A Bench Scale Rock-Plant Filter Investigation

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ABSTRACT

Three bench-scale rock filters containing 2 feet of gravel were used in this investigation. Two of the filters were planted with Sagittaria lancifolia and Scirpus validus, while the third filter was an unvegetated control filter. In a preliminary portion of this study, average BOD_5 mass removal rates were 75%, 60%, and 44% for the Scirpus, Sagittaria, and control systems, respectively, after over a month at a BOD_5 surface loading rate of 4.96 g/day/m^2 Following this constant loading rate, an 80-day experiment was run on the filters using eight combinations of two flow rates and four influent BOD_5 concentration with each combination remaining constant for ten days. These combinations resulted in BOD_5 surface loadings rates from 4.63 to 30.96 g/day/m^2. Overall average BOD_5 removal percentages during this latter portion of the study were 69%, 57%, and 47% for the Scirpus, Sagittaria, and control systems, respectively. ORP and DO measurements within these systems indicated no free oxygen available at any depth; however, nitrification may have occurred in the thin aerobic zone surrounding the plant root. TKN removal was higher in the plant systems relative to the control, with the Scirpus system achieving a higher overall removal than the Sagittaria system.

KEY WORDS: Rock filter, aquatic plants, wastewater treatment

INTRODUCTION

In the last few decades, population growth and increasingly stringent environmental regulations have required revisions of current wastewater treatment methods, as well as the development of new treatment methods. One attractive wastewater treatment alternative, particularly for residential and rural areas, is aquatic plants grown in a rock filter, or a rock-plant filter. Due to low operation and maintenance costs, rock-plant filter systems are increasing in popularity, especially in the southeastern United States; yet, no proven design criteria have been established. Although aquatic plants in wastewater treatment have been studied in Europe and the United States over the past 20 years, much of this research has centered on floating plants, such as water hyacinths and duckweed. These plants are advantageous in upgrading treatment ponds; however, clogging of waterways, die-off in cool climates, and the production of anaerobic conditions have posed problems in many installations. By contrast, rock-plant filters employ emergent aquatic plants which are more resistant to cool climates and do not affect waterways. To more firmly establish optimal designs for rock-plant filters, data from this bench-scale study will be used, along with data from a full-size filter, to develope a mathematical model for predicting effluent five-day biochemical oxygen demand (BOD_5) concentrations given the influent concentration and filter specifications.

RELATED RESEARCH

Since the 1970's, research on rock-plant filters has been conducted using various types of aquatic plants, retention times, and wastewater sources. Organic and nutrient removal rates observed have been varied and sometimes inconsistent, however, as discussed below.

In one of the earlier studies, Spangler, et al. (1976) planted bulrush (Scirpus validus) in flow-through trenches which were PVC lined and gravel filled to study the effect of retention time, nature of wastewater applied (primary or secondary treatment effluent), and frequency of harvesting on effluent quality. The retention times they used (5 hours, 16 hours, and 10 days) yielded equivalent BOD_5 reductions for both control and bulrush basins. It was noted, however, that flow regulation was poor in the control basin and higher loadings were actually applied to the bulrush basins as compared to the control. For primary effluent, BOD_5 reduction was nearly 10% greater when compared to secondary effluent. Furthermore, harvesting resulted in no observed changes in effluent quality.

Contrary to Spangler, et al.'s observations, a study by Wolverton (1982) indicated a significant difference in BOD_5 removal between an unvegetated filter and a filter containing reed (Phragmites communis). BOD_5 removal rates for the control filter were 62% and 83% after 6 and 24 hours retention time, respectively; the rock-reed filters achieved 87% and 96% BOD_5 removal for the same retention times. TSS removal after 24 hours retention was 44% for the control filter and 83% for the rock-reed filter. In addition, nutrient removals were an order of magnitude higher in Wolverton's rock-reed filter relative to his control.

Relatively equal levels of BOD_5 removals in vegetated and unvegetated filters were, however, observed by Wolverton, et al. (1983) in a later study. This batch experiment began by first settling raw sewage anaerobically for 24 hours, then delivering the effluent to various rock filters each containing a different aquatic emergent plant plus an unvegetated control. Plants used include reeds (Phragmites communis), cattails (Typha latifolia), rush (Juncus effusus), and bamboo (Bambusa multiplex). The filter influent BOD_5 was adjusted to approximately 60 mg/l and 300 mg/l on separate occasions by adding different amounts of water hyacinth juice to the raw sewage. The results of this study indicated retention times of 6 and 29 hours were required to achieve the 30 mg/l BOD_5 secondary treatment standard for the 60 mg/l and 300 mg/l influent BOD_5 loading, respectively. Although the BOD_5 removal in the vegetated filters was comparable to the control, the system containing reeds performed slightly better than the other systems.

The fate of nitrogen in secondary treatment effluent subjected to bulrush, cattail, and reed filter systems was studied by Gersburg, et al. (1983, 1984). They found denitrification to be responsible for the majority of the nitrogen losses within the aquatic filters. Enhancement of the denitrification process was effected by adding a carbon source to elevate the carbon: nitrate ratio to 1.7, the ratio found to be optimal for denitrification. Without a carbon supplement, nitrogen removal was only about 25% in vegetated and unvegetated beds; however, with the addition of methanol, nitrogen removal increased to approximately 95% in the vegetated beds. Retention time within the beds was about 3 days for this study.

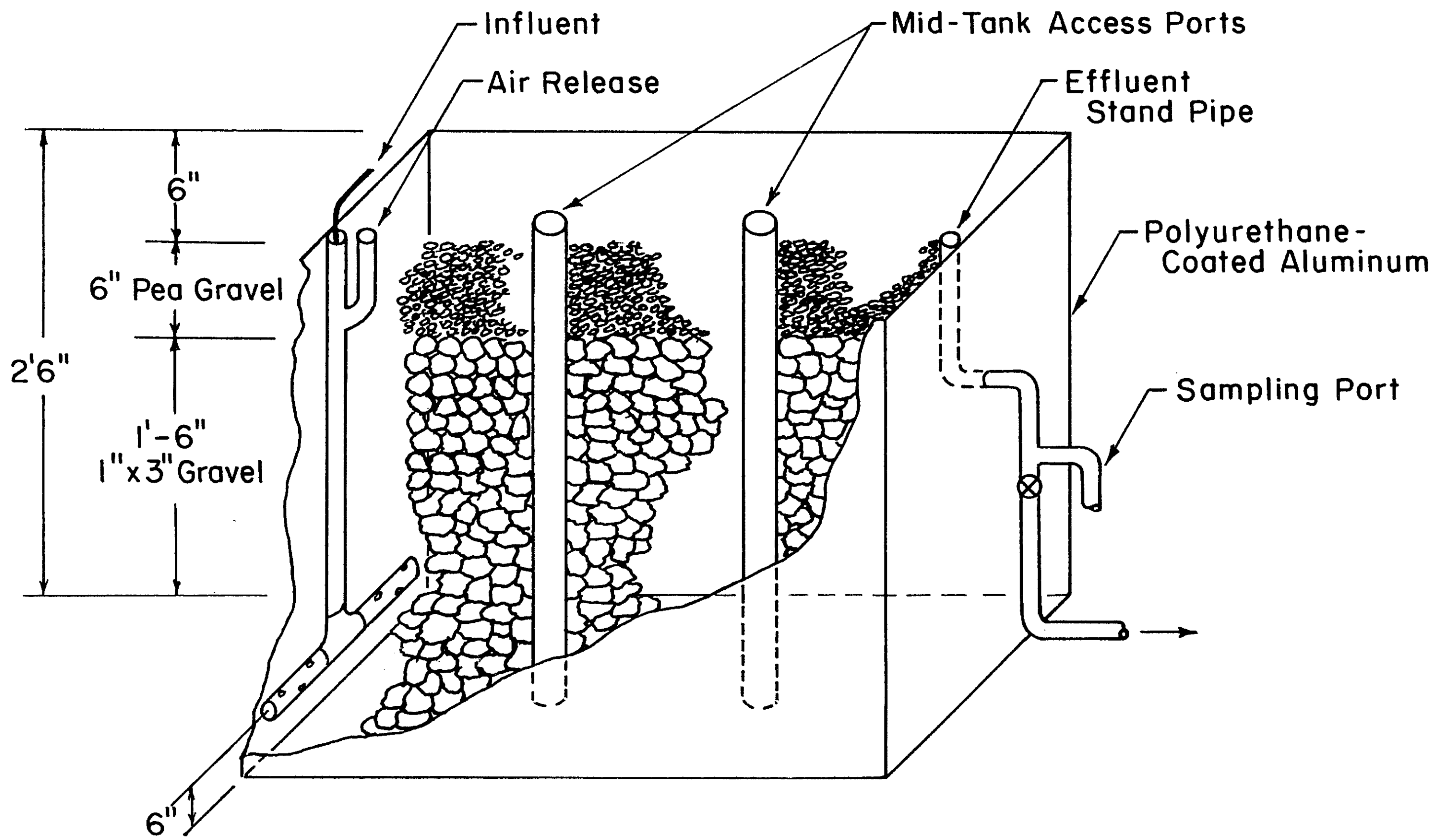
In a later study, Gersberg, et al. (1986) treated primary wastewater in four 2.5 feet deep gravel ditches containing bulrush (Scirpus validus), reed (Phragmites communis), and cattail (Typha latifolia), plus an unvegetated control. Parameters monitored during this study included ammonia, BOD_5, and TSS. Ammonia removals were found to be 94%, 78%, and 28% for bulrush, reed, and cattail, respectively. BOD_5 removals for bulrush, reed, cattail, and the control were 96%, 81%, 74%, and 69%, respectively. Essentially equal TSS removal was observed in all ditches and was, therefore, assumed to be an exclusively physical process. In addition, depth of root zones were recorded for each species. Cattail was found to have the shallowest root zone of approximately 12". The bulrush root zone extended to a depth of over 24"; while the root zone of reed averaged around 30".

METHODS AND PROCEDURES

Three 5 foot long by 1.5 feet wide, rectangular, welded-aluminum tanks housed the filter systems. Each tank had an interior urethane coating and was constructed as shown in Figure 1. The influent flow entered near the bottom of one end of each tank through a perforated PVC pipe spanning the width of the tank while the effluent spilled into a standpipe at the opposite end of the tank. Oxidation/ reduction potential (ORP) probes were placed near the mid-tank access ports at mid-depth. These tanks were installed in a greenhouse which supplied an equal amount of sunlight to all tanks. The water temperature of all three tanks remained within 1°C of each other and varied from 21°C to 31°C during this study.

On November 19, 1988, one tank was planted with ten Sagittaria lancifolia (duck potato) seedlings and another tank with ten Scirpus validus (bulrush) seedlings. These plants grew for 5 months prior to beginning analyses. During this 5 months, a solution containing Hydrosol (a hydroponic fertilizer by Peters), CaNO3, and dextrose was recirculated through each tank at a flow of 500 to 1000 ml/min. This solution was replenished twice per week with daily dextrose

FIGURE 1. ROCK-AQUATIC PLANT FILTER SYSTEMS
INNER TANK DETAILS
(Not to Scale)



additions. On January 25 and then again on March 8, 1989, the tanks were seeded with activated sludge mixed liquor.

After the 5 month start-up period, the flow through the tanks was changed to once-through flow using a synthetic wastewater containing constituents listed in Table 1. Although using a synthetic wastewater creates a somewhat unrealistic situation, it allows the effluent to vary while the influent is controlled. The wastewater recipe shown in Table 1 is a result of several trial mixtures. Initial mixtures contained glucose and ammonium sulfate as carbon and nitrogen sources, respectively. This was changed when most of the BOD_5 was consumed in the reservoir before entering the filters. Nutrient broth corrected this situation satisfactorily; however, the nitrogen source in nutrient broth is solely organic, which is found in primary wastewater but not usually in secondary wastewater where ammonia is the typical nitrogen form. To feed each filter with synthetic wastewater, separate chemical feed pumps (Cole Parmer Model N-07141-28) distributed wastewater from a common reservoir to each filter. This wastewater was mixed fresh daily and aerated for 30 minutes to saturate with dissolved oxygen.

Initially, the goal was to arrive at a steady percentage of organic removal before stepping to a different hydraulic/ organic loading scheme. No steady removal rate was found, however, after over a month at a flow of 80 ml/min and an organic loading of
4.96 g BOD_5/day/m^2 surface area (30 mg/l BOD_5 influent).

Although BOD_5 mass removal was the major focus of this study, many of the organic removal measurements were calculated through chemical oxygen demand (COD) values due to the greater ease, speed, and accuracy of the COD analysis in comparison with the BOD_5 analysis. Ordinarily this relationship is not reliably consistent; however, with a controlled wastewater, such as the one used in this study, the ratio of these parameters should be relatively constant. Measurements of both were performed here to verify this relationship.

Table 1. Synthetic Wastewater Recipe

Constituent	Concentration (mg/l)
$MgSO_4 \cdot 7H_2O$	300
$FeCl_3 \cdot 6H_2O$	14
$MnSO_4 \cdot H_2O$	5
K_2HPO_4	120
KH_2PO_4	30
$CaCO_3$	14
Difco Nutrient Broth	77, 153, 227, 304

Analyses performed on each system effluent and a composite of the system influent (half fresh and half 24 hours old) during this preliminary portion of the study, included daily pH measurements; COD three times per week; and BOD_5, total Kjeldahl nitrogen (TKN), ammonia, and nitrate once per week. Each of these analyses were performed in triplicate. In addition, daily measurements of the air and water temperature, influent and effluent flow rates for each tank, and ORP at two points within each tank were obtained. Measurements of pH were taken at each of the four sample points with an Orion pH meter. COD measurements were facilitated through the use of standard range COD twist-tubes supplied by O.I. Corporation. For BOD_5, total Kjeldahl nitrogen (TKN), ammonia, and nitrate analyses, methods specified in the 16th edition of Standard Methods for the Examination of Water and Wastewater (APHA, 1975) were employed. Flow rates were obtained manually by measuring the volume accumulated in one minute. Platinum probes installed at two points in each tank yielded ORP measurements. Data on plant growth and nitrogen content were recorded by randomly selecting 6 or 12 plants from each tank and drying them at 70°C to a constant weight. By counting the number of plants in each tank at the time of sampling, the above-grade dry weight of plant matter for each system was estimated. A small portion of dried plant matter from each tank was ground in a Wiley mill equipped with a #40 sieve for TKN analysis to obtain a plant TKN mass estimate for each tank.

When steady-state operation was not obtained in a feasible time-frame, an alternative monitoring program was contrived. This program involved randomly changing the influent BOD_5 concentration in consecutive ten-day periods at two flow rates. The four influent BOD_5 concentrations (28, 78, 107, and 51 mg/l) were first applied under a flow of 80 ml/min (24 hour theoretical retention time), which resulted in BOD_5 surface loadings of 4.63, 12.90, 17.69, and 8.43 g/day/m^2. The influent concentrations listed above were then repeated under a 140 ml/min flow (42 hour theoretical retention time), giving BOD_5 surface loadings of 8.10, 22.57, 30.96, and 14.76 g/day/m^2. During each ten-day period, the effluent from each filter and an influent composite were analyzed on days 4, 8, 9, and 10 for BOD_5, TKN, and ammonia; and on days

2, 4, 6, 8, 9, and 10 for COD. Only random nitrate analyses were performed since negligible amounts of this compound were measured during the preliminary portion of this study. Daily measurements of water temperature, pH, and ORP in each tank were also obtained. The influent pH was adjusted daily to between 7.0 and 7.5 by addition of sulfuric acid. Ambient air temperature and influent and effluent flow measurements were also recorded daily. Above-grade dry plant matter weight and TKN plant mass were analyzed at the end of every 10 day period for each vegetated filter.

RESULTS

During the preliminary period of this study, oscillation of the COD data at a constant influent BOD_5 of approximately 30 mg/l and a flow of 80 ml/min, even after a month, indicated that a steady-state situation had not been achieved. To verify this statistically, the 95% confidence interval about the mean for each filter separately was calculated using individual triplicate COD analyses from the last five samples. Values lying to each side of this confidence interval in all three cases suggested a steady-state had not been reached in any of the three filters. An analysis of variance conducted on this data, however, indicated a very significant difference in COD removal between filter systems, below the 0.5% confidence level. Overall average BOD_5 removal percentages (by mass) were 75%, 60%, and 44% for the Scirpus, Sagittaria, and control systems, respectively.

As shown in Figure 2, the Scirpus performed slightly better in COD removal than the Sagittaria system, with the control lagging behind 10 to 40 percent. Ranking of the filter systems by COD removal was substantiated by the pH measurements for each system. A larger drop in pH throughout the system indicates microbial activity due to the organic acids or CO_2 produced by microbial metabolism. For the systems containing plants, the pH of the effluent was consistently between 7.2 and 7.7, while the feed water and control effluent pH consistently ranged between 7.6 and 8.7, with the control having a higher pH than the feed water on several days.

FIGURE 2 - MASS %COD REMOVED VS TIME DURING PRELIMINARY EXPERIMENT

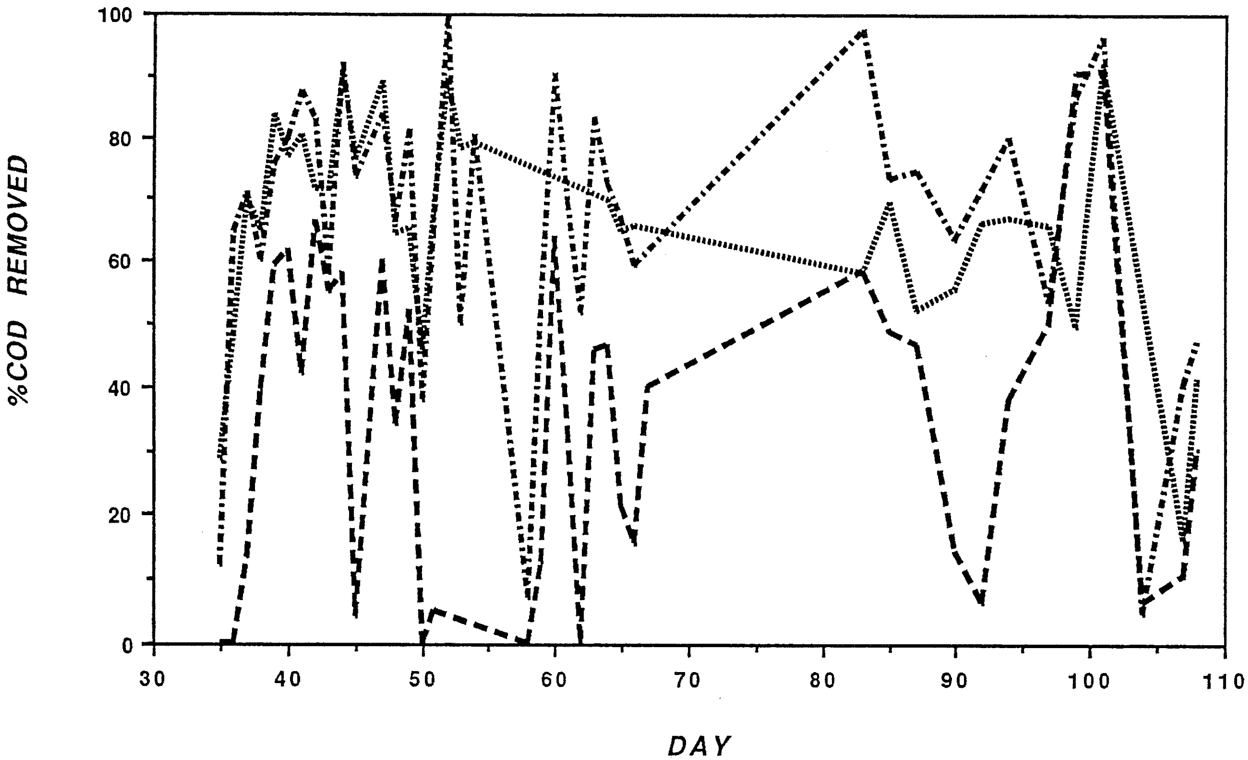
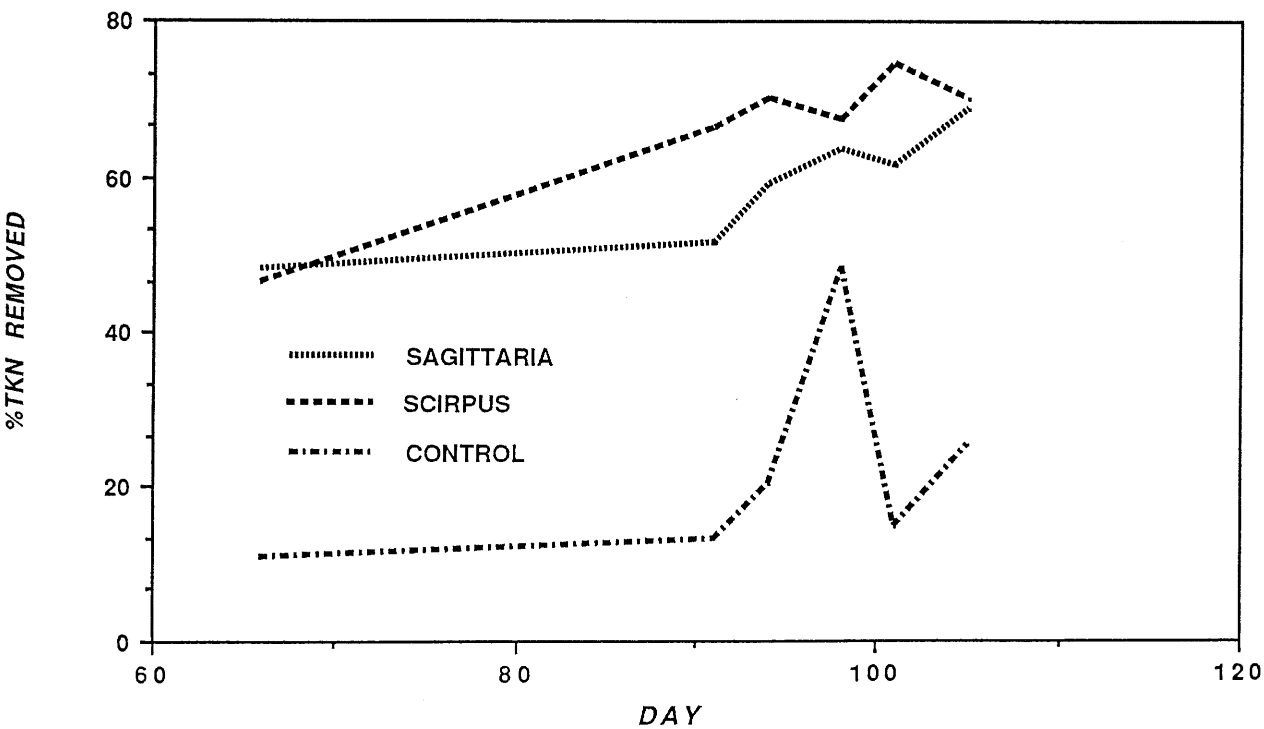


FIGURE 3 - MASS %TKN REMOVED VS TIME



Higher pH readings than the feed water was probably due to the presence of algae on the surface of the control filter.

Similarly, mass percent TKN removals, shown in Figure 3, were enhanced by the systems containing plants. Within the dried plant tissue, Sagittaria contained essentially the same percentage of TKN (25 mg N/ g dry plant weight, average) as the Scirpus (22 mg N/g dry plant weight, average). Due to the higher moisture content of the Sagittaria (91%) compared to Scirpus (84%), however, the total mass of Kjeldahl nitrogen was higher for the Scirpus (50 g) as opposed to the Sagittaria (36 g).

The final parameter of significance in the preliminary analysis was ORP, which is a function of the Gibbs free energy of a reaction and is an indication of the reactions taking place within the system. Certain reactions are characteristic of particular ORP value ranges; for example, below approximately +350 mV ORP, oxygen will not be present since it is completely reduced to water below this point. ORP measurements taken near the influent and effluent one-third of the three filter systems indicate each of the systems, with negative ORP values, were well into the anaerobic range. Dissolved oxygen (DO) profiles within the systems also revealed an absence or negligible (<0.5 mg/l) amount of DO at any depth on either end of each system. An earlier DO profile taken when the flow was 500 to 1000 ml/min, in recycling-flow mode, showed around 1 mg/l near the surface of the water level decreasing to 0.5 mg/l or less near the bottom of the tank for each system. An increase in organic loading at the end of this preliminary study resulted in a decreased ORP in both ends of each system, as expected. The plant systems appeared to maintain a higher ORP, at least at lower organic loadings. This is probably due to the oxygen known to be transferred from the shoots to the roots within aquatic plants. This action creates a thin aerobic zone in the root area, too thin to be directly measured by this study, but significant enough to perhaps raise the ORP 10 to 100 mV.

On August 26, 1989, the 80-day experiment began, using four influent BOD_5 concentrations at two flow rates (8 combinations) lasting 10 days each. Average BOD_5/COD values for each 10-day period are listed in Table 2. Taking into account experimental error, the values in Table 2 justify the use of COD as a representative parameter for BOD_5. Results of the 80-day experiment showed that, during the 80 ml/min flow, the average percentage of COD mass removals were 70%, 56%, and 42% for the Scirpus, Sagittaria, and control systems, respectively. This performance ranking, which is identical to the preliminary experiment, was consistent during this first half of the 80-day experiment except during the first 10 days, as shown in Figure 4. Prior to beginning the 80-day experiment, the feed tank was cleaned with dilute Clorox and rinsed thoroughly. This operation took 24 hours, during which the water level in the tanks containing plants dropped approximately one foot. Subsequently, a considerable die-off in the Sagittaria system occurred, although the Scirpus system appeared unaffected. Root damage and loss of dead plant matter through the effluent may have accounted for the increase in COD (and BOD_5) over the first ten day period in the Sagittaria system. In addition to poorer performance, variability in performance was greater in the control system. Standard deviations for the Sagittaria, Scirpus and control systems were 8.7%, 9.6%, and 12.6%.

At the higher flow, the average percentage of COD mass removals were 68%, 59%, and 52% for Scirpus, Sagittaria, and the control, respectively. Although the system performances were more equivalent at the higher flow, the trend noted previously is still generally present, as shown in Figure 5. Likewise, the variability in the control was higher again than the vegetated systems with standard deviations of 7.7%, 6.5%, and 15.3% for the Sagittaria, Scirpus, and control.

To evaluate the relation between influent organic mass and organic removal, the influent COD mass was plotted against the mass percentage of COD removal for the average of the last three days of each 10 day period. As shown in Figures 6 and 7 for the 80 and 140 ml/min flow respectively, there was not a strong correlation between influent COD mass and percentage of

Table 2. Average BOD_5/COD Ratios

Flow (ml/min)	BOD_5 (mg/l)	Influent	Sagittaria Effluent	Scirpus Effluent	Control Effluent
80	28	0.31	0.30	0.29	0.38
80	78	0.45	0.29	0.36	0.40
80	107	0.37	0.43	0.43	0.48
80	51	0.53	0.43	0.43	0.50
140	28	0.29	0.36	0.34	0.32
140	78	0.45	0.42	0.42	0.38
140	107	0.24	0.34	0.42	0.33
140	51	0.48	0.31	0.43	0.42
Avg.		0.39	0.36	0.39	0.40
Std. Dev.		0.10	0.06	0.05	0.06

FIGURE 4: %COD Removed - 80 ml/min Flow Rate

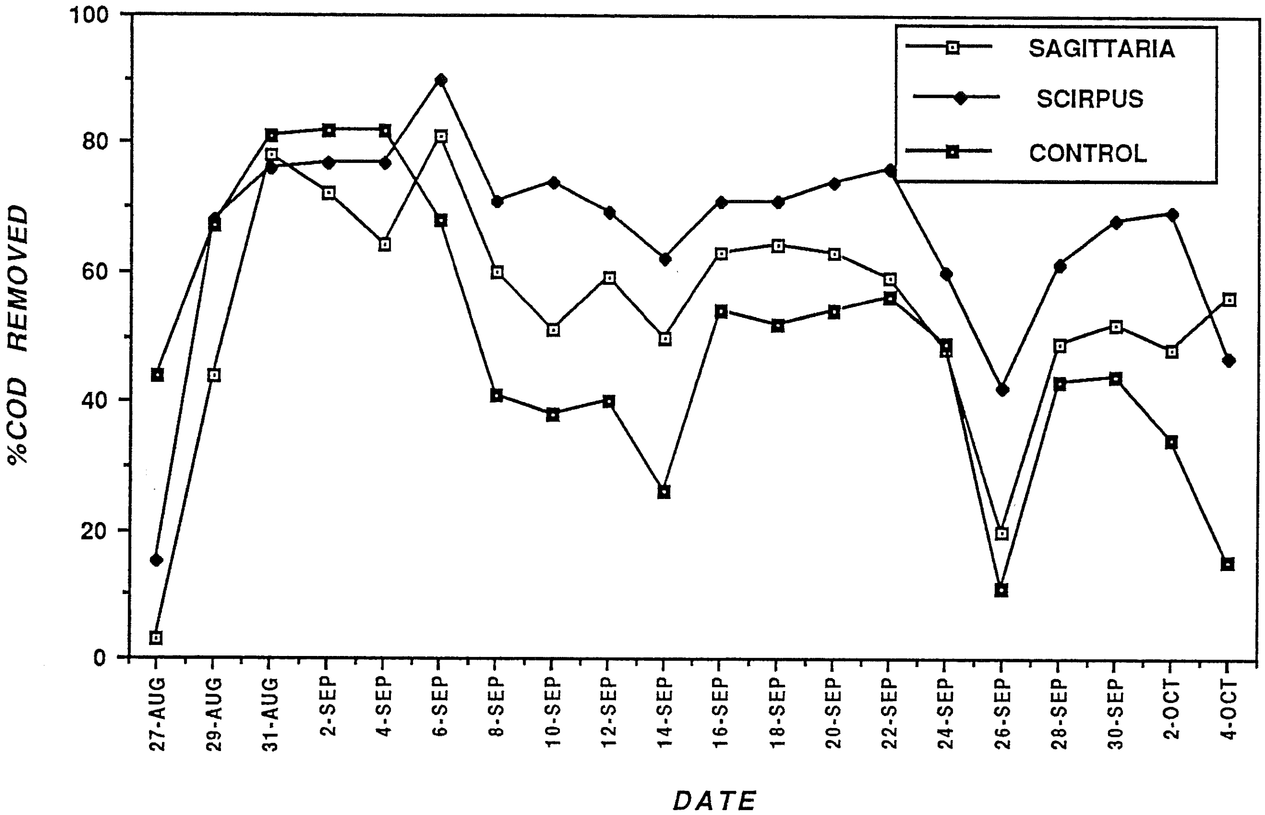


FIGURE 5 : %COD Removed - 140 ml/min Flow Rate

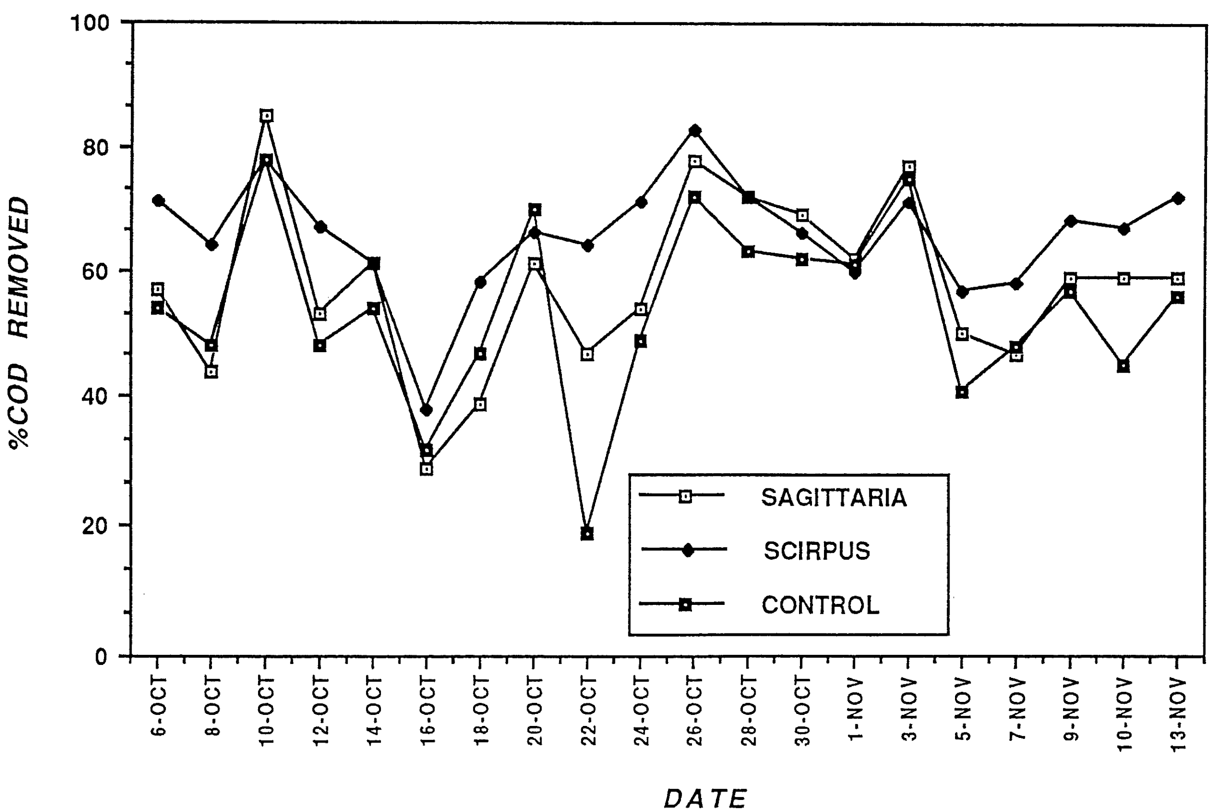


FIGURE 6 - Influent COD Mass vs %COD Removed
80 ml/min Flow Rate

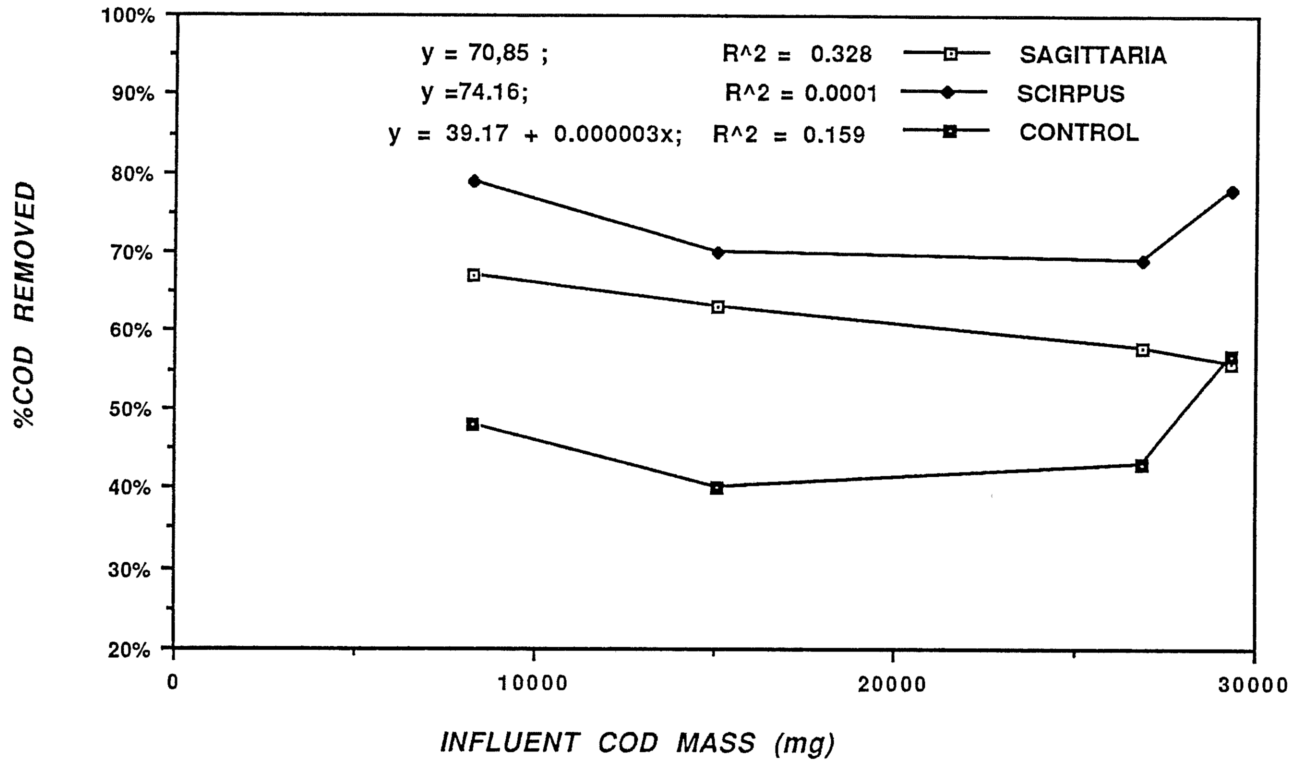
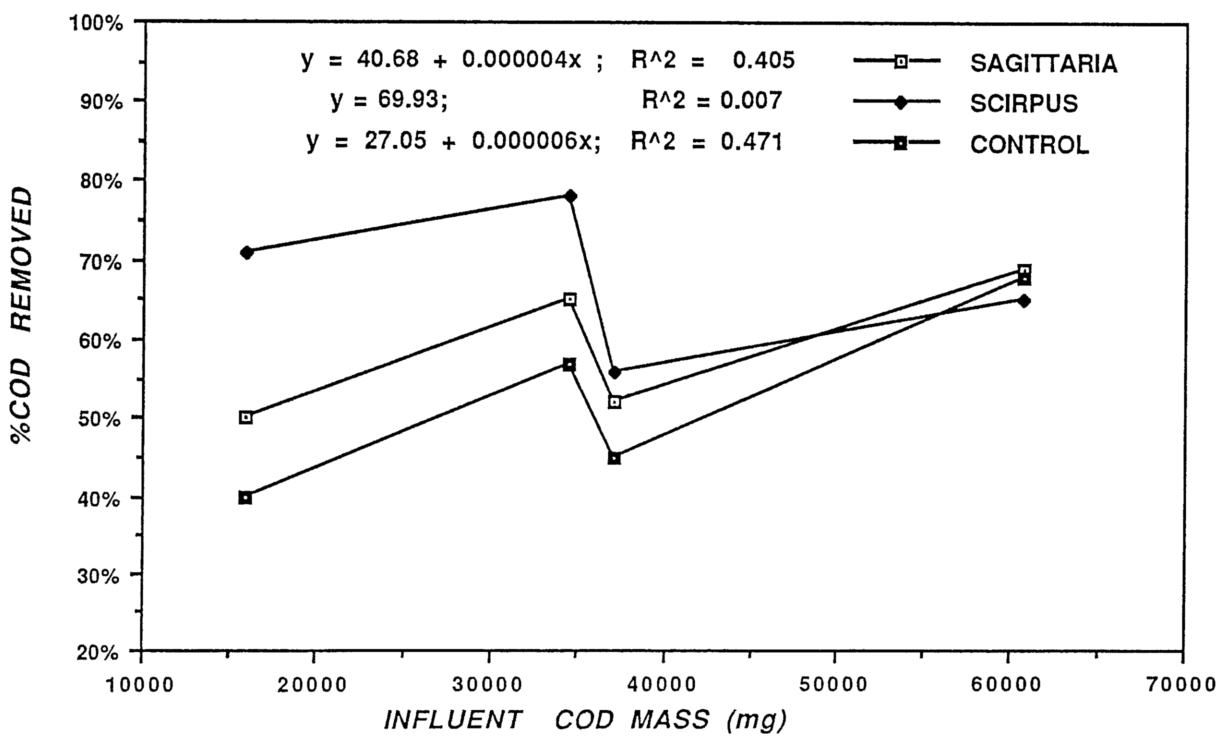


FIGURE 7- Influent COD Mass VS%COD Removed
140 ml/min Flow Rate



COD removed in any of these systems. Averages of the last three days are plotted on these figures; although the regression calculations were based on individual daily COD data. These graphs also suggest differences between the three systems, although at the higher flow these differences appear to be merging. It should be noted that, during the higher flow portion of the study, the number of daylight hours decreased by approximately 2 hours per day and the water and air temperatures dropped by approximately 5°C. Decreased sunlight and temperatures lower plant productivity and, therefore, may decrease the performance enhancement produced due to the plants. Likewise, lower temperatures, in the range found in this study, produce slightly less microbial activity. Other factors that could tend to equalize the systems under the higher flow conditions include decreased adsorption by the plant roots and greater outflow of degraded plant material.

As noted in the preliminary period above, ORP measurements during this 80-day experiment were below -200 mV at all times. This indicates an absence of dissolved oxygen since oxygen gas is completely reduced to water below +350 mV. Random dissolved oxygen readings confirmed a negligible level of oxygen.In addition to its relation to oxygen content, ORP was monitored to determine its suitability as an estimating parameter for organic removal. A lack of correlation, however, between ORP and the COD mass percentage removal nullified this use of the easily measured ORP.

Although the ORP and DO measurements indicate anaerobic conditions in these systems, nitrification could occur in the thin aerobic zone surrounding the root systems; therefore, it is reasonable to assume that the lack of nitrate in any system could be due to denitrification. Nitrification is suggested by the overall average TKN percentage removals (based on mass) of 19%, 32%, and 10% for the Sagittaria, Scirpus, and control systems, respectively. The 10-day average TKN mass percentage removed for the 80 ml/min flow and the 140 ml/min flow are graphically illustrated in Figures 8 and 9, respectively. This removal rate appears to vary slightly with the influent TKN concentration. The average TKN removal percentages (mass basis) at the

FIGURE 8 : %TKN Removed - 80 ml/min Flow Rate

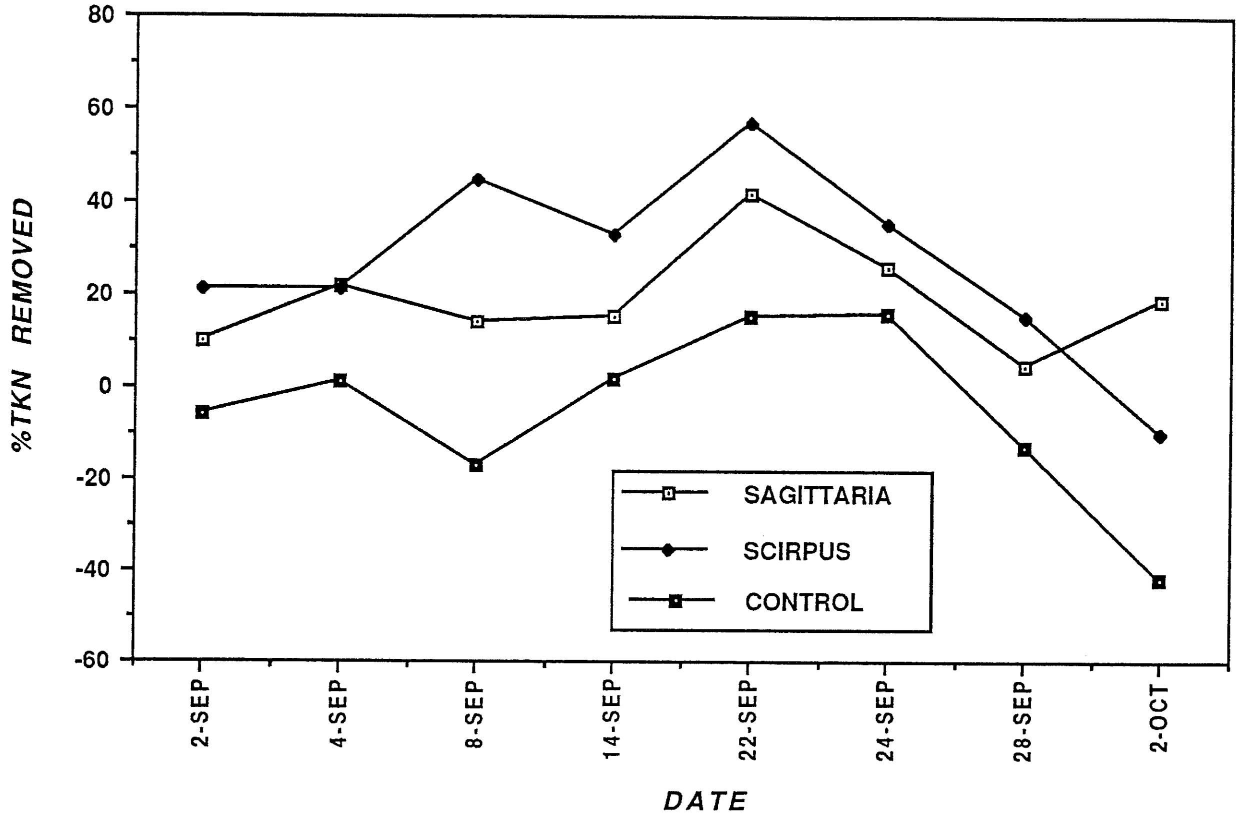
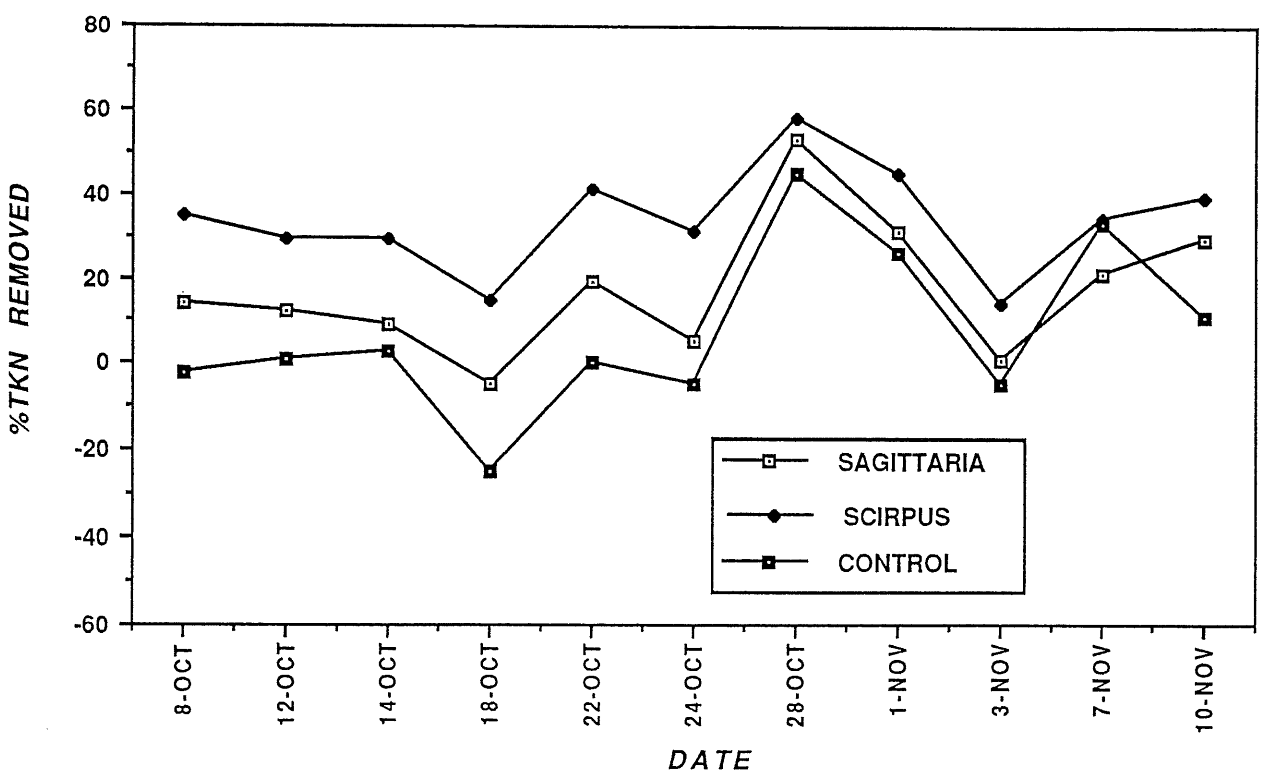


FIGURE 9 : %TKN Removed - 140 ml/min Flowrate



lower flow were 18% and 28% for the Sagittaria and Scirpus systems, respectively, compared to only 1% in the control system. At the higher flow, the Sagittaria system had a TKN removal of 17%, which was equivalent to the 18% removal in the control, and the Scirpus system had a 34% TKN removal. This trend for a lesser degree of difference between the plant systems and the control system at the higher flow agrees with the COD results.

DISCUSSION

Results of this bench-scale study were similar to BOD_5 removals found by Gersberg, et al. (1986) in their outdoor pilot-scale study at the Santee Water Reclamation Facility in Santee, California. The wastewater source in this pilot-scale study was primary wastewater which flowed through trenches at a rate resulting in a 6 day retention. BOD_5 removals found by Gersberg, et al. were 96%, 81%, 74%, and 69% for Scirpus, Phragmites, Typha, and control systems, respectively; which gives a 39%, 17%, and 7% increase over the control system in the Scirpus, Phragmites, and Typha systems. In the bench-scale study described herein, approximately 15% and 25% increases over the control were observed for the Sagittaria and Scirpus systems, respectively; although the average percentages of removal for the three bench-scale systems were lower overall than the percentages found by Gersberg, et al. The BOD_5 removal percentages found in the bench-scale study were also slightly lower than those cited by Wolverton (1987) from a 6 or 7 day retention time artificial wetland. Removal rates obtained by Maddox and Kingsley (1989), however, in their 2.3 to 5 day retention time filter which contained sand and Eleocharis dulcis (Chinese water chestnut) and received livestock waste were nearly identical to the removal rates found in this bench-scale study. Other COD removal data similar to this bench-scale study was reported by Wood and Hensman (1989) who treated septic sewage in their gravel and Arundo donax, 2.5 day retention time filters.

The other major parameter of importance in this investigation was nitrogen removal. Since organic nitrogen was the primary nitrogen source in the synthetic wastewater, ammonia removals are not comparable to other studies because much of the organic nitrogen transformed into ammonia within the filters which raised the effluent ammonia concentration higher than the influent, where very little ammonia was present. Gersberg, et al. (1986) found ammonia removals up to 94%; however, Wood and Hensman (1989) noted only an 18% ammonia reduction in their gravel-filled filter planted with Arundo donax receiving septic sewage. Although not directly correlated to ammonia removal, the TKN removal rates measured in the bench-scale study were as high as 45%, which falls between the ammonia removal rates found in the above two studies.

Root zone comparisons between the bench-scale study and the field study by Gersberg, et al. (1986) showed deeper root systems in the field study. Gersberg, et al. measured root zones on the Typha, Scirpus, and Phragmites plants to be 12", 24", and 30" deep. In the bench-scale study, the root zones of both the Scirpus and Sagittaria plant systems were approximately 12". Although the depth of both sets of filters was equal (30"), the location (indoor vs. outdoor) and water levels may have been the difference. Another observation made during the disassembling of the bench-scale systems was the presence of a black, gelatinous mass which filled the pore spaces in the influent quarter of each system. This accumulation is most likely bacterial growth, iron sulfide precipitate, or a combination of the two and may be the cause of clogging problems experienced in a large, municipal rock-plant filter systems recently.

CONCLUSIONS

From this bench-scale study, the following conclusions were drawn:

1. Oxidation-reduction potential measurements and dissolved oxygen readings indicated that the filter systems analyzed in this study were anaerobic throughout.
2. COD data generated by this study indicated the plant systems were superior in removing organic material compared to the unvegetated system. Overall, organic removals averaged approximately 60%, 70%, and 50% for the Sagittaria, Scirpus, and control systems, respectively.

3. The correlation between COD mass applied and COD mass percentage removed under the conditions of this study was very low. There was, however, a greater difference in removal rates between the systems during the 80 ml/min flow than during the 140 ml/min flow.

4. During the 80 ml/min flow, TKN removal rates in the Sagittaria and Scirpus systems were 17% and 27% higher, respectively, than the 1% average TKN removal rate found in the control system. Similar values for the 140 ml/min flow were 0% and 16% higher than the 18% average TKN removal rate found in the control system. As noted in the organic removal calculations, TKN removal percentages revealed a greater difference in removal rates between the systems during the 80 ml/min flow than during the 140 ml/min flow. Overall average TKN removal rates were 18%, 31%, and 10% for the Sagittaria, Scirpus, and control systems.

REFERENCES

1. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, (1975), Standard Methods for the Examination of Water and Wastewater, 16th edition, Washington, D.C., American Public Health Association.

2. Gersberg, R.M., B.V. Elkins, S.R. Lyon and C.R. Goldman, (1986), "Role of Aquatic Plants in Wastewater Treatment by Artificial Wetlands", Water Resources, v.20, n.3, pp.363-368.

3. Gersberg, R.M., B.V. Elkins, and C.R. Goldman, (1983), "Nitrogen Removal in Artificial Wetlands", Water Resources, v.17, n.9, pp.1009-1014.

4. Gersberg, R.M., B.V. Elkins, and C.R. Goldman, (1984), "Use of Artificial Wetlands to Remove Nitrogen from Wastewater", Journal of the Water Pollution Control Federation, v.56, n.2, pp.152-156.

5. Maddox, J.J. and J.B. Kingsley, (1989), "Waste Treatment for Confined Swine with an Integrated Artificial Wetland and Aquaculture System", Constructed Wetlands for

Wastewater Treatment, D.A. Hammer, Ed. (Chelsea, Mich: Lewis Publishers, Inc.), pp. 191-200.

6. Spangler, F.L., W.E. Sloey, and C.W. Fetter, (1976), "Artificial and Natural Marshes as Wastewater Treatment Systems in Wisconsin", presented at Freshwater Wetlands and Sewage Effluent Disposal: Ecosystem Impacts, Economics, and Feasibility", May 10 - 11, Univ. of Mich., Ann Arbor.

7. Wolverton, B.C., (1982), "Hybrid Wastewater Treatment System Using Anaerobic Microorganisms and Reed (Phragmites communis)", Economic Botany, v.36, n.4, pp.373-380.

8. Wolverton, B.C., R.C. McDonald, and W.R. Duffer, (1983), "Microorganisms and Higher Plants for Wastewater Treatment", Journal of Environmental Quality, v.12, n.2, pp.236-242.

9. Wolverton, B.C., (1987), "Aquatic Plants for Wastewater Treatment: An Overview", in Aquatic Plants for Water Treatment and Resource Recovery, K.R. Reddy and W.H. Smith, Eds. (Orlando, FL: Magnolia Publishing, Inc.), p.3.

10. Wood, A. and L.C. Hensman, (1989), "Research to Develop Engineering Guidelines for Implementation of Constructed Wetlands in Wastewater Treatment in Southern Africa", Constructed Wetlands for Wastewater Treatment, D.A. Hammer, Ed. (Chelsea, Mich: Lewis Publishers, Inc.), pp. 581-589.