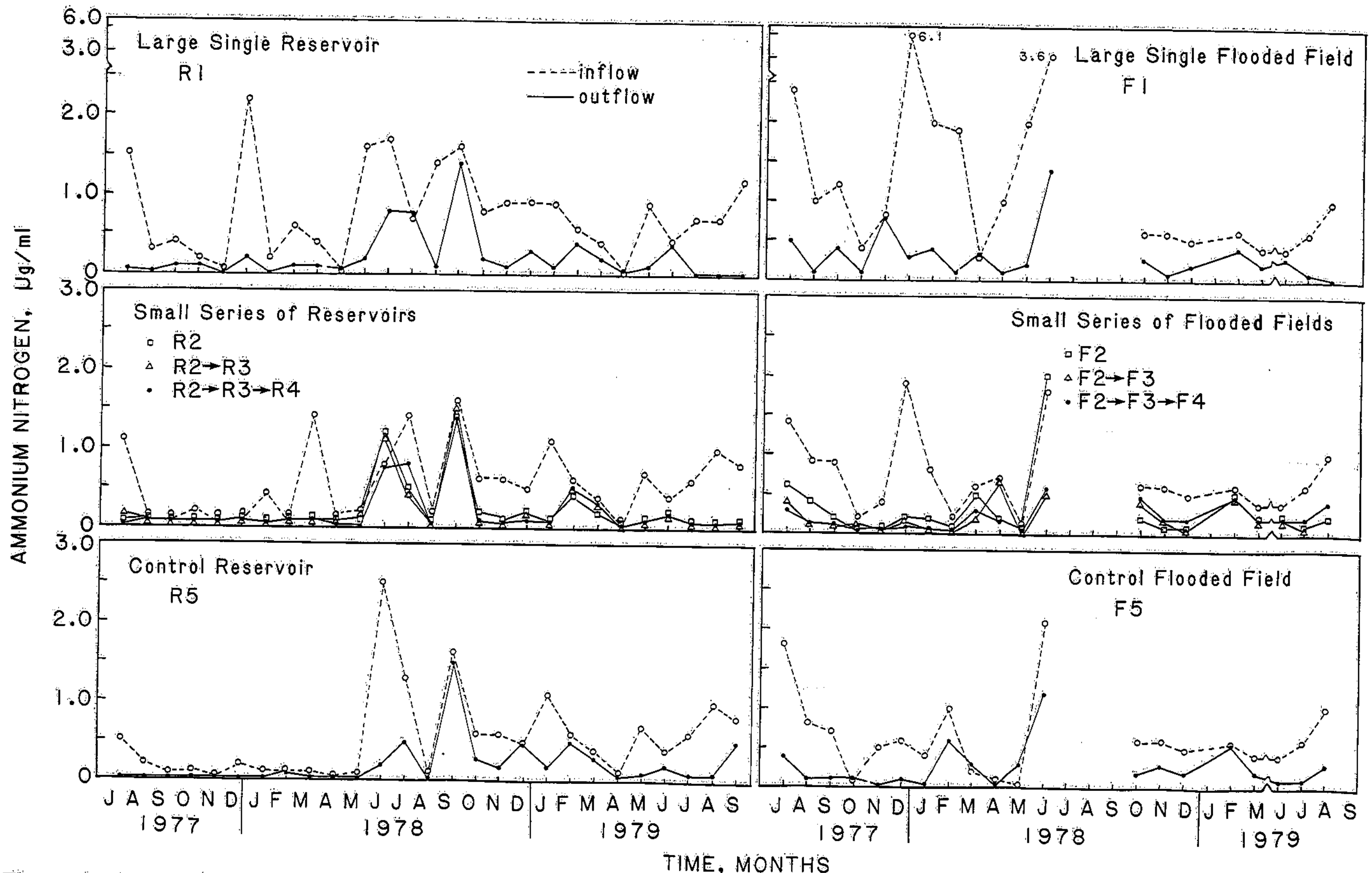

Figure 4. Ammonium N concentration of the drainage water at the inflow and outflow of each treatment system.

rates were 4.0, 7.3, 26.3, 4.1, and 4.6 kg/ha/yr of NO_3^-–N, NH_4^+–N, TKN, ortho-P, and total P, respectively (Table 4).

Data on the seasonal changes in N and P concentration of the inflow drainage water are shown in Figures 3, 4, 5, and 6. Agricultural drainage water quality from the organic soils was closely associated with the agricultural practices, rainfall, and biochemical reactions in the organic soil. Increase in NO_3^- concentration of the drainage water during winter months was probably due to fertilizer application to vegetable crops (Hortenstine and Forbes 1972). Although soil solution NO_3^- concentration of the organic soils has been shown to be high (Hortenstine and Forbes 1972), the resulting NO_3^- in the drainage water was low. Significant losses of NO_3^- as a result of denitrification were observed in organic soils (Guthrie and Duxbury 1977). During summer months, flooding (a common practice used by the farmers in summer) resulted in low NO_3^- levels of drainage water, primarily due to dentrification. During the winter months, fertilizer application and dieoff of water-hyacinths in the drainage canals increased the NH_4^+ levels of the drainage water (Reddy and Sacco 1981). During the summer months, NH_4^+ accumlation occurred in the organic soils as a result of flooding and

Table 4. Nutrient loading into Lake Apopka as a result of pumping drainage water from organic soils.

	Nutrient loading into Lake Apopka				
	Mean	Max	Min	Based on organic soil cultivated	Based on Lake Apopka surface area
Parameter	Metric tons/year			kg/ha/yr	
Ammonium N	48.5	92.3	14.8	6.7	4.0
Nitrate N	88.4	168.4	27.0	12.1	7.3
TKN	319.6	608.7	97.5	43.9	26.3
Ortho-P	49.3	93.9	15.0	6.8	4.1
Total P	56.1	106.9	17.1	7.7	4.6

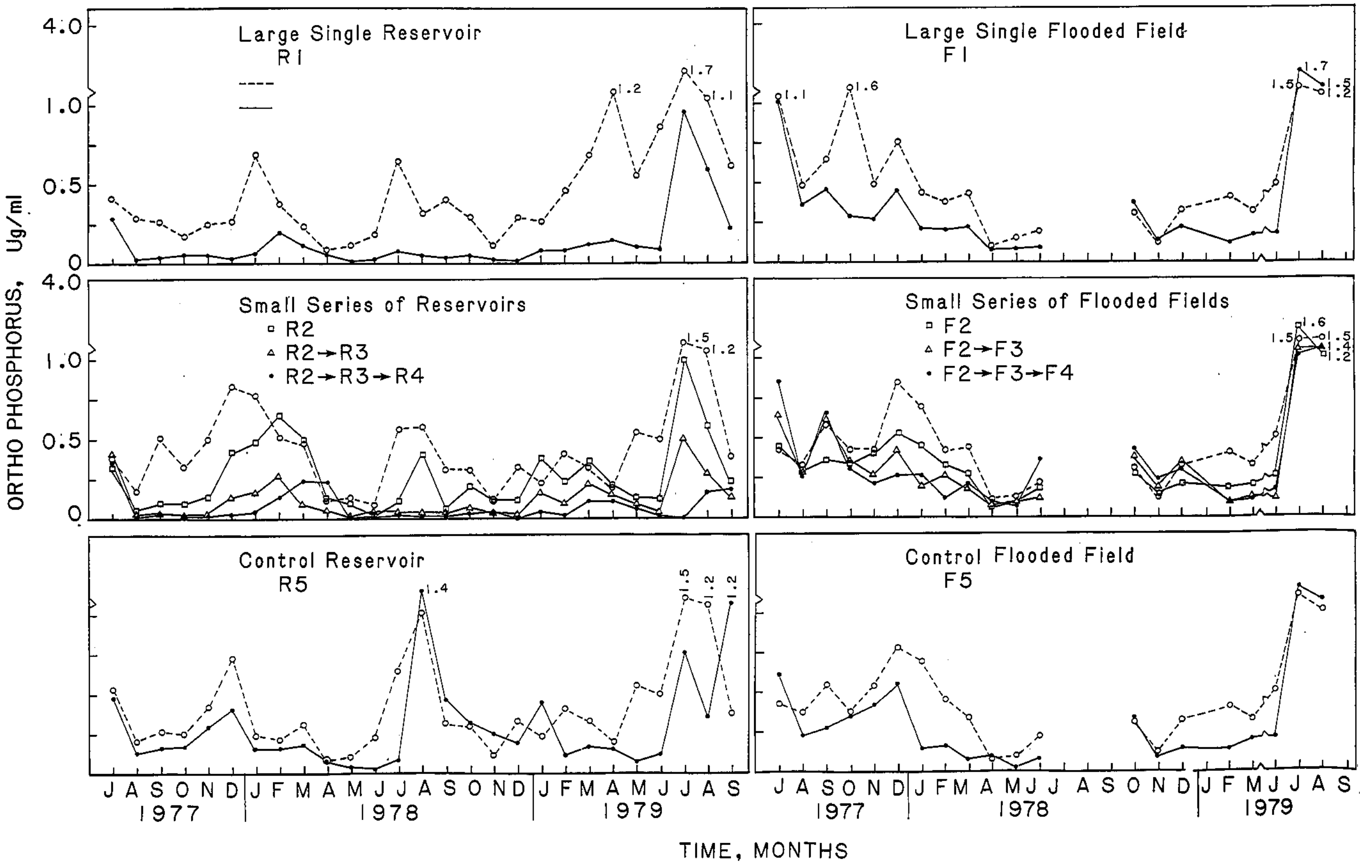

Figure 5. Ortho-phosphorus concentration of the drainage water at the inflow and outflow of each treatment system.

leached into the adjacent drainage canals during excessive rain events.

Ortho-P and total P concentration of the drainage water were closely related to rainfall. Ortho-P accounted for about 70 to 80% of the total P. High ortho-P levels during summer months were due to leaching from the flooded organic soils and release from dead hyacinth plants (Reddy and Sacco 1981). Anaerobic conditions in organic soils were shown to increase the soluble P concentration (Reddy and Graetz 1981). During winter months, soluble P concentration of drainage water was due to increased waterhyacinth plant dieoff in the canals as the result of freezing temperatures and fertilizer application for winter vegetable crops.

Nutrient Removal Efficiency of Reservoirs

Nitrogen: During the 27-month study, NO_3^- concentration in the outflow water (Figure 3) was decreased by an average of 54% in the large single reservoir R1, compared to 68% in the drainage water flowing through series of small reservoirs R2, R3, and R4. The control reservoir R5 (with no plants) removed about 55% of the incoming drainage water NO_3^- (Table 5). Nitrate concentration of the drainage water flowing through R2 was decreased by 51%, compared to 66 and 68% reduction after flowing through R2 and R3, and R2, R3 and R4, respectively. Thus most of the reduction occurred in the reservoir with waterhyacinths, while elodea and cattails provided little additional removal.

No significant differences were observed among reservoir systems in the removal of NH_4^+ (Figure 4). Ammonium removal efficiency was in the range of 34 to 58% (Table 5). Very little or no reduction in organic N (about −1.6 to 10% removal) was observed in all treatments.

Phosphorus: Ortho-P concentration was decreased by 63% in the large single reservoir where drainage water was flowing through waterhyacinths, elodea, and cattail plant stands (Table 5 and Figure 5). In series of small reservoirs, ortho-P concentration was decreased by 18%

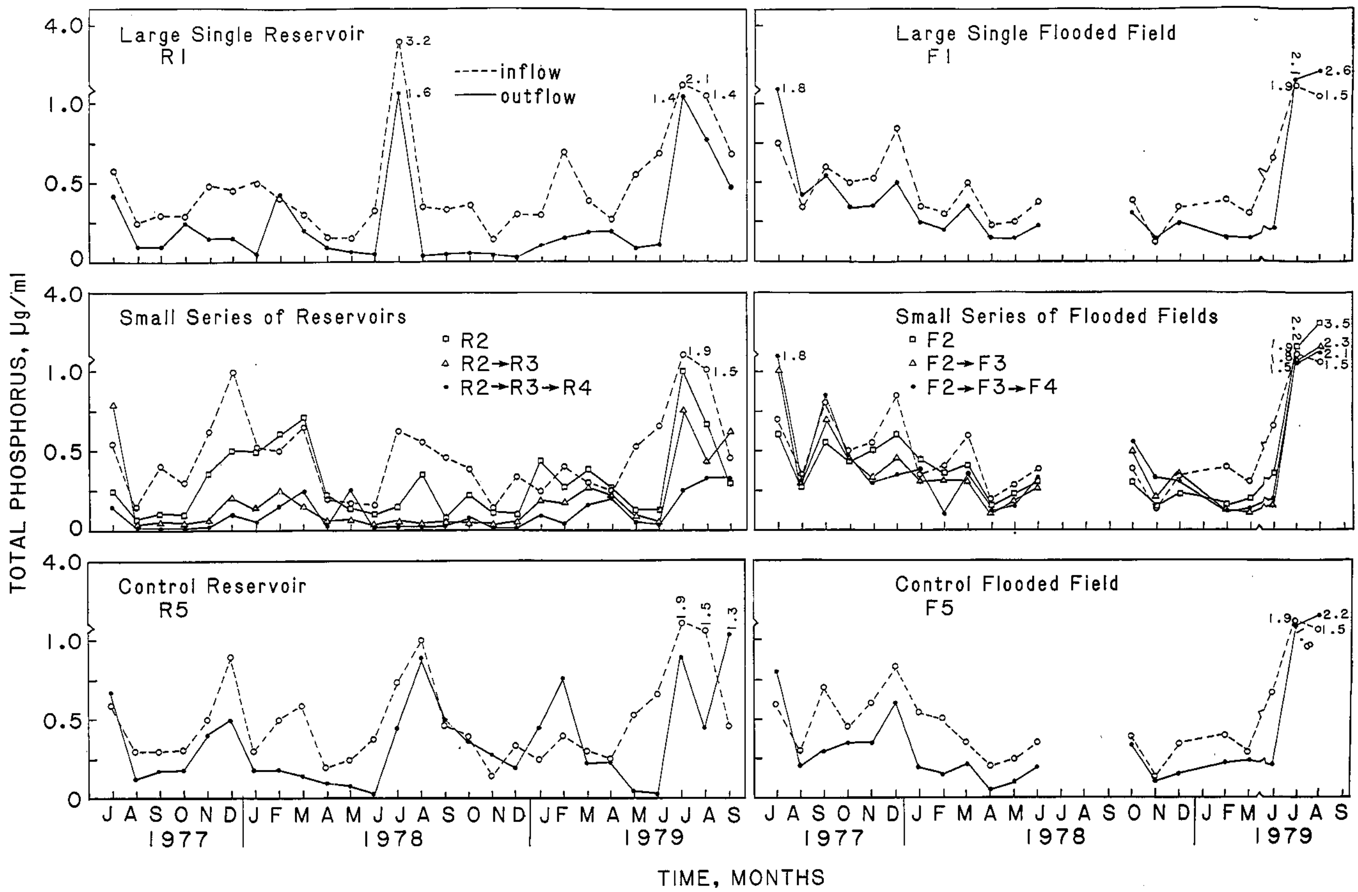

Figure 6. Total phosphorus concentration of the drainage water at the inflow and outflow of each treatment system.

Table 5. Efficiency of the reservoir systems evaluated, expressed as percent reduction or increase in concentration.[a]

Reservoir system	NO_3–N	NH_4–N	TKN	PO_4–P	TP
	Percent reduction or increase in concentration				
R1	54.4 b[b]	41.8 a	9.8 a	62.5 a	44.4 a
R2	50.9 b	49.3 a	4.2a	18.3 b	9.8 b
R2 → R3	65.9 ab	38.1 a	−0.1 ab	59.8 a	44.5 a
R2 → R3 → R4	68.1 a	57.5 a	4.8 a	75.1 a	60.9 a
R5	55.4 b	33.5 a	−1.6 b	20.9 b	25.6 b

[a]Percent reduction or increase in concentration = {(I − 0)/I} × 100 where I is the inflow concentration of the drainage water and 0 is the 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.

[b]Values following with same letter are not significant at 0.05 level or probability.

in R2 followed by 60 and 75% reduction in ortho-P concentration of the water flowing through R2 and R3, and R2, R3, and R4, respectively. The control reservoir (R5) removed about 21% of the incoming ortho-P. Even though the plant community, residence time, and flow rates were the same for the single large reservoir (R1) and three small reservoirs (R2, R3, and R4), ortho-P removal efficiency was higher in the three independent reservoirs. However, these differences were not significant statistically, but were found to be superior compared to the control reservoir with no plants. Similar trends were also observed in the removal of total P with relatively low removal efficiency (Figure 6 and Table 5).

Nutrient Removal Efficiency by Flooded Fields

Nitrogen: Flooded fields also functioned as effective treatment systems for reducing the NO_3^- levels of the drainage water (Table 6 and Figure 3). A single large

Table 6. Efficiency of the flooded field system, expressed as percent reduction or increase in concentration.[a]

Flooded field	NO_3–N	NH_4–N	TKN	PO_4–P	TP
	Percent reduction of increase in concentration				
F1	50.7 ab	43.5 a	−4.7 a	24.2 a	15.7 a
F2	41.3 b	36.3 a	−18.2 a	−18.9 a	13.5 a
F2 → F3	65.2 a	54.4 a	−13.2 a	18.1 a	14.3 a
F2 → F3 → F4	64.2 a	51.9 a	−7.6 a	16.7 a	7.3 a
F5	48.4 ab	38.7 a	−2.9 a	28.2 a	11.1 a

[a] Percent reduction or increase in concentration = {(I − 0)/I}1 × 100 where I is the inflow concentration of the drainage water and 0 is the 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.

flooded field was less effective compared to a series of small flooded fields in the removal of NO_3^-. Nitrate concentraion of the drainage water was decreased by 51% in the large flooded field F1, 64% by series of small flooded fields F2, F3, and F4, and 48% by a control flooded field F5 (with no plants). No significant differences in the NO_3^- removal efficiency were observed among the flooded field systems evaluated. However, in the series of flooded fields, NO_3^- concentration of the drainage water flowing through F2 was decreased by 41%. Allowing the water to flow from F2 to F3 significantly improved the NO_3^- removal efficiency with about 65% reduction, whereas, allowing the water to flow through an additional flooded field, F4, did not increase NO_3^- removal capacity. Flooded fields functioned as poor sinks for NH_4^+ (Figure 4) and organic N.

Phosphorus: Flooded fields did not function effectively in the removal of ortho-P and total P from the drainage water (Table 6 and Figures 5 and 6). No significant differences were observed among three treatment systems evaluated. The ortho-P removal efficiency ranged from 17 to 29% and total P removal efficiency ranged from 7 to 16%.

Associated Processes

Both biotic and abiotic processes probably accounted for the removal of N and P from the drainage water during flow across the reservoirs and flooded fields. Nitrate uptake by aquatic plants, NO_3^- reduction, and denitrification in the water and underlying anaerobic soil probably accounted for NO_3^- removal from the inflow drainage water. Several studies (Engler and Patrick 1974, Reddy and others 1978, 1980) have indicated that NO_3^- removal from the overlying floodwater was due to diffusion of NO_3^- into underlying soil followed by denitrification. In the reservoirs, NO_3^- removal by reservoir R1, or reservoir R2 (first reservoir in series of small reservoirs) was probably due to assimilation by waterhyacinth plants (Dunigan and others 1975, Cornwell and others 1977) and to denitrification in the anaerobic water column and underlying sediments. The water column underneath floating waterhyacinth plants was anaerobic with dissolved oxygen values less than 1 μg/ml, thus creating favorable conditions for denitrification. This explains the large proportion (51%) of NO_3^- removal in R2. Allowing the water to flow through reservoirs R3 and R4 increased NO_3^- removal by only 15–17%. In the control reservoir, NO_3^- removal was probably due to assimilation by algae (Neel and others 1961, Gates and Borchardt 1964), and denitrification at the sediment water interface. In the flooded fields, underlying organic soil functioned as a sink for NO_3^- from the drainage water flowing over these fields (Reddy and others 1980).

Ammonium was probably removed through assimilation by aquatic plants and algae, and through nitrification and NH_3 volatilization processes. A significant portion of the incoming NH_4^+ was probably removed by aquatic plants. Dunigan and others (1975) observed 60% reduction in NH_4^+ concentration of the water containing waterhyacinth plants, and 36% reduction in NH_4^+ concentration in the water containing no plants. Cornwell and others (1977) measured about 20% reduction of NH_4^+ by waterhyacinth plants growing in waste water polishing ponds. Beneath the dense cover of floating waterhyacinth plants, anaerobic conditions existed, and under these conditions NH_4^+ was stable, because the nitrification reaction occurs only in the presence of O_2. The pH of this water was around 7, thus creating less favorable conditions for NH_3 volatilization. A portion of the NH_4^+ removal from the drainage water flowing through elodea and cattail plant stands was probably due to nitrification and NH_3 volatilization. Drainage water flowing through these plant stands was aerobic with dissolved oxygen levels greater than 7 μg/ml. These conditions, with high bicarbonate alkalinity probably increased the nitrification process (Reddy and Graetz 1981). In the control reservoir, NH_4^+ removal was due to assimiliation by algae, NH_3 volatilization, and nitrification. Ammonia volatilization was likely the dominant process because diel variations in the physico-chemical characteristics of the drainage water in the control reservoir (R5) showed that the pH of the water increased to as high as 10 during certain times of the day (Reddy 1981). Similar processes probably accounted for NH_4^+ removal in flooded fields.

Phosphorus removal from the drainage water was probably due to assimilation by aquatic plants and algae, and adsorption and precipitation reactions. Waterhyacinth plants functioned as a poor sink for P removal. Ornes and Sutton (1975) and Dunigan and others (1975) also observed poor efficiency of waterhyacinth plants in ortho-P removal from the wastewaters. Another probable reason for high ortho-P concentration of the water with an overlying dense cover of waterhyacinth was the release of soluble ortho-P from the dead plant parts of *Eichhornia* (Reddy and Sacco 1981). Ortho-P removal in the reservoirs stocked with elodea was probably due to adsorption and precipitation reactions and uptake by elodea. In a recent study, Reddy (1980) showed that ortho-P removal from the drainage water was due to precipitation of P with Ca compounds in the drainage water. Additional ortho-P was removed from the drainage water flowing through cattail plant stands, probably due to adsorption and precipitation reactions. Ortho-P uptake by cattail was minimal because these plants were rooted in the underlying sediments. However, the beneficial effect of cattail plants was probably the depletion of interstitial ortho-P of the sediments, thus increasing the retention of ortho-P from the overlying water column. In the control reservoir, ortho-P removal was probably due to assimilation by algae and precipitation with Ca compounds in the water.

Equilibrium P concentration (EPC values at which P is neither gained nor lost from the system) of 0.05 and 2.25 μg P/ml have been determined for reservoir sediments and flooded organic soils, respectively (Reddy and Graetz 1981). These results indicate that in reservoirs, underlying sediments functioned as a sink for the ortho-P of the overlying water column. In flooded fields, underlying organic soil functioned as a source and sink for ortho-P to the overlying water column, thus resulting in a less effective treatment system.

Management of Reservoirs for Reducing Nutrient Loads into Lake Apopka

The results presented in this study have shown that reservoirs stocked with aquatic macrophytes can be effectively used in reducing the nutrient removal. To maximize the nutrient removal, aquatic plants must be periodically harvested. Currently, economical methods of plant harvesting are not available. The reservoir systems presented in this study were designed to function as flow-through systems and this has resulted in treating limited amounts of drainage water. For example, three 0.12-ha small reservoirs (R2, R3, and R4) are capable of treating 342 m^3 drainage water/day, with a storage capacity of 3224 m^3, and in a residence time of 9.4 days. Drainage water discharge from vegetable fields into Lake Apopka was about 32 $\pm$ 12 m^3/ha/day (average value based on six years pumping data), although during the months of heavy rainfall, drainage water discharge into the lake reached a maximum rate of 100 m^3/ha/day. On a 1:10 (1-ha reservoir size to 10-ha farmland cultivated) ratio basis, the reservoir systems are adequate to treat the excess drainage water discharged from the vegetable farmland.

Results obtained in this study (Table 5) also show that waterhyacinth (R2) and elodea (R3) reservoirs removed about 66% of NO_3^- and 60% of PO_4^{-3} in 7.2 days. These values are based on yearly average, although at certain times of the year, nutrient removal rates were >95%. Adapting the two reservoir series with waterhyacinths and elodea can decrease the residence time and the capacity of the system to treat more drainage water can be increased. Currently, studies are in progress at the University of Florida Agricultural Research and Education Center to determine the optimum residence time for maximizing the nutrient removal. This will decrease the reservoir size requirement per unit area of farmland cultivated.

A study conducted by Brezonik and others (1978) showed that about 52 and 66% of the total external N and P input, respectively, were contributed by the drainage water discharge into Lake Apopka. Using the reservoir systems presented in this paper, annual inorganic N and PO_4^{-3} loads into the lake can be reduced by at least 50 to 60%. On a short-term basis, reducing the nutrient levels in the agricultural discharge will have very little or no influence on improving the lake water quality. Lake Apopka sediments are primarily organic and rich in nutrient content. A significant amount of N and P can be released from the underlying sediments to the overlying water column, as a result of diffusion and wind action. Phosphorus release as a result of diffusion from organic sediments to the overlying waters was found to be 5.25 to 9.18 mg P/m^2/day (Pollman and Brezonik 1979, Reddy and Rao 1981). In improving lake water quality, this internal source (which can contribute as much as 50% total nutrient input) input to the water should be considered.

Conclusions

The use of a series of reservoirs stocked with aquatic plants functioned effectively in the removal of N and P from agricultural drainage water, compared to a single large reservoir. Allowing the drainage water to flow through the reservoir stocked with waterhyacinth plants with a residence time of 3.6 days was adequate time for the removal of 50% of the incoming inorganic N. Allowing the drainage water to flow through reservoir R2 (waterhyacinths) and R3 (elodea) with a total residence time of 7.2 days, was necessary to remove at least 60% of the incoming ortho-P. By treating the agricultural drainage water using these treatment systems, nutrient loading into Lake Apopka from organic soils can be reduced by at least 50 to 60%. At this time, no data are available to show the cost effectiveness of these treatment systems. To maintain high nutrient removal efficiency, aquatic plants must be harvested. At this time, economical harvesting techniques are not available. Flooded fields were found to be effective in the removal of inorganic forms of N, but showed poor efficiency in the removal of ortho-P. Another disadvantage of using flooded fields was their poor capacity to handle high pumping rates of drainage water. About six times more drainage water can be pumped into the reservoirs while obtaining the same removal efficiency.

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