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Vol. 11, no. 4, October-December 1982, Copyright © 1982, ASA, CSSA, SSSA
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Use of Biological Filters for Treating Agricultural Drainage Effluents

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ABSTRACT

A field study was conducted for 1 year (1979–1980) to evaluate the efficiency of reservoir systems stocked with aquatic macrophytes for reducing nutrient levels of agricultural drainage water. Reservoir R2 containing water hyacinths (*Eichhornia crassipes* (Mart) Solms), R3 with elodea (*Egeria densa* Planch), and R4 with cattails (*Typha latifolia* L.) were connected in series by riser panels. Drainage water was pumped through the plant stands in the order of water hyacinths, elodea, and cattails. Drainage water was also pumped into a reservoir (R5) containing submerged *Chara* spp. Nutrient removal rates by each treatment system were calculated using water flow data.

Nitrate and ammonium removal rates by the treatment systems were in the range of 1–14 kg N/ha per day and 0.1–2 kg P/ha per day, respectively, while soluble P removal were in the range of 0.05–1.3 kg/ha per day. Reservoirs with aquatic macrophytes were found to be more effective than the reservoir containing *Chara* spp. About 78–81% of the input NO_3^- and NH_4^+, and 54% of the input soluble P were removed in 3.6 d by the R2 reservoir containing water hyacinths. Allowing the water to flow through an additional reservoir, R3, and increasing the residence time by an additional 3.6 d increased NO_3^- removal efficiency to 91% and soluble P removal efficiency to 71%, but NH_4^+ removal efficiency was not affected. Allowing the water to flow through the third reservoir (R4) and increasing the residence time by an additional 2.2 d, improved soluble P removal efficiency by an additional 14%.

Additional Index Words: **aquatic plants, waste water, aquatic systems, reservoirs, nitrogen removal, phosphorus removal, floating plants, emergent plants, submersed plants.**

Reddy, K. R., K. L. Campbell, D. A. Graetz, and K. M. Portier. 1982. Use of biological filters for treating agricultural drainage effluents. J. Environ. Qual. 11:591–595.

Lake Apopka (12,500 ha), located in central Florida, is currently eutrophic. One of the causes of the lake's gradual decline was nutrient loading from the discharge of drainage water from adjacent organic soils (Histosols) planted to vegetable crops (USEPA, 1979). Organic soils are naturally productive and contain large fractions of soluble C, N, and P. These soils are poorly drained under natural conditions. The water table is at the soilsurface and the water-holding capacity is high; therefore, drainage is often necessary before these soils can be planted with vegetable crops. During the periods of heavy rainfall, considerable amounts of drainage water must be pumped off the farms into adjacent Lake Apopka, resulting in increased nutrient loads to the lake. To reduce nutrient loads it was proposed that either existing swamps be used as nutrient sinks or recycle reservoirs (with an area ratio of 1:10, reservoir/farmland drained) built to store water and reduce nutrient levels of drainage water (Sinclair and Forbes, 1980). Currently, seven recycle reservoirs are in operation along the north shore of Lake Apopka.

Several research workers (Boyt et al., 1977; Fetter et al., 1978; Tilton and Kadlec, 1979) have attempted to use wetlands or swamps for reducing nutrient levels of waste waters. Other researchers (Boyd, 1969; Wooten and Dodd, 1976; Cornwell et al., 1977; Reddy et al., 1982) have used aquatic plants stocked in ponds for reducing nutrient levels of waste waters. Reddy et al. (1982) showed that shallow reservoirs stocked with aquatic macrophytes were more effective than flooded fields. The objectives of this study were to evaluate (i) the capacity of a reservoir system to function as a sink, and (ii) the role of aquatic plants, in the removal of N and P from drainage water. Most of the studies reported so far evaluate the efficiency of a treatment system based on changes in concentrations, not on mass balance. Also, these researchers relate the nutrient removal efficiency primarily to the plant uptake rather than to any biochemical processes functioning in the system.

MATERIALS AND METHODS

The experimental reservoirs are located at the Agricultural Research and Education Center–Sanford's research farm in the Zellwood Drainage District, near Lake Apopka. The major soil type in this area is organic (Lithic Medisaprists, euic hyperthermic), with a muck-layer thickness of 20–120 cm underlain by an approximately 25-cm-thick calcareous marly clay layer. Reservoirs were constructed with 2.0-m-high levees of organic soil, and with bottoms composed of calcareous marly clay. The reservoir sediments had 0.62% total N and 6.67% total organic C. The pH and bulk density (g/cm^3) of the sediment were 6.8 and 1.1, respectively.

Three reservoirs, R2, R3, and R4, each with the surface area of 1,240 m^2, were connected in series by riser panels (Fig. 1). Reservoir R2 was stocked with *Eichhornia crassipes* (water hyacinth, floating plant), followed by *Egeria densa* (elodea, submersed plant) in R3, and *Typha latifolia* (cattails, emersed plant) in R4. Drainage water used in the study was pumped from the drainage canals located in the adjacent organic soils planted with vegetable crops. The most common vegetables planted in this area include carrots (*Daucus carota* L.), sweet corn (*Zea mays* L.), radish (*Raphanus sativus* L.), and lettuce (*Lactuca sativa* L.). Drainage water was pumped diagonally through the R2 reservoir and was allowed to flow by gravity through R3 and R4. Drainage water was also pumped into an additional reservoir, R5 (1,240 m^2), without aquatic macrophytes, but contained filamentous algae and submerged *Chara* sp. Depth of the water column was 1 m in R2, R3, and R5, and 0.6 m in R4. Drainage water was pumped 6 h/d and 6 d/week from 15 Jan. 1979 to 30 Jan. 1980 (Table 1). Water flow rate was measured at the outflow of R2 and R3 by triangular critical-depth flumes and stage recorders, and at R4 and R5 by V-notch weirs and stage recorders. Water samples were collected 3 h after the start of pumping, three times a week at the inlet and outlet of each reservoir, and analyzed for various physical and chemical constituents.

Plant samples from R2 and R4 were obtained bimonthly from four 1-m^2 random locations in each reservoir. Plant samples from R3 and R5 were obtained bimonthly from eight 1/16-m^2 random locations in each reservoir. All biomass measurements are reported on a dry-weight basis. Plant samples were dried at 70°C for 48 h and ground for chemical analysis. Once every 3 months about 50% of the water hyacinths were harvested from the reservoirs. Aboveground portions of the cattails were harvested every 4 months. Elodea and *Chara* sp. were not harvested.

Analytical Methods

Dissolved O_2 and pH of the water were measured on site, using a YSI oxygen meter and an Orion pH meter, respectively. Water samples collected on site were placed in an ice chest and transported to

[1] Florida Agric. Exp. Stn. J. Ser. no. 2942. Received 16 Jan. 1982.

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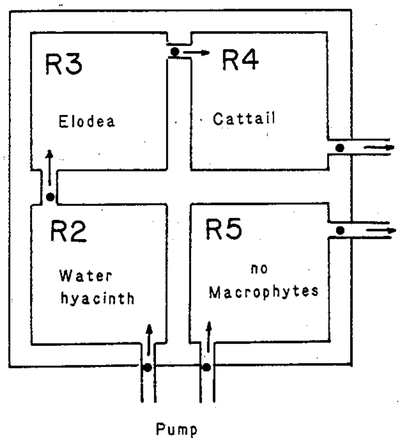

Fig. 1—Schematic presentation of the field layout of the reservoirs.

the laboratory for analysis. A portion of the water sample was filtered through 0.45-μm filter paper, and the filtered water sample was analyzed for ortho-P by the single-reagent method (Murphy and Riley, 1962). Ammonium N was analyzed by steam distillation (Bremner, 1965), and organic N was determined by digestion followed by steam distillation. Nitrate N was determined by the Brucine method (APHA, 1971). Total P was determined by persulfate digestion and ascorbic acid methods (APHA, 1971). Total N and P in the plant samples were measured by the procedures described by Jackson (1956).

RESULTS AND DISCUSSION

Changes in Nutrient Concentration of the Water

Nitrate concentration of the untreated drainage water was in the range of 0.2–5.0 μg N/mL, with maximum values observed during the periods of peak rainfall months (Fig. 2). Ammonium concentration was in the range of 0.1–1.0 μg N/mL, with maximum values observed during winter and summer months (Fig. 3). Organic N concentration ranged from 1.5 to 10.0 μg N/mL, with peak values observed during summer months. Phosphorus concentration of the untreated water also showed similar trends, with peak values observed during summer months (Fig. 4). High drainage-water P during summer months was probably due to drainage of flooded fields. In Florida, organic soils are flooded during the summer months to control weeds and soilborne pests, and to reduce soil subsidence. Flooding the organic soils was shown to increase the P concentration in soil solution (Reddy, 1981a). Even though the N and P concentrations of the drainage water were not appreciably high compared with other waste waters, the amount of water pumped into Lake Apopka results in a loading of 4.0, 7.3, 26.3, 4.1, and 4.6 kg/ha per year as NO_3-N, NH_4-N, TKN, PO_4-P, and total P, respectively (Reddy et al., 1982).

All treatment systems evaluated were found to be effective in reducing the NO_3^- and NH_4^+ concentrations of the water, but were less effective in reducing organic N levels of the water. Nitrate and NH_4^+ levels of the water were reduced to <0.5 μg/mL at all times during the year (Fig. 2 and 3). Ortho-P concentration of the water leaving three of the reservoirs was <0.15 μg/mL. Reservoir R5, containing *Chara* sp., was found to be less effective in P removal compared to the reservoirs stocked with aquatic macrophytes. For both N and P removal, water

Table 1—Reservoir sizes and drainage water pumping rates.

Treatment system	Surface area	Volume water	Avg pumping rate	Residence time
	m^2	m^3	m^3/d	d
	Reservoirs in series with macrophytes			
R2	1,240	1,240	342	3.6
R2 → R3	2,480	2,480	342	7.2
R2 → R3 → R4	3,720	3,224	342	9.4
	Reservoir with no macrophytes			
R5	1,240	1,240	114	10.9

flowing through series of reservoirs, R2 → R3 or R2 → R3 → R4, was found to be most effective compared with other treatment systems.

Plant Biomass Yield

Annual plant biomass produced in the reservoirs was equivalent to 57, 15, and 3.3 t (dry wt)/ha per year for water hyacinths, cattails, and elodea, respectively. Biomass production of *Chara* sp. in R5 was about 3.5 t (dry wt)/ha per year.

Nutrient Removal Rate by the Reservoir

Nutrient input loading to each reservoir was calculated using the following equation:

$$N_i = [C \times \mathrm{IR}]/1{,}000, \qquad [1]$$

where

N_i = nutrient input to the reservoir, kg/ha per day;
C = monthly average concentration of N or P in the untreated drainage water, μg/mL; and
IR = average inflow rate, m^3/ha per day.

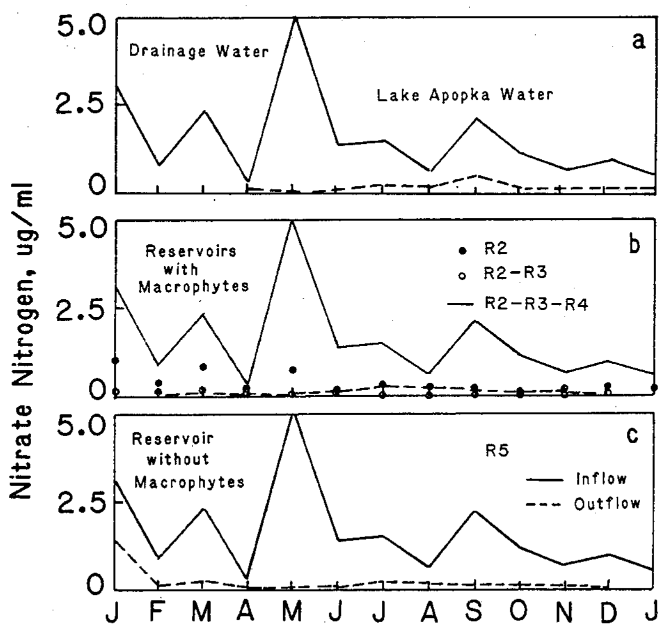

Fig. 2—Nitrate-N concentrations of the lake water (dotted line in *a*) and untreated (solid lines in *a*, *b*, and *c*) and treated (dotted lines in *b* and *c*) drainage waters. Reservoirs R2, R3, R4, and R5 contained water hyacinths, elodea, cattails, and *Chara* spp., respectively.

Nutrient output for each reservoir was calculated as follows:

$$N_o = [C \times OR]/1{,}000, \quad [2]$$

where

N_o = nutrient output from the reservoir, kg/ha per day;

C = monthly average N or P concentration of the water leaving the reservoir, $\mu g/mL$; and

OR = average outflow rate, m^3/ha per day.

Seasonal N and P loading to the treatment systems followed trends similar to seasonal variations in N and P concentrations of the drainage water. Nutrient loading (expressed on a unit-area basis) to R2; R2 and R3; and R2, R3, and R4 were in the ratio of 1:0.50:0.33. For example, NO_3^- loading to R2 reservoir was in the range of 1–14 kg N/ha per day, and loading rates per unit-area were reduced by one-half for R2 and R3 reservoirs in series, and by one-third for R2, R3, and R4 reservoirs in series. Reservoir R5 received the same loading of N and P as the three series of reservoirs (R2, R3, and R4). The difference between input and output values gives the nutrient removal rate per day by the system. It should be noted that the data on nutrient removal rates by the R5 reservoir can only be compared with the series of reservoirs (R2 → R3 → R4), but not separately with each reservoir, because of varying residence times used in the study.

All treatment systems evaluated were found to be effective in the removal of NO_3^- during all times of the year, showing very little or no seasonal variation. Most of the input-drainage-water NO_3^- and NH_4^+ were removed by the R2 reservoir (containing water hyacinths), with very little or no additional removal occurring in the R3 and R4 reservoirs. The major portion of P removal occurred by allowing the water to flow through R2 and R3, with very little additional removal in the third (R4) reservoir. Although water hyacinth (R2) plants were functioning as an effective sink for nutrient removal, it is possible that elodea and cattails would prove equally effective if they were at the head of the system. The reservoir with *Chara* sp. (R5) functioned effectively in the NO_3^- removal but was less effective for NH_4^+, organic N, and total P. None of the treatment systems were loaded to their saturation points to test their maximum nutrient-removal capacity.

Water and Nutrient Budget for Reservoirs

The data on the cumulative volumes of drainage water for the inflow and outflow of reservoirs indicate that about 35–48% of the water was lost from the R2, R3, and R4 reservoirs as a result of lateral seepage and evapotranspiration (ET). Lateral seepage through reservoir berms probably accounted for significant amounts of the water loss.

The mass balance of N indicates about 58% of the input N was recovered in the plants and water in series of R2, R3, and R4 reservoirs and the remaining was lost from the system, while 85% of the input N was recovered in the R5 reservoir containing no aquatic macrophytes (Table 2). Plant uptake of N accounted for about 17–46% of the input inorganic N. Significant amounts of inorganic N released from sediments in R4 were removed by cattails. Data on P budget (Table 3) indicate about 48–60% of the input P was accounted in the plants and the water column, and the remaining was assumed to be lost from the system. The R5 reservoir

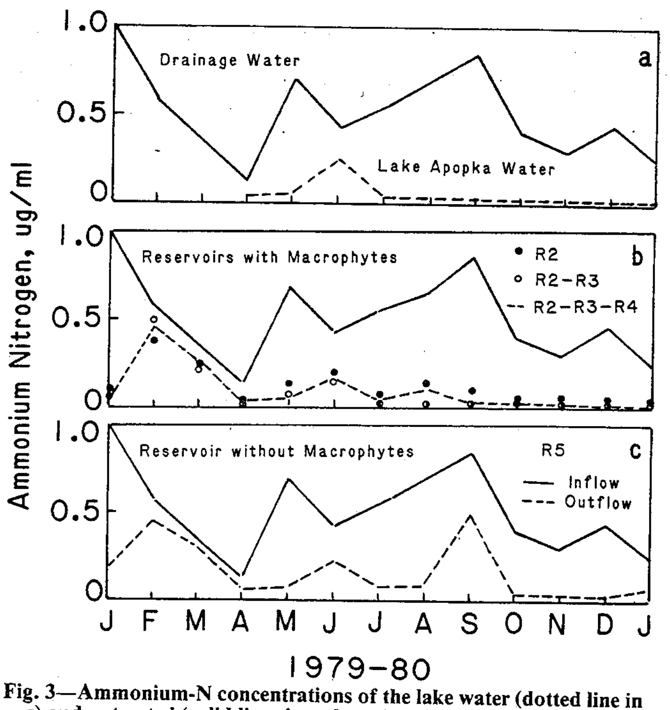

Fig. 3—Ammonium-N concentrations of the lake water (dotted line in *a*) and untreated (solid lines in *a, b,* and *c*) and treated (dotted lines in *b* and *c*) drainage waters. Reservoirs R2, R3, R4, and R5 contained water hyacinths, elodea, cattails, and *Chara* spp., respectively.

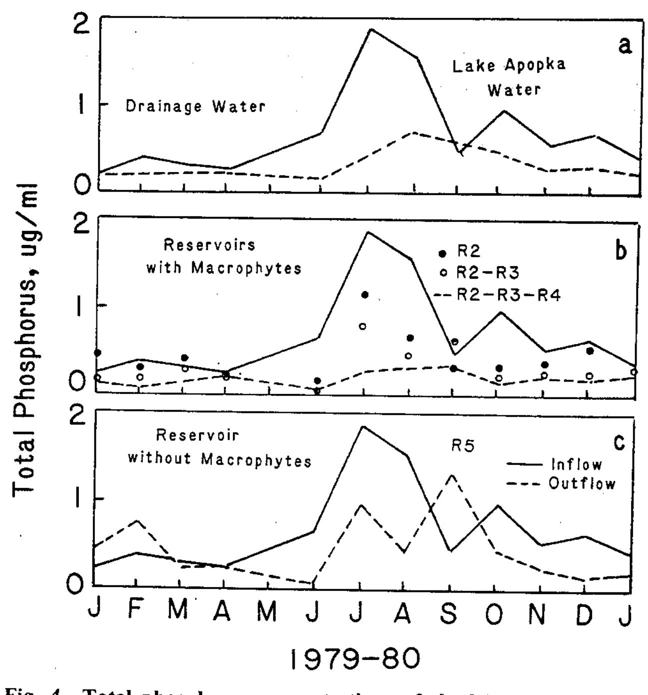

Fig. 4—Total phosphorus concentrations of the lake water (dotted line in *a*) and untreated (solid lines in *a, b,* and *c*) and treated (dotted line in *b* and *c*) drainage waters. Reservoirs R2, R3, R4, and R5 contained water hyacinths, elodea, cattails, and *Chara* spp., respectively.

Table 2—Nitrogen budget for reservoir systems (January 1979–January 1980).

Treatment system	Input (untreated water)				Output					
						Treated water				
	NO_3^--N	NH_4^+-N	Organic N	Total N	Plant uptake	NO_3^--N	NH_4^+-N	Organic N	Total N recovered	N unaccounted for
	kg N/ha									
	Reservoirs in series with macrophytes									
R2	1,219	375	2,167	3,761	731	150	53	955	1,889	1,872
R3	150	53	955	1,158	35	27	21	427	510	648
R4	27	21	427	475	77	19	16	338	450	25
R2 – R3 – R4	407	125	723	1,255	353	19	16	338	726	529
	Reservoir with no macrophytes									
R5	407	125	723	1,255	124	74	57	818	1,073	182

Table 3—Phosphorus budget for reservoir systems (January 1979–January 1980).

Treatment system	Input		Output				
	Untreated water			Treated water			
	Ortho-P	Total P	Plant uptake	Ortho-P	Total P	Total P recovered	P unaccounted for
	kg P/ha						
	Reservoirs in series with macrophytes						
R2	391	551	159	117	172	331	220
R3	117	172	5	29	57	62	110
R4	29	57	5	12	26	31	26
R2 – R3 – R4	130	184	62	12	26	88	96
	Reservoir with no macrophytes						
R5	130	184	13	65	146	159	25

without macrophytes recovered about 86% of the input P in the algal biomass and water.

Nitrogen lost from the reservoirs ranged from 15 to 53% of input N, whereas P losses ranged from 13 to 52% of input P. These losses were probably due to water loss through seepage and to biochemical reactions functioning in the soil-water system. To differentiate seepage N and P losses from other mechanisms, recovery of N and P in the outflow water was calculated by assuming that inflow water equals outflow water, and no water is lost through seepage or ET. Nitrogen and phosphorus not accounted for under these conditions were compared with the N and P losses calculated using measured outflow water data (Table 4). Losses of N and P were considerably reduced and were in the range of 22–33% of input N and 23–42% of input P, respectively. Seepage losses of nutrients in the reservoirs stocked with aquatic plants were about 17–21% of the input nutrient loading.

Both biotic and abiotic processes likely accounted for the removal of N and P from the drainage water during its flow across the reservoirs. Plant uptake, denitrification in the water, and the underlying sediments probably accounted for NO_3^- removal from drainage water (Dunigan et al., 1975; Cornwell et al., 1977; Reddy et al., 1980). Ammonium N was probably removed through assimilation by aquatic plants, and through nitrification and NH_3 volatilization. Dunigan et al. (1975) observed 60% reduction in NH_4^+ concentration of the water containing water hyacinth plants, and 36% reduction in the water containing no plants. In a recent study, Reddy (1983) observed about 40% of the added inorganic ^{15}N was removed by water hyacinths and pennywort (*Hydrocotyle umbellata* L.) plants, 33% of the added ^{15}N was removed by the cattails and elodea plants, and 4% of the added ^{15}N was removed by algae. Added ^{15}N loss in these systems was in the range of 40–53% of added ^{15}N. The physico-chemical environments of the water in the reservoirs with and without aquatic plants and their relationships to nutrient transformations were discussed in detail by Reddy (1981b).

Phosphorus removal from the water was due to plant uptake, assimilation by algae, and adsorption and precipitation reactions. Water hyacinths were found to be less effective in P removal than in inorganic N removal (Ornes and Sutton, 1975; Dunigan et al., 1975). Soluble P removal in the reservoir stocked with elodea plants was probably due to the precipitation of insoluble P compounds, which resulted from alkaline pH condi-

Table 4—Nitrogen and phosphorus losses as estimated using water budget (WB) or assuming no water loss through seepage and evapotranspiration (NL).

Treatment system	Input unaccounted for			
	Nitrogen		Phosphorus	
	WB	NL	WB	NL
	%			
	Reservoirs in series with macrophytes			
R2	49.8	33.1	39.9	23.0
R2 – R3	53.2	29.8	48.9	29.7
R2 – R3 – R4	42.2	22.1	52.2	42.4
	Reservoir with no macrophytes			
R5	14.5	27.8	13.4	27.2

Table 5—Efficiency of treatment systems in reducing N and P levels of agricultural drainage water.

Treatment system	NO_3-N	NH_4-N	Organic N	PO_4-P	Total P
	% reduction or increase				
	Reservoirs in series with macrophytes				
R2	87.7	85.9	55.9	70.1	68.8
R2 – R3	95.6	88.8	60.6	85.1	79.3
R2 – R3 – R4	95.3	87.2	53.3	90.8	85.9
	Reservoir with no macrophytes				
R5	81.8	54.4	−13.1	50.0	20.7

Table 6—Efficiency of treatment systems in reducing N and P levels of agricultural drainage water.†

Treatment system	NO_3-N	NH_4-N	Organic N	PO_4-P	Total P
	% reduction or increase				
	Resevoirs in series with macrophytes				
R2	81.1	78.1	32.0	54.0	32.2
R2 – R3	91.5	77.8	24.0	71.3	43.6
R2 – R3 – R4	92.1	80.0	21.7	84.6	66.2
	Reservoir with no mactophytes				
R5	85.0	62.4	6.2	58.5	6.9

† Values calculated assuming water inflow = water outflow, and no seepage and ET losses.

tions existing in this water. Depletion of CO_2 by elodea plants during photosynthesis increased the pH levels of the water (Reddy, 1981b). The reservoirs containing water hyacinths and elodea were found to be effective in the removal of soluble P from the drainage water.

Efficiency of Treatment Systems

The efficiency of the treatment system was calculated as the reduction or increase in N or P load based on the difference between input and output values (Table 5). Nitrate-removal efficiency of the treatment system ranged from 82 to 95% of the input NO_3^-. Ammonium-N-removal efficiency of the reservoirs with macrophytes ranged from 86 to 89% of the input NH_4^+, while only 54% of the input NH_4^+ was removed by the reservoirs without macrophytes. Ortho-P removal efficiency was about 70% with the R2 reservoir containing water hyacinths, and efficiency was increased to 85% by allowing the water to flow through an additional R3 reservoir with elodea. Removal rate was increased to 91% by allowing the water to flow through the third reservoir, R4, with cattail plants. Total-P-removal efficiency by the reservoirs with plants was slightly lower and was in the range of 69–86%. The reservoir with no macrophytes was found to be less effective in the removal of soluble P (50% removal efficiency) and total P (21% removal efficiency). It should be noted that these nutrient-removal efficiencies included a portion of the nutrient load that is returned to the drainage water system in seepage. The removal efficiency values adjusted for seepage losses are shown in Table 6. Nitrate and NH_4^+ removal efficiencies were in the range of 62–92%, while soluble-P-removal efficiency ranged from 54 to 85%. Organic N and total-P-removal efficiencies were in the ranges of 6–32% and 7–66%, respectively.

Although biological filters offer several advantages in treating waste waters, there are certain limitations. These systems can be used successfully only in the areas where climatic conditions are favorable for growing aquatic plants throughout the year. Aquatic plants must be harvested periodically to maintain nutrient-removal efficiencies. At present, suitable harvesting methods are not available. Large amounts of plant biomass produced in these systems can be put to some beneficial use (e.g., methane production) to improve cost-effectiveness of the treatment system.

ACKNOWLEDGMENTS

This research was supported in part by the funds from the Center for Environmental and Natural Resources Programs, Institute of Food and Agricultural Sciences, University of Florida, Gainesville.

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