1997

Ecological Water Treatment System for Removal of Phosphorus and Nitrogen from Polluted Water

Ray W. Drenner
Texas Christian University

Donald J. Day
Texas Christian University

Stacy J. Basham
Texas Christian University

J. Durward Smith
Texas Christian University

Susan I. Jensen
University of Nebraska - Lincoln

Ecological Applications, 7(2), 1997, pp. 381–390

ECOLOGICAL WATER TREATMENT SYSTEM FOR REMOVAL OF PHOSPHORUS AND NITROGEN FROM POLLUTED WATER

RAY W. DRENNER,[1] DONALD J. DAY,[1] STACY J. BASHAM,[1] J. DURWARD SMITH,[1] AND SUSAN I. JENSEN[2]

[1]*Biology Department, Texas Christian University, Fort Worth, Texas 76129 USA*
[2]*Department of Forestry, Fisheries and Wildlife, University of Nebraska, Lincoln, Nebraska 68583-0814 USA*

Abstract. We propose that phosphorus and nitrogen can be removed from polluted water using an ecological water treatment system consisting of periphyton and fish. In the proposed system, polluted water flows through a series of vessels, and the nutrients are taken up by periphyton growing on porous screens. Algal-grazing fish feed on the periphyton and either assimilate or egest the nutrients in mucus-bound feces that settle from the water into a sediment trap. Both the fish and their feces can be harvested as nutrient sinks. In this study we examined the effects of an algal-grazing cichlid (*Tilapia mossambica*) and a stoneroller minnow (*Campostoma anomalum*) on nutrient removal by the proposed water treatment system. In two experiments using tank-mesocosms, we found that the algal-grazing fish consumed the periphyton and transferred nutrients into the fish's body tissues or the sediments. The mass of phosphorus sequestered in the nutrient sink in the body tissues of the fish was approximately equivalent to the phosphorus sink in the sediments. High removal rates for phosphorus and nitrogen suggest that the proposed ecological water treatment system may be an effective ecotechnology for removal of nutrients from polluted water.

Key words: Campostoma anomalum; *eutrophication; nitrogen; nutrient removal; periphyton; phosphorus; tank-mesocosms;* Tilapia mossambica.

INTRODUCTION

Excessive loading of phosphorus (P) and nitrogen (N) into lake ecosystems from point and nonpoint source pollution can result in deterioration of water quality (Baker 1992, Edmondson 1994). Primary production and biomass of phytoplankton increase with loading of P and N into lake systems (McCauley et al. 1989, Elser et al. 1990). Lakes with excessive concentrations of P and N can experience undesirable algal blooms, reduced water transparency, anaerobic hypolimnions, taste and odor problems, and increased cost for treatment of water for domestic uses.

Efforts to prevent eutrophication have focused primarily on reducing P loading into rivers and lakes from point sources such as sewage effluents (Schindler 1974). To reduce concentrations of P in sewage, some states have limited the concentrations of P in detergents (Hartig et al. 1990). Despite these limits, most conventional wastewater treatment plants used today release high concentrations of P (>1 mg total phosphorus [TP]/L) in their treated effluents because the plants are only required to meet secondary standards. Treatment to secondary standards removes at least 85% of suspended and biodegradable matter but not plant nutrients (Jewell 1994). Conventional tertiary treatment using chemical precipitation is effective at P removal, but this process is costly and generates extra sludge for disposal.

Manuscript received 22 September 1995; revised 14 April 1996; accepted 20 May 1996.

Treatment systems utilizing controlled periphyton production have been suggested as an alternative to conventional nutrient removal methods (Sladeckova et al. 1983, Vymazal 1988, Davis et al. 1990, Adey et al. 1993, Sladeckova 1994). Periphyton has the potential to uptake both P and N from nutrient-enriched water at very high rates (up to 160 mg $P \cdot m^{-2} \cdot d^{-1}$ and 1900 mg $N \cdot m^{-2} \cdot d^{-1}$) (Davis et al. 1990). Because periphyton naturally adjusts its population growth and nutrient uptake rates with changes in nutrient loading (Horner and Welch 1981, Bothwell 1989) and grows in fast-flowing water currents (Horner and Welch 1981), periphyton can potentially be used to remove nutrients from large volumes of rapidly flowing water. However, without mechanical harvesting or grazing, periphyton communities may senesce and slough off, returning nutrients to the water (Jacoby 1987, Mulholland et al. 1991).

From an economic viewpoint, one difficulty in using periphyton-based systems to remove nutrients from polluted water is the separation of periphyton from the purified water (Vymazal 1988). Such separation has been accomplished by mechanically harvesting periphyton using rotating discs (Hemens and Stander 1970), hand tools, and vacuuming (Adey et al. 1993). Although periphyton is consumed by many types of organisms including fish and invertebrates, few studies have addressed whether algal-consuming organisms can be used to enhance nutrient removal using a periphyton-based system. Basham (1994) conducted a mesocosm experiment to test the effects of algal-graz-

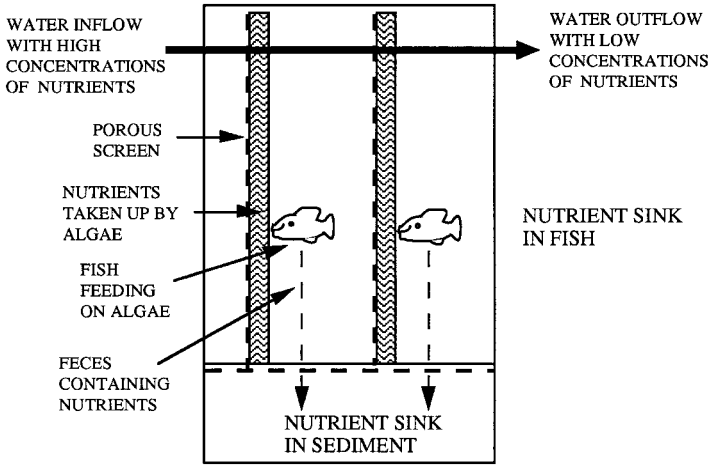

FIG. 1. Ecological water treatment system for removal of phosphorus and nitrogen from nutrient-enriched water.

ing cichlid fish and chironomid insects on periphyton and the removal of P from nutrient-enriched water. The experiment consisted of a factorial design in which three levels of fish (no fish, *Tilapia aurea*, and *T. mossambica*) were cross-classified with two levels of insects (presence and absence). Both fish and insects reduced periphyton and transferred nutrients into the sediments. Fish acted as a sink for P by assimilating it from the periphyton and accumulating P as they grew. In contrast, only a small mass of P was incorporated into the bodies of insects.

Based on the results of Basham's (1994) experiment, we hypothesized that a flow-through system consisting of periphyton and algal-grazing fish could be used to strip nutrients from nutrient-enriched water. The proposed system would involve a process in which nutrients in water are first taken up by periphyton communities growing on screens in flowing water (Fig. 1). The periphyton is then grazed by fish that either assimilate and incorporate nutrients into their tissue or egest the nutrients in their feces. The feces, which consist of mucus-bound algal particles, settle from the water column and collect as sediments. Because both the fish and sedimented fecal matter can be harvested from the system, each provides a sink for nutrients. This paper presents two flow-through mesocosm experiments examining the ability of a periphyton–fish system to remove P and N from nutrient-enriched water.

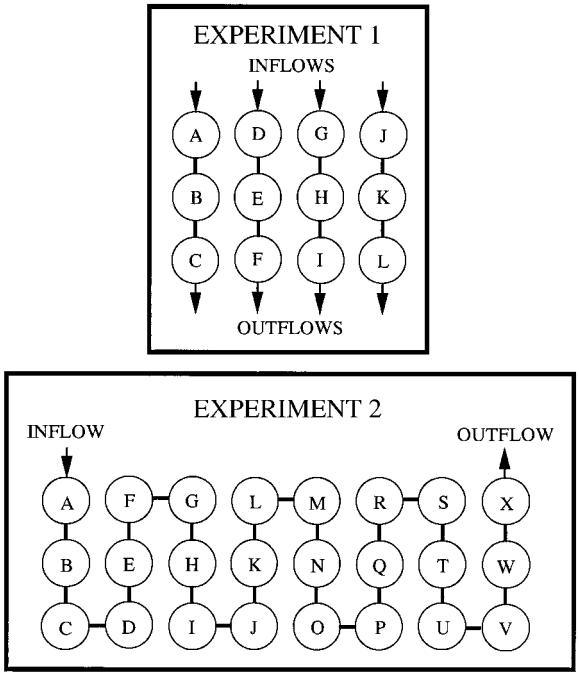

FIG. 2. Layout of the experimental tanks for Experiments 1 and 2.

METHODS

Experiment 1

The objective of the first experiment was to examine the effects of an algal-grazing cichlid, *Tilapia mossambica*, on nutrient removal by the periphyton-based system. *Tilapia mossambica* is an omnivore that consumes plant and animal matter, including periphyton and detritus (Bowen 1982). It has been introduced into the southern U.S. from Africa (Lee et al. 1980). The experiment was conducted in 12 conical-bottom tank mesocosms at the Eagle Mountain Fish Hatchery, Fort Worth, Texas. Tanks were arranged in four lanes of three tanks (Fig. 2), with the tanks in a lane connected by flexible rubber hoses 4 cm in diameter and 45 cm in length. Each tank contained a centrally vented air bubbler and ≈35 000 cm^2 of 0.64-cm mesh plastic screen that functioned as a substrate for periphyton growth (Fig. 3).

Water inflow to each lane was ≈1640 L/d from a 665-L, 3 m high water tower located beside the tanks that received water from Eagle Mountain Lake, a reservoir supplying water to the hatchery. Using a variable flow peristaltic pump, we added liquid agricultural fertilizer (10 (N)–34 (P)–0 (K)) to the water tower to increase the concentrations of P and N to levels typical

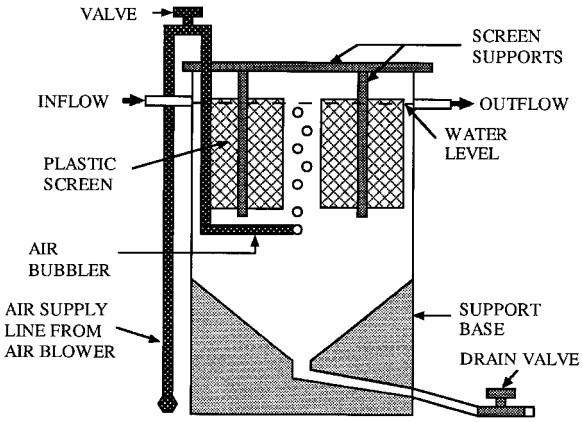

FIG. 3. Conical-bottom tank mesocosm used in Experiments 1 and 2.

of effluents from major wastewater treatment plants in the Dallas–Fort Worth metropolitan area (0.5–7.0 mg P/L, 1.0–7.0 mg N/L) (Qasim and Parker 1990). During the experiment, total phosphorus (TP) and total nitrogen (TN) in the inflow to the tanks averaged 1.35 mg TP/L (range 1.3–1.4 mg/L) and 3.10 mg TN/L (range 2.1–3.8 mg/L), respectively.

The experiment consisted of two treatments: fish and no fish. Each tank in lane 1 (tanks A, B, and C) and lane 3 (tanks G, H, and I) (Fig. 2) were stocked on 24 August 1993, with 3–11 *T. mossambica,* an average of 60.7 g wet mass of fish/tank (Table 1). The experiment was terminated in 3 wk because cold weather threatened the survival of the fish. *Tilapia mossambica* is killed by temperatures below 14°C (Philippart and Ruwet 1982).

Beginning 24 August, 20-mL water samples were collected daily from the inflow and outflow of each lane. Samples were composited weekly and kept frozen in Nalgene bottles. Water column samples for TP and TN were collected from each tank once per week by dipping a pitcher below the water surface, and samples were frozen until analysis. Drain samples for TP and TN analysis were collected once per week from each tank by discharging 5 L into a bucket. The bucket was mixed to suspend particles and a subsample was collected and frozen. Drain samples were thawed and homogenized in an Oster blender prior to analysis. Samples for TP were digested with potassium persulfate (Menzel and Corwin 1965) and analyzed using a modification of the malachite green method (Van Veldhoven and Mannaerts 1987) in which 1 mL of color reagent was added to subsamples of the total digestions and absorbance measured at 610 nm. Samples for TN were digested with alkaline potassium persulfate (D'Elia et al. 1977) and absorbance measured at 220 nm (APHA 1985). The TP and TN content of the sediment was calculated by subtracting the mass of TP and TN in 5 L of the water column from the TP and TN present in the 5-L drain sample on the same date. Areal TP removal rates into the sediments were estimated by dividing the mass of TP removed through sedimentation by the water surface area of the tank (0.6 m^2) and the detention time (7 d). Temperature of the water column was measured weekly with a YSI Model 43TD telethermometer (Yellow Springs Instruments, Yellow Springs, Ohio) and ranged from 27.9° to 35.0°C during the experiment.

TABLE 1. Number and biomass (in grams) of *Tilapia mossambica* stocked and recovered from tank-mesocosms during Experiment 1.

Tank	Stocked numbers	Stocked biomass	Recovered numbers	Recovered biomass	Mass gained
A	6	59.2	6	117.4	58.2
B	3	63.4	3	89.7	26.3
C	7	59.8	7	85.2	25.4
G	8	58.8	8	109.9	51.1
H	3	69.7	3	96.9	27.2
I	11	53.3	11	82.8	29.5

Note: Tanks D, E, F and J, K, L do not appear in the table because no fish were stocked in them.

Experiment 2

The objective of Experiment 2 was to examine the ability of a flowing-water system to remove nutrients from inflowing water and produce an outflow that contained lower concentrations of P and N. Experiment 2 was conducted in 24 conical-bottom tanks at the Eagle Mountain Fish Hatchery. We selected this number of tanks based on the results of Experiment 1 that showed that total nutrient removal rates from 24 tanks would be sufficient to reduce nutrients in a flow-through system under similar nutrient loadings. Arrangement of plastic screens and the air bubbler in each tank was the same as in Experiment 1 (Fig. 3). Tanks were connected by flexible rubber hoses 4 cm in diameter and 45 cm in length to form a flow-through series of 24 tanks (Fig. 2). To facilitate water flow from tank A to tank X, each tank was elevated 2–4 cm higher than the tank immediately downstream. Tank A received ≈2246 L/d of fertilized water from the water tower system used in Experiment 1. As in Experiment 1, we attempted to conduct the second experiment at P and N levels typical of effluents from wastewater treatment plants. At the start of the experiment we used the 10:34:0 liquid fertilizer to supplement the nutrient concentrations in the water. Later in the experiment we also added 32:0:0 liquid fertilizer to increase the N:P ratio in the inflowing water. Effluents from wastewater treatment plants have an N:P ratio of 2.4:1 (Baker 1992). During the experiment, TP and TN in the inflow to the tanks averaged 0.39 mg TP/L (range 0–0.98 mg/L) and 1.09 mg TN/L (range 0.33–1.85 mg/L), respectively, for a N:P ratio of 2.8:1.

At the beginning of the experiment water temperatures were too cool for tilapia to survive, and only stonerollers (*Campostoma anomalum*) were stocked

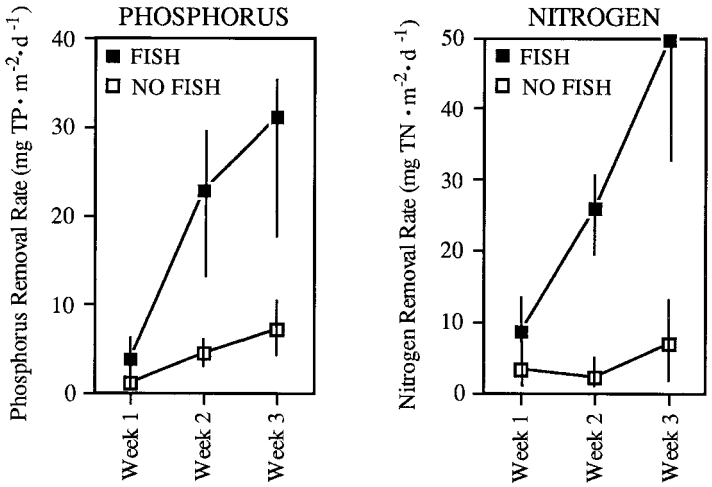

FIG. 4. Phosphorus and nitrogen removed in sediments from drains from fish and no fish treatments during each week of Experiment 1. Bars indicate ranges for the six tanks in the two lanes of tanks for each treatment.

into the tanks. Stonerollers are algal-grazing minnows that are native to streams of the central U.S. (Lee et al. 1980). All tanks were stocked with stonerollers on 23 March 1994 (total of 120 individuals) and again on 6 April (125 individuals), 7 May (156 individuals), 18 May (112 individuals), and 9 June (44 individuals). We stocked a total of 557 stonerollers at a total biomass of 3176 g wet mass. *Tilapia mossambica* were first stocked on 9 June (total of 47 individuals) and again on 22 June (108 individuals) for a total of 155 tilapia at a total biomass of 2833 g wet mass (118 g wet mass/tank).

Sampling began 28 March with daily 20-mL water samples collected from the inflow and outflow, composited each week and kept frozen in Nalgene bottles. The drain and water column of each tank were sampled as in Experiment 1 at 7-d intervals for 18 wk, beginning on 1 April. Concentrations of TP and TN of inflow, outflow, drain, and water column samples were determined as in Experiment 1.

Immediately after the tanks were drained and fish removed from the tanks (29 July), we collected periphyton samples by scraping a vertical strip from the wall of each tank using a 3.9 cm wide razor blade. The periphyton sample was preserved in a solution of 6 parts dissolved water: 3 parts ethanol: 1 part 37% formaldehyde. To analyze the periphyton, sample volumes were standardized to 125 mL and one 1-mL aliquot of each sample was allowed to settle in a settling chamber for 24 h. Algae other than diatoms were then identified and enumerated from 10 fields of view at 400× using a Nikon Diaphot-TMD inverted microscope (Prescott 1962, 1980). Diatoms were counted as a group with the inverted microscope, then later identified to species using a Reichert Microstar IV compound microscope at 1000× from an alcohol dilution series. At least 200 diatom cells were identified, and diatom tank counts were calculated from the percentages of the diatoms identified to species (Patrick and Reimer 1966, 1975, Germain 1981, Hustedt 1985).

RESULTS

Experiment 1

During the 1st wk of Experiment 1, rates of TP and TN removal via sedimentation were low, even in the presence of fish (Fig. 4). Observations of tanks with and without fish during the 1st wk revealed very sparse periphyton growth on the tank walls and screens. Periphyton growth increased in all tanks during weeks 2 and 3, as did the rate of nutrient removal in the sediments in tanks with fish. Visual inspection of the tanks found that periphyton growth was thicker in the tanks without fish. The rate of nutrient removal by sedimentation in tanks with fish increased through the course of the experiment without leveling off, and by week 3, TP and TN in the sediments were being removed at rates of 31.2 mg $TP \cdot m^{-2} \cdot d^{-1}$ and 49.5 mg $TN \cdot m^{-2} \cdot d^{-1}$, respectively. These TP and TN removal rates were 4.3 and 7.3 times higher, respectively, than those obtained in tanks without fish.

At the end of the experiment we recovered all stocked fish at an average biomass of 97.0 g wet mass of fish/tank for an average mass gain of 36.3 g wet mass/tank (Table 1). The mass of TP incorporated into fish tissue was estimated by assuming dry mass of the fish to be 23.9% of wet mass and phosphorus content of the fish to be 2.39% of dry mass (Tan 1971). Areal TP removal rates into the fish tissue were estimated by dividing the mass of TP incorporated into fish tissue by the water surface area of the tank (0.6 m^2) and the detention time (21 d). Estimated P removal rates associated with fish growth as a function of tank surface area was 16.4 mg $TP \cdot m^{-2} \cdot d^{-1}$, which was 53% of the P removal rate by sedimentation in the 3rd wk of the experiment.

Although more nutrients were removed from tanks with fish than without fish, we found minimal difference in the nutrient concentrations of the inflows and outflows, even from the lanes of tanks with fish. During the last week of the experiment, TP in the inflows and

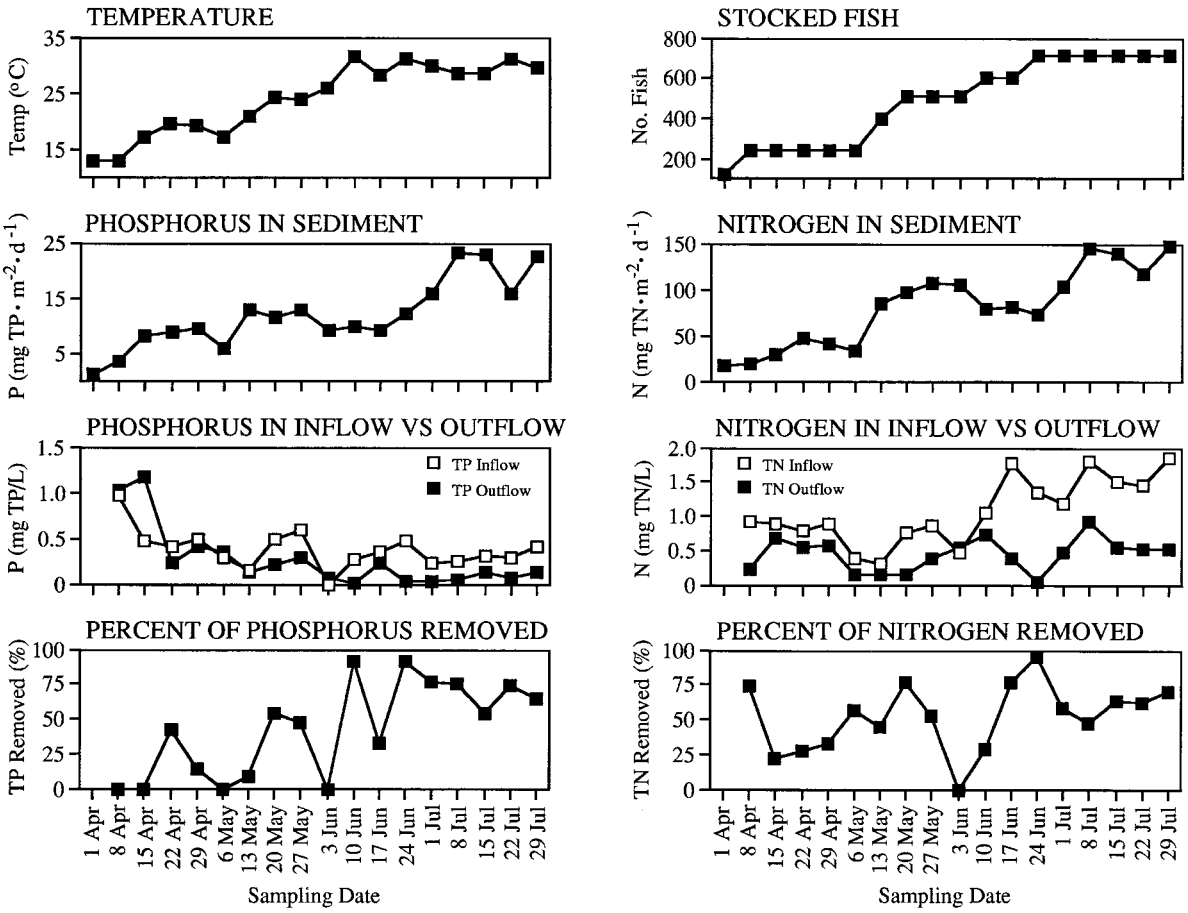

FIG. 5. Changes in temperature, numbers of stocked fish (stonerollers and tilapia), TP and TN removed as sediment from the drains, TP and TN in the inflow and outflow, and percentage of phosphorus and nitrogen removed by the system during Experiment 2.

outflows of the lanes of tanks with fish averaged 1.37 mg TP/L and 1.29 mg TP/L, respectively, while TN in the inflows and outflows of the lanes of tanks with fish averaged 3.53 mg TN/L and 3.86 mg TN/L, respectively. The periphyton–fish system failed to reduce nutrient concentrations of the water as it passed down the lane of tanks, because the removal rates of TP (31.2 mg $TP \cdot m^{-2} \cdot d^{-1}$) and TN (49.5 mg $TN \cdot m^{-2} \cdot d^{-1}$) in the sediments were only 2.5% of the TP loading rates (1250 mg $TP \cdot m^{-2} \cdot d^{-1}$) and 1.6% of the TN loading rates (3125 mg $TN \cdot m^{-2} \cdot d^{-1}$) to the lanes of tanks during the last week of the experiment. It was these results that we used to estimate the number of tanks that were necessary to produce a reduction in the concentrations of P and N in the flowing water system used in Experiment 2.

Experiment 2

In Experiment 2 the removal rates of TP and TN in the sediments collected from the drains increased during the first 14 wk and then leveled off at 21.1 mg $P \cdot m^{-2} \cdot d^{-1}$ and 137.3 mg $N \cdot m^{-2} \cdot d^{-1}$ during the last 4 wk of the study (Fig. 5). The increases in removal of TP and TN in the sediments corresponded with increases in temperature where P removal rates (mg $P \cdot m^{-2} \cdot d^{-1}$) were a log function of temperature ($y = 35.95 \log(x) - 37.06$, $r^2 = 0.54$). However, increased numbers of stonerollers and tilapia stocked during the experiment may also have contributed to increases in nutrient removal rates.

At the start of the experiment, the system removed N more efficiently than P (Fig. 5). During April and May the concentration of TN in the outflow was lower than the inflow TN, while the outflow concentrations of TP were not consistently lower than the inflow concentrations, showing that only small masses of P were being removed from the water as it flowed through the tank system. After 10 June, the system began to consistently remove P from the water, as shown by the reduction in TP concentration in the outflow vs. the inflow. During the last month of the experiment most of the P and N in the inflow was being removed by the system, and the outflow contained concentrations of nutrients <50% of the concentrations of the inflow.

Changes in the nutrient concentrations of the water as it moved through the tanks also indicated that N was

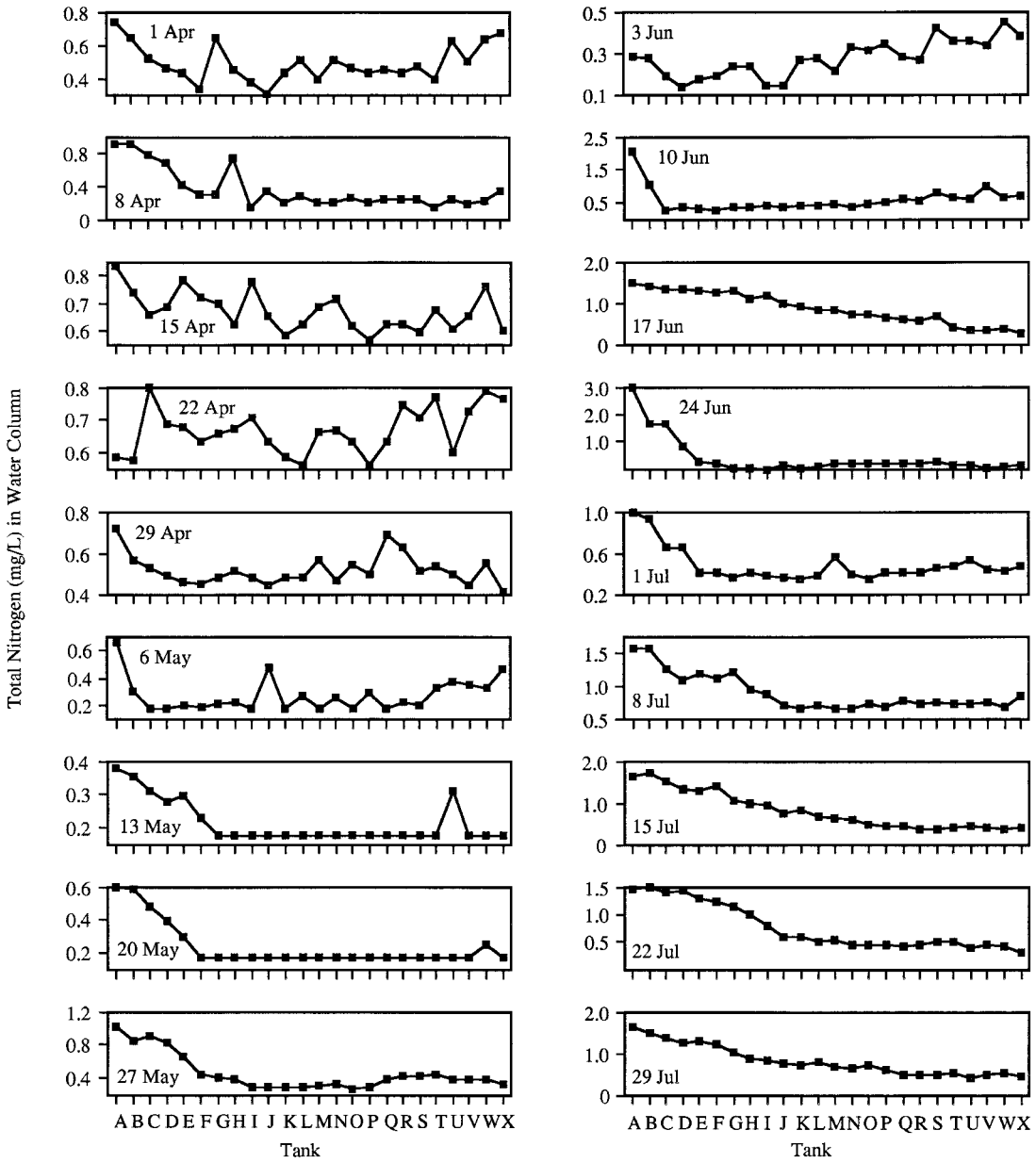

FIG. 6. Concentrations of nitrogen in the water of each tank on each sampling date (in 1994) during Experiment 2.

being removed more efficiently than P at the start of the experiment (Figs. 6 and 7). By the second (8 April), third (15 April), and fifth (29 April) weeks of the experiment, concentrations of TN of the water column decreased from Tank A to Tank X, showing that N was being removed as the water passed through the tanks (Fig. 6). In contrast, we detected little consistent change in TP of the water column as a function of tank position during April, with water in Tank X having concentrations of TP as great or greater than water in Tank A. Beginning on 6 May, TP of the water column decreased from Tank A to Tank X (Fig. 7), indicating removal of P as the water passed down the system. An exception occurred on 3 June when TP and TN of the water column increased from Tank A to Tank X. During the days before the 3 June samples were collected, the fertilizer pump had broken and the nutrient content of water being added to tanks from the water tower had decreased.

Total numbers and mass of stonerollers and *T. mossambica* stocked and recovered from each tank are shown in Table 2. While *T. mossambica* survived and grew rapidly during the experiment, considerable stoneroller mortality resulted because they became trapped in the drains of the tanks, and jumped out of the tanks. At the end of the experiment (29 July) we recovered 146 stonerollers at a biomass of 451 g wet mass and 151 tilapia at a biomass of 6277 g wet mass

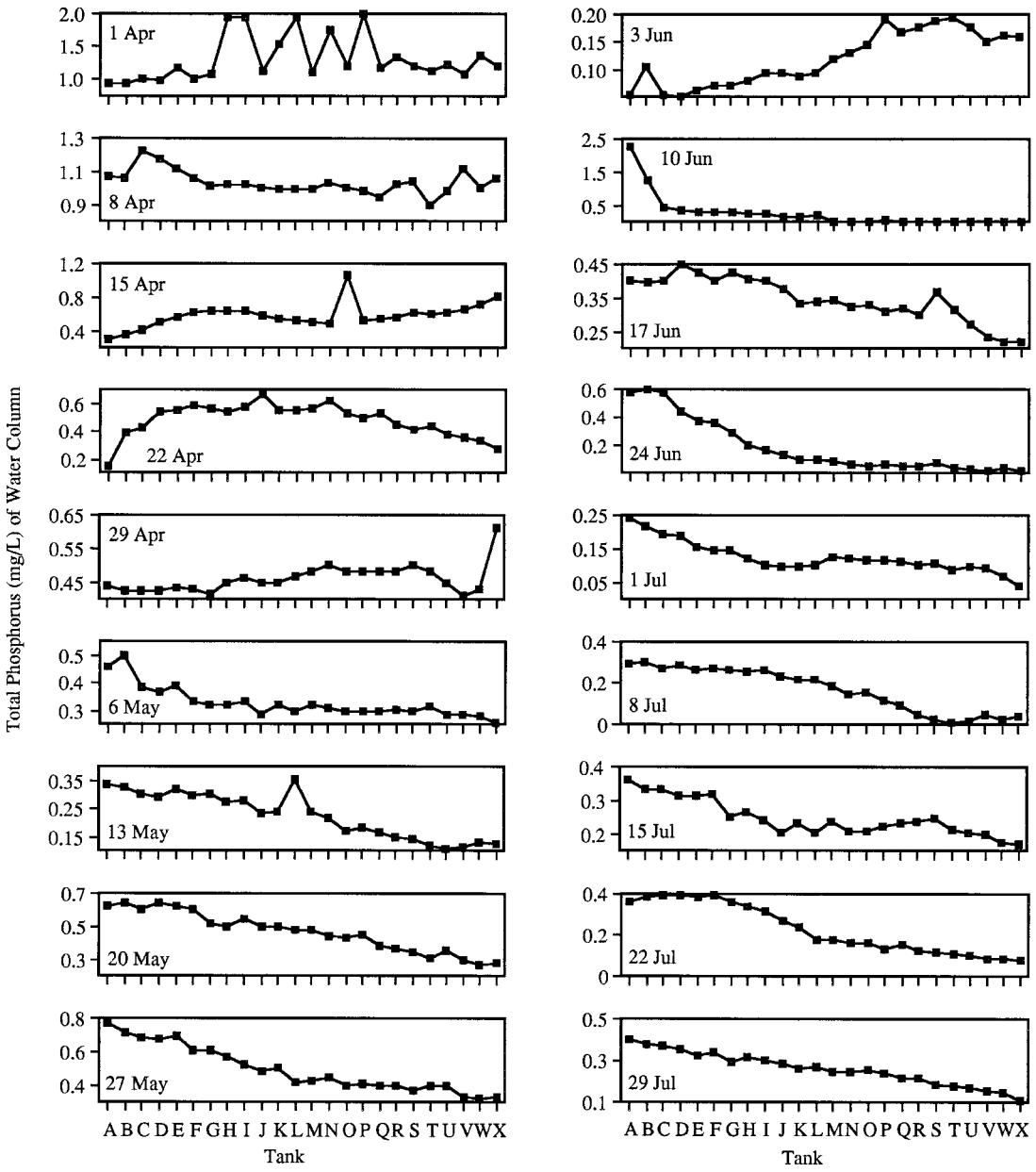

FIG. 7. Concentrations of phosphorus in the water of each tank on each sampling date (in 1994) during Experiment 2.

(not including hundreds of tilapia fry that had been spawned during the experiment). We estimated P removal rates by incorporation into tilapia tissues using the approach in Experiment 1. Estimated P removal rates associated with fish growth as a function of tank surface area was 27.3 mg $TP \cdot m^{-2} \cdot d^{-1}$, which was slightly greater than the P removal rates by sedimentation (21.1 mg $TP \cdot m^{-2} \cdot d^{-1}$) during the last 4 wk of the experiment.

At the end of the experiment, the biovolume and species composition of the periphyton varied with tank position (Fig. 8). Biovolume of periphyton was greater in the tanks in the front of the treatment system. Most of the biovolume of periphyton in all tanks consisted of filamentous green algae (principally *Cladophora glomerata* (L.) Kuetzing). The percentage of biovolume of periphyton accounted for by filamentous green algae and associated diatoms (principally *Cyclotella meneghiniana* Kutz, *Gomphonema subtile* Ehr., and *Nitzschia amphibia* Grun.) decreased in the tanks at the back of the treatment system. The biovolume of colonial green algae (principally *Scenedesmus bijuga* (Turp.) Lagerheim and *Pediastrum boryanum* var. *longicorne* Raciborski), desmids (principally *Cosmarium* sp.) and bluegreen algae (principally *Calothrix* sp. and *Lyngbya aerugineo-caerulea* (Kutz.)) increased in the

TABLE 2. Number and biomass (in grams) of stonerollers and *T. mossambica* stocked and recovered from tank-mesocosms during Experiment 2. Treatment codes are: SR (stonerollers) and TM (*T. mossambica*).

	Stocked numbers		Stocked biomass		Recovered numbers		Recovered biomass		Mass gained†	
Tank	SR	TM	SR	TM	SR	TM	SR	TM	SR	TM
A	31	7	193.6	99.3	6	6	12.5	274.9	−181.1	175.6
B	34	9	212.6	124.7	6	9	20.3	347.1	−192.3	222.4
C	24	5	151.6	102.6	3	4	6.5	280.9	−145.1	178.3
D	30	5	171.1	102.2	1	5	1.0	281.0	−170.1	178.8
E	32	12	104.7	156.6	16	12	40.1	241.6	−64.6	85.0
F	44	4	126.0	98.9	0	4	0.0	285.5	−126.0	186.6
G	20	5	88.5	100.9	12	8	40.1	287.8	−48.4	186.9
H	14	8	151.8	146.1	7	5	22.4	267.3	−129.4	121.2
I	19	5	136.2	97.8	6	4	13.0	279.0	−123.2	181.2
J	26	5	145.6	101.3	0	10	0.0	268.8	−145.6	167.5
K	21	10	103.4	132.3	5	4	18.1	161.0	−85.3	28.7
L	21	4	138.8	95.7	8	4	20.8	269.9	−118.0	174.2
M	26	4	174.0	105.3	10	7	38.4	280.3	−135.6	175.0
N	22	8	149.0	143.7	9	4	31.9	271.4	−117.1	127.7
O	23	4	146.2	100.1	5	5	12.1	191.5	−134.1	91.4
P	17	5	68.6	103.0	6	11	15.1	224.4	−53.5	121.4
Q	14	12	94.6	168.5	0	5	0.0	403.5	−94.6	235.0
R	11	6	79.8	101.2	4	5	21.2	186.6	−58.6	85.4
S	18	5	79.4	99.6	8	7	17.5	275.1	−61.9	175.5
T	17	8	69.9	157.9	4	5	12.5	272.8	−57.4	114.9
U	22	5	139.7	100.9	9	5	27.1	186.8	−112.6	85.9
V	24	5	123.4	96.9	7	5	23.0	168.9	−100.4	72.0
W	17	10	130.7	198.4	4	10	26.7	372.4	−104.0	174.0
X	30	4	196.4	98.6	10	7	30.3	198.4	−166.1	99.8

† Mass gained = stocked biomass − recovered biomass. All stoneroller biomasses were negative, because less stoneroller biomass was recovered than was stocked. All tilapia biomasses were positive.

tanks at the back of the treatment system but never accounted for >20% of total biovolume.

DISCUSSION

Only a few studies have examined nutrient removal using periphtyon-based systems. Vymazal (1988) found that a trough system containing screens with periphyton removed both P and N. Adey et al. (1993) examined nutrient removal from agricultural runoff by natural algal populations in raceways. Using hand and vacuum harvesting of the periphyton, they achieved P removal rates ranging from 104 to 139 mg $TP \cdot m^{-2} \cdot d^{-1}$.

Nutrient removal rates were lower in our study compared to removal rates found by Adey et al. (1993). In Experiment 1 the presence of the fish resulted in an increase in movement of P and N from the water to the sediment sink, and significant masses of P were also incorporated into their tissue as the fish grew. In this experiment we found a P removal rate of 47.6 mg $TP \cdot m^{-2} \cdot d^{-1}$ when the sediments and fish growth sinks were combined during the last week of the experiment, but the length of the experiment was not adequate to achieve maximal removal rates. In Experiment 2 we found nutrient removal rates during the last 4 wk of 21.1 mg $TP \cdot m^{-2} \cdot d^{-1}$ in the form of sediment removal, with an equivalent mass of P (27.3 mg $TP \cdot m^{-2} \cdot d^{-1}$) incorporated into fish tissue, for a combined total removal rate of 48.4 mg $TP \cdot m^{-2} \cdot d^{-1}$. Three factors may account for the lower P removal rates in our experiment: (1) We used fish to harvest the periphyton while Adey et al. (1993) vacuumed the periphyton. Fish excrete P into the water, potentially resulting in a lower net nutrient removal rate. (2) Our experiment involved inflows with very low N:P ratios, perhaps causing the system to be N limited and not P limited. (3) Finally, the tanks used for these experiments were selected because of availability and low cost and were not optimally designed for periphyton production and nutrient uptake. Feces remained on the bottom in contact with the water column for days before being removed from the tanks during weekly sampling of the drains. At summer temperatures, the feces may have partially broken down by bacterial action and released some of the nutrients back to the water column.

In the future we may be able to increase the nutrient removal efficiency of the periphyton–fish system through continual removal of feces using a modified-clarifier system. Even if we achieve optimal nutrient removal rates reported for periphyton (>100 mg $TP \cdot m^{-2} \cdot d^{-1}$ Adey et al. 1993), a periphyton–fish system would require extensive surface areas to treat large volumes of nutrient-enriched water. For example, to remove 1 mg of P/L from an effluent volume of 3.785 $\times 10^3$ 1 m^3/d would require a surface area of 37 853 m^2, assuming a nutrient removal efficiency of 100 mg $TP \cdot m^{-2} \cdot d^{-1}$.

Pressure to meet stringent water quality standards has created a worldwide need for alternative, low-cost, low-maintenance, and effective wastewater treatment (Stott and Wright 1991). Ideally, such systems should

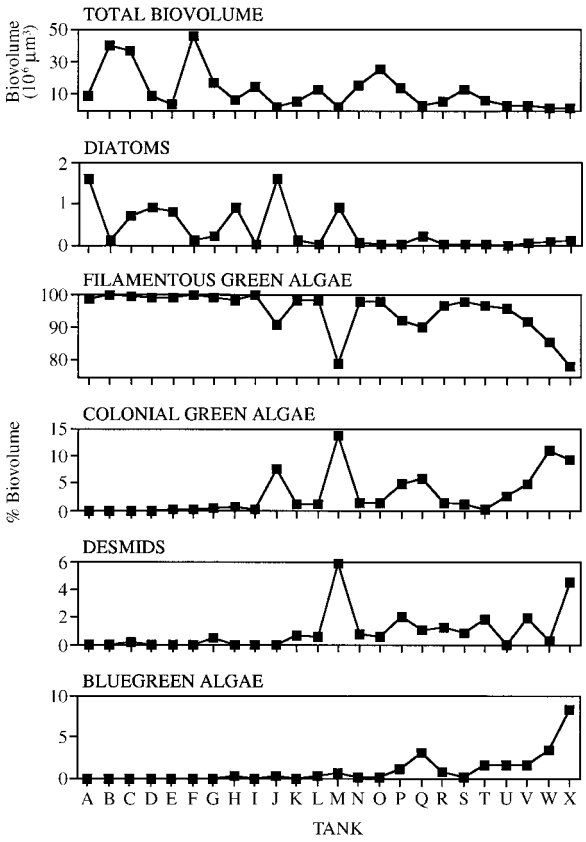

FIG. 8. Biovolume of periphyton as a function of tank position.

harvest the nutrients in a usable form so that they can be recycled. Nutrients in fertilizers are crucial for maintaining agricultural production and should be treated as a resource and not a liability. One advantage of the fish–periphyton system is that it offers the possibility of recycling nutrients. In addition, nutrients and fish harvested from the system may be commercially valuable and could be marketed to help offset costs associated with operation of the periphyton–fish system. For example, species of cichlids such as *T. aurea* can be used as food for humans, but the water being treated must be relatively toxicant-free, because the toxicants might concentrate in the fish. *Tilapia mossambica* can be sold commercially in Texas to stock private ponds as forage for largemouth bass, but care should be taken to avoid introduction of tilapia into environments where they could be detrimental to native fishes.

A periphyton–fish system may have potential for monitoring and removal of toxicants from water, especially those contaminants such as heavy metals and PCBs that biomagnify in aquatic food chains. For a wide variety of toxicants that are now found at very low concentrations in rivers, there are no practical ways to detect their presence or efficiently remove them from river water. Although we have not had the opportunity to test toxicant uptake by the treatment system, Stewart et al. (1993) pointed out that movement of contaminants in streams should be analogous to movement of inorganic ions such as phosphorus. Periphyton represents a ''sticky'' surface for many toxicants, especially those with low solubility in water. Toxicants are taken up actively or adsorbed onto the periphyton and are thus available to algal consumers such as fish. In the periphyton–fish system, part of the toxicants would pass through the fish along with undigested algal material and be transferred to the sediment sink for later disposal. Toxicants that are assimilated by fish will concentrate in the fish's tissue, allowing monitoring of toxicants that normally occur in the environment at undetectable concentrations. The presence of toxicants in the fish would alert water managers about toxicants that might biomagnify in the food chain and be dangerous to fish-consuming wildlife and humans. If the periphyton–fish system can remove both nutrients and toxicants from polluted water, it may be a valuable tool in our efforts to protect and restore our freshwater resources.

ACKNOWLEDGMENTS

We thank Robert Baca, Barbie Click, Vickie Day, Michael Edwards, Kirsten Gallo, Tyson Hale, Gary Keil, Brenda Miller, Regina Steinkamp, Kristina Stewart, and Jim Williams for assistance and Mark Ernst, Woody Frossard, and John Mancini for helpful suggestions. This research was supported by the Tarrant County Water Control and Improvement District Number One and a Research Fund Grant and an Adkins Fellowship from Texas Christian University. The periphyton–fish system is covered by U.S. Patent Number 5254252.

LITERATURE CITED

Adey, W., C. Luckett, and K. Jensen. 1993. Phosphorus removal from natural waters using controlled algal production. Restoration Ecology **1**(March):28–39.

APHA (American Public Health Association). 1985. Standard methods for the examination of water and wastewater. Sixteenth edition. American Public Health Association, Washington, DC, USA.

Baker, L. A. 1992. Introduction to nonpoint source pollution in the United States and prospects for wetland use. Ecological Engineering **1**:1–26.

Basham, S. J. 1994. A periphyton–fish system for removal of phosphorus and nitrogen from wastewater: effects of grazing insects and tilapia. Thesis. Texas Christian University, Fort Worth, Texas, USA.

Bothwell, M. L. 1989. Phosphorus-limited growth dynamics of lotic periphytic diatom communities: areal biomass and cellular growth rate responses. Canadian Journal of Fisheries and Aquatic Sciences **46**:1293–1301.

Bowen, S. H. 1982. Feeding, digestion and growth—qualitative considerations. Pages 141–156 *in* R. S. V. Pulin and R. H. Lowe-McConnell, editors. The biology and culture of tilapias. ICLARM Conference Proceedings 7. International Center for Living Aquatic Resource Management, Manila, The Philippines.

Davis, L. S., J. P. Hoffmann, and P. W. Cook. 1990. Production and nutrient accumulation by periphyton in a wastewater treatment facility. Journal of Phycology **26**: 617–623.

D'Elia, C. F., P. A. Streudler, and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnology and Oceanography **22**:760–764.

Edmondson, W. T. 1994. Sixty years of Lake Washington: a curriculum vitae. Lake and Reservoir Management **10**:75–84.

Elser, J. J., E. R. Marzolf, and C. R. Goldman. 1990. Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: a review and critique of experimental enrichments. Canadian Journal of Fisheries and Aquatic Sciences **47**:1468–1477.

Germain, H. 1981. Flore des diatomees. Societe Novelle des Editions Boubee, Paris, France.

Hartig, J. H., C. Trautrim, D. M. Dolan, and D. E. Rathke. 1990. The rationale for Ohio's detergent phosphorus ban. Water Resources Bulletin **26**:201–207.

Hemens, J., and G. J. Stander. 1970. Nutrient removal from sewage effluents by algal activity. Pages 701–715 *in* Advances in Water Pollution Research. Proc. of the Fourth International Conference, Prague. Pergamon, Oxford, UK.

Horner, R. R., and E. B. Welch. 1981. Stream periphyton development in relation to current velocity and nutrients. Canadian Journal of Fisheries and Aquatic Sciences **38**: 449–457.

Hustedt, F. 1985. The pennate diatoms: a translation of Hustedt's ''Die Kieselalgen, Teil 2'', with supplement by N. G. Jensen. Koeltz Scientific, Koenigstein, Germany.

Jacoby, J. M. 1987. Alterations to periphyton characteristics due to grazing in a Cascade foothill stream. Freshwater Biology **18**:495–508.

Jewell, W. J. 1994. Resource-recovery wastewater treatment. American Scientist **82**:366–375.

Lee, D. S., C. R. Gilbert, C. H. Hocutt, R. E. Jenkins, D. E. McAllister, and J. R. Stauffer, Jr. 1980. Atlas of North American freshwater fishes. Museum of Natural History, North Carolina State University, Raleigh, North Carolina, USA.

McCauley, E., J. A. Downing and S. Watson. 1989. Sigmoid relationships between nutrients and chlorophyll among lakes. Canadian Journal of Fisheries and Aquatic Sciences **46**:1171–1175.

Menzel, D. W., and N. Corwin. 1965. The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate oxidation. Limnology and Oceanography **10**:280–282.

Mulholland, P. J., A. D. Steinman, A. V. Palumbo, J. W. Elwood, and D. B. Kirschtel. 1991. Role of nutrient cycling and herbivory in regulating periphyton communities in laboratory streams. Ecology **72**:966–982.

Patrick, R., and C. W. Reimer. 1966. Diatoms of the United States. Volume 1. Academy of Natural Sciences, Philadelphia, Pennsylvania, USA.

Patrick, R., and C. W. Reimer. 1975. Diatoms of the United States. Volume 2. Academy of Natural Sciences, Philadelphia, Pennsylvania, USA.

Philippart, J-Cl., and J-Cl. Ruwet. 1982. Ecology and distribution of tilapias. Pages 15–59 *in* R. S. V. Pullin and R. H. Lowe-McConnell, editors. The biology and culture of tilapias. ICLARM Conference Proceedings 7. International center for Living Aquatic Resource Management, Manila, The Philippines.

Prescott, G. W. 1962. Algae of the western Great Lakes area. William C. Brown, Dubuque, Iowa, USA.

———. 1980. How to know the freshwater algae. William C. Brown, Dubuque, Iowa, USA.

Qasim, S. R., and C. E. Parker. 1990. Control of nutrients from municipal wastewater treatment plants in the Upper Trinity River Basin. Pages 247–257 *in* R. Jensen, editor. How healthy is the Upper Trinity River? Biological and water quality perspectives. Texas Water Resources Institute, Texas A&M University, Texas Agriculture Experiment Station, College Station, Texas, USA.

Schindler, D. W. 1974. Eutrophication and recovery in experimental lakes: implications for lake management. Science **184**:897–899.

Sladeckova, A. 1994. The role of periphyton in waste treatment technology. Internationale Vereinigung für theoretische und angewandte Limnologie, Verhandlungen **25**:1929–1932.

———., P. Marvan, and J. Vymazal. 1983. The utilization of periphyton in waterworks pre-treatment for nutrient removal from enriched influents. Pages 299–303 *in* R. G. Wetzel, editor. Periphyton of freshwater ecosystems, Dr. W. Junk, The Hague, The Netherlands.

Stewart, A.J., W. R. Hill, and H. L. Boston. 1993. Grazers, periphyton and toxicant movement in streams. Environmental Toxicology and Chemistry **12**:955–957.

Stott, R. F., and S. J. L. Wright. 1991. Sewage treatment with plants. Letters in Applied Microbiology **12**:99–105.

Tan, W. T. 1971. Proximate composition of freshwater fish—grass carp, *Puntius gonionotus*, and tilapia. Hydrobiologia **37**:361–366.

Van Veldhoven, P. P., and G. P. Mannaerts. 1987. Inorganic and organic phosphate measurements in the nanomolar range. Analytical Biochemistry **161**:45–48.

Vymazal, J. 1988. The use of periphyton communities for nutrient removal from polluted streams. Hydrobiologia **166**:225–237.