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## PHOSPHORUS REMOVAL FROM WASTEWATER USING AN ALGAL TURF SCRUBBER

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### ABSTRACT

Algal turf scrubbing is a novel technology for the treatment of agricultural runoff and eutrophic lake water and may have application for wastewater treatment. The algal turf scrubber (ATS)<sup>™</sup> consists of a natural, mixed assemblage of attached periphyton, microalgae and bacteria which colonise an inclined flowway over which wastewater flows in a series of pulses. A large-scale ATS (152.4 m long 6.5 m wide) was constructed in Patterson, California and tested in conjunction with UV disinfection over one year for its ability to treat secondary effluent from an evaporation pond. The hydraulic loading rate of the wastewater was varied between 436 and 1226 m<sup>3</sup> per day and various operational parameters were tested. The biomass was mechanically harvested from the flowway at one or two week intervals depending upon the season. This paper will present the results for phosphorus removal and productivity of the algal turf. Phosphorus removal from the secondary wastewater was measured twice a week during four, 8 week quarters corresponding to the solar seasons. The phosphorus content of the harvested solids was also measured during these periods. Based on the mean percentage of P (2.1 %) in the harvested solids and the mean productivity (35 g m<sup>-2</sup> d<sup>-1</sup>), the yearly mean removal of phosphorus was 0.73 ± 0.28 g m<sup>-2</sup> d<sup>-1</sup>. An inverse relationship was found between reduction in hydraulic loading rate and increase in pH, phosphorus removal and hardness reduction by the ATS. This indicated that pH mediated precipitation probably accounts for much of the phosphorus removal by the ATS and for the high mean phosphorus content of the harvested solids. Measurement of nutrient concentrations in influent and effluent of the ATS over 24 hours showed that at night phosphorus removal declined. These results indicate the potential of the ATS for phosphorus removal from wastewaters and suggest that removal may be easily controlled by altering the hydraulic loading rate.

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### KEYWORDS

Algal Turf Scrubber; Periphyton; pH; Phosphorus; Precipitation; Secondary sewage effluent.

### INTRODUCTION

Urbanisation, industrialisation and agriculture have increased demand for potable water resources, while at the same time, have caused widespread pollution of natural water bodies (Gloyne, 1971). In the past, dilution of wastewaters discharged to lakes and rivers was an adequate method of treatment. However, both the concentration and volume of the sewage effluent and agricultural run-off now discharged, are too great to be treated by dilution alone (Harlin and Darley, 1988). Every year over 200 million tons of phosphorus are discharged to US surface waters (Leedan *et al.*, 1990). Eutrophication of freshwaters, particularly due to excessive phosphorus concentrations is an increasing problem, with more than 30 % of rivers and lakes in the US affected (Hecky and Kilham, 1988). Moreover, the remediation of natural water bodies which are now eutrophic is of major environmental concern. Traditional bacterial wastewater treatment methods rely on mechanical processes and are costly to construct and operate (Metcalf and Eddy, 1991). They also have low treatment efficiencies, especially for inorganic nutrients (Oswald, 1988). Despite the scarcity and cost of producing potable water, little wastewater is currently reused. In the US, much of this potentially valuable

resource is "abandoned" in ponds after primary or secondary treatment to evaporate or infiltrate into ground waters. In 1986, 89 % of American states reported sewage as the main contaminant of ground waters (Leedan *et al.*, 1990). More efficient and economical alternative treatment methods which enable recycling of this water resource are therefore required.

Algal Turf Scrubbing represents a novel algal wastewater treatment technology which cultures attached or benthic bacteria, microalgae and periphyton (filamentous algae) on an inclined flowway. The Algal Turf Scrubber (ATS)<sup>™</sup> is essentially an artificial stream which has been designed and engineered to promote biological wastewater treatment using periphyton. The use of such a community for small-scale water treatment was developed by Adey and associates at the Smithsonian Institution, Washington D.C. over the last fifteen years (Adey and Loveland, 1991). The capability to remove nutrients from agricultural run-off has previously been demonstrated in a small-scale outdoor pilot plant in Florida (Adey *et al.*, 1993). To maintain efficiency of nutrient removal and exponential growth rates, the periphyton community is harvested. This is simply achieved by stopping the flow of wastewater, draining the flowway for one hour and vacuuming the biomass from the surface. Hence, all pollutants accumulated by the algal turf are easily removed in the harvested solids.

The project at Patterson, California was undertaken to determine whether the ATS, in conjunction with ultra-violet (UV) disinfection, could treat the effluent from the Patterson wastewater treatment facility to meet Californian regulations for discharge and to evaluate the ATS/UV system and mechanical harvesting at large-scale. Here, we report on the phosphorus removal capability of the ATS/UV system and the productivity of algal biomass using secondary treated wastewater as a substrate.

## MATERIALS AND METHODS

**Patterson Wastewater Treatment Facility.** The city of Patterson (latitude 37° 30', 21" and longitude 121° 04', 58") is situated in the Central Valley of California, approximately 70 miles south east of San Francisco. The treatment train at the Patterson wastewater treatment facility includes influent screening, comminution, extended aeration in an oxidation ditch, clarification and sludge removal. Part of the sludge is used to reseed the oxidation ditch while the majority is dried in the drying beds and ploughed into the ground. The facility has a design flow of 1.0 million gallons per day, and the treated wastewater is presently disposed of on-site to 51 acres of evaporation and infiltration ponds.

**Patterson Algal Turf Scrubber / UV system.** Algal turf scrubbers are low-cost treatment systems which are simple in design and construction. The large-scale ATS/UV treatment system built at Patterson had several components (Fig. 1): an ATS flowway with a pneumatic wave maker, a 400 µm rotary screen strainer, a sand filtration system, an ultra-violet disinfection system, and a harvester.

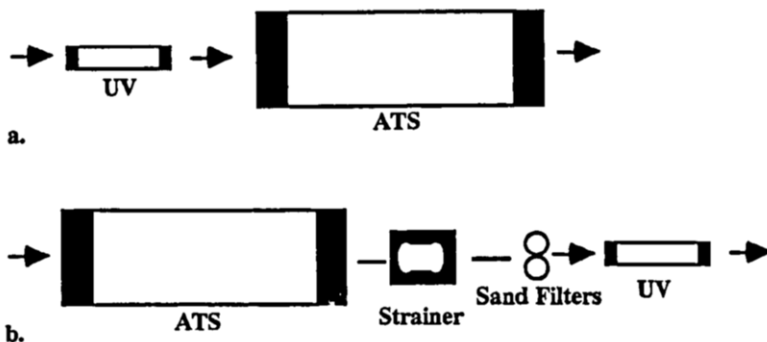


Figure 1. Configurations of the ATS/UV system.

The ATS flowway consisted of a liner which covered laser graded soil and lay between and was attached to, two precast concrete grade beams. The liner (60 mil. textured high density polyethylene landfill liner (Polyflex Corporation, Houston TX)) provided a surface for periphyton attachment. The grade beams

provided both a vertical edge to the flowway and rails to support and distribute the weight of a mechanical harvester. To maintain the uniform flow down the ATS, the top half was inclined at a 0.5 % slope and the bottom at a 0.25 % slope. The total change in elevation was approximately 0.61 m over the entire length. The flowway was 152.4 m long and 6.5 m wide, had a total surface area of 1012 m<sup>2</sup>, and was oriented so that water flowed from north to south. The influent was delivered with a surging device which produced a series of waves to raise the efficiency of treatment by increasing the contact between the algae and the wastewater (Adey and Hackney, 1989; Adey and Loveland, 1991). The surge was produced using two compressed air cylinders (0.1 m bore by 0.3 m stroke) to drive a 6.1 m wooden beam in and out of a 1022 litre influent trough. The rotary screen strainer collected any algae that sloughed off the flowway surface. The strainer was made from a coarse mesh barrel (0.76 m diameter, 1.22 m long) with a stainless steel screen (400 µm) wrapped around its outer surface. The barrel rotated continuously and high pressure jets (using the filtered effluent) washed the filtrate from the screen onto a drying bed. Two pressurised sand filters (Efficco, California) were used to filter microscopic particles from the effluent. Both filters had a volume of 0.3 m<sup>3</sup>, and contained 5 µm spherical sand over a 0.05 m bottom layer of coarse grain sand. The UV disinfection unit (Trojan technologies, Canada) was composed of three troughs (2.44 m long, 0.53 m wide and 0.37 m high). The unit held a total of 42 lamps (40 Watt), with seven mounts of two lamps in each trough. The lamps were enclosed within a quartz shield which had to be cleaned periodically. The harvester removed the algal turf from the flowway and transferred it to a tanker. An internal combustion gasoline engine powered the entire harvester unit including hydraulic wheel drive, an articulated vacuum nozzle, cyclone separator and transfer pump.

*Sampling Protocol and Analytical Methods.* Evaluation of the ATS/UV system was conducted over one year from the 30<sup>th</sup> of August 1993 to the 24<sup>th</sup> of October 1994 including a preliminary study period and four, 8 week quarters, corresponding to the solar seasons. This enabled performance to be related to seasonal variations. Samples for both soluble reactive phosphorus and total phosphorus analysis were taken on Wednesday and Friday and concentrations were measured against deionized water blanks by the ascorbic acid method (APHA, 1992). Various physical parameters of the wastewater including dissolved oxygen concentration, temperature (DO/Temperature Meter, Model 820, Orion Research Inc, Massachusetts), pH (pH Meter (Model 240, Corning Science products, NY), alkalinity (acid titration, APHA, 1992), conductivity (Conductivity probe, Lectro mho-meter, lab-line inst. inc., Illinois) and hardness (chelation titration, APHA, 1992) were measured Monday through Friday, except alkalinity and hardness which were measured on Monday, Wednesday and Friday.

Samples were collected at 11:00 am. Each quarter included a 5-day intensive week with daily testing of all parameters, and two diurnals, during which parameters were measured at 4 hour intervals to determine the daily variations in treatment. All water quality parameters were measured from duplicate samples except during diurnal tests when only single samples were taken. Samples were taken in dilute HCl acid-washed glass vials from the influent and effluent of the combined ATS/UV system (Fig. 1). Soluble reactive phosphorus samples were prefiltered through a disposable Millipore filter immediately after sampling. All samples were stored on ice or in a refrigerator until analysed. Appropriate standards and spiked samples were analysed to ensure adequate quality control. Preliminary samples taken between August 30<sup>th</sup> and November 21<sup>st</sup>, 1993 were analysed by A&L laboratories in Modesto, CA. Samples from the four quarters were analysed by the Applied Algae Research Group at the Environmental Engineering and Health Sciences Laboratory, UC Berkeley, CA. Harvested solids (algal and bacterial biomass, trapped particulates and precipitated compounds) of the top and bottom halves of the flowway were both sampled from five random 0.093 m<sup>2</sup> sites and used to calculate the mean productivity for the flowway. At several times during the test period samples of solids from the top, middle and bottom of the flowway were dried and analysed for chemical composition by A&L laboratories in Modesto, CA.

*Operation.* Two configurations of the treatment system were tested. For the preliminary period and the first three quarters the UV disinfection unit was placed in front of the ATS (Fig. 1a). During the fall quarter the complete ATS/UV system was in place, consisting of the ATS, rotating drum strainer, sand filters, and UV units in series (Fig. 1b). The influent was taken from two sources: the Patterson treatment plant effluent stand-pipe during the spring quarter, or the evaporation/ infiltration Pond 3A during the remainder of the study. The influent was pumped using two 3 HP pumps (Dayton Electric Mfg. Co., Illinois). The influent flow rate was varied from 954 m<sup>3</sup> d<sup>-1</sup> during the winter quarter, to 1226 m<sup>3</sup> d<sup>-1</sup> during the spring, to 899 m<sup>3</sup> d<sup>-1</sup> during the summer and first month of fall quarter, and finally to 436 m<sup>3</sup> d<sup>-1</sup> in the last month on the fall quarter. The flow rate was measured using a Doppler flow meter (Dynamic fluid systems, New York, model HFM-1).

## RESULTS

This was the first large-scale ATS to be built, hence, many of the operational parameters were changed during the evaluation period to optimise treatment performance. The yearly means  $\pm$  s.d. and range values and fall quarter means  $\pm$  s.d. of the parameters measured during the study are shown in Tables 1a & b. The large standard deviations of the yearly and fall means reflect the wide variations in the influent concentrations (Tables 1a & b).

TABLE 1A YEARLY MEANS  $\pm$  SD OF PARAMETERS MEASURED IN THE INFLUENT AND EFFLUENT OF THE ATS/UV SYSTEM

Parameter	Yearly	
	Mean $\pm$ s.d. (n = 76)	Effluent
Temperature ( $^{\circ}$ C)	18.9 $\pm$ 5.3	24.4 $\pm$ 6.9
Dissolved Oxygen (mg l <sup>-1</sup> )	4.8 $\pm$ 3.1	24.9 $\pm$ 4.9
pH	8.4	9.5
Alkalinity (mg l <sup>-1</sup> as CaCO <sub>3</sub> )	235.0 $\pm$ 34.4	210.4 $\pm$ 30.8
Hardness (mg l <sup>-1</sup> as CaCO <sub>3</sub> )	460.7 $\pm$ 27.0	435.0 $\pm$ 23.1
Conductivity (mS m <sup>-1</sup> )	215.3 $\pm$ 10.1	206.0 $\pm$ 9.1
Soluble Reactive Phosphorus (mg l <sup>-1</sup> )	2.7 $\pm$ 1.2	1.2 $\pm$ 1.0
Total Phosphorus (mg l <sup>-1</sup> )	3.1 $\pm$ 1.0	1.7 $\pm$ 0.9

However, the yearly means indicate the general trends of treatment by the ATS/UV system, which are most clearly seen in the fall quarter means when the complete ATS/UV system was operating. The ATS/UV system reduced the concentrations of both soluble reactive and total phosphorus in the wastewater (Tables 1a & b). The alkalinity, conductivity and hardness of the wastewater were also reduced, while the temperature, dissolved oxygen concentration (DO) and pH were all increased (Tables 1a & b).

TABLE 1B FALL QUARTER MEANS  $\pm$  SD OF PARAMETERS MEASURED IN THE INFLUENT AND EFFLUENT OF THE ATS/UV SYSTEM AT TWO HYDRAULIC LOADING RATES

Parameter	Fall Quarter 889 m <sup>3</sup> d <sup>-1</sup>		Fall Quarter 436 m <sup>3</sup> d <sup>-1</sup>	
	Mean $\pm$ s.d. (n = 8)	Effluent	Mean $\pm$ s.d. (n = 11)	Effluent
Temperature ( $^{\circ}$ C)	23.6 $\pm$ 1.2	29.3 $\pm$ 2.1	19.0 $\pm$ 2.8	25.5 $\pm$ 3.4
Dissolved Oxygen (mg l <sup>-1</sup> )	5.0 $\pm$ 1.3	21.1 $\pm$ 3.6	3.3 $\pm$ 1.0	23.0 $\pm$ 3.8
pH	8.1	9.3	7.7	9.8
Alkalinity (mg l <sup>-1</sup> as CaCO <sub>3</sub> )	245.1 $\pm$ 17.6	223.9 $\pm$ 18.2	244.8 $\pm$ 11.3	192.9 $\pm$ 14.8
Hardness (mg l <sup>-1</sup> as CaCO <sub>3</sub> )	480.8 $\pm$ 8.1	454.2 $\pm$ 10.4	484.1 $\pm$ 17.7	422.0 $\pm$ 20.2
Conductivity (mS m <sup>-1</sup> )	215.6 $\pm$ 6.3	206.0 $\pm$ 5.1	218.1 $\pm$ 10.6	202.7 $\pm$ 6.4
Soluble Reactive Phosphorus (mg l <sup>-1</sup> )	3.1 $\pm$ 0.1	0.9 $\pm$ 0.3	3.0 $\pm$ 0.5	0.4 $\pm$ 0.3
Total Phosphorus (mg l <sup>-1</sup> )	3.5 $\pm$ 0.1	1.2 $\pm$ 0.3	3.7 $\pm$ 0.3	0.8 $\pm$ 0.2

Various hydraulic loading rates were used throughout the year-long study. The effects of hydraulic loading on treatment by the ATS/UV system are demonstrated by the fall quarter results when two hydraulic loading rates were tested. Lowering the hydraulic loading rate caused greater reduction of alkalinity, conductivity and hardness, and increased removal of both total phosphorus and soluble reactive phosphorus (Table 1b). When these parameters are plotted against flow rate for the entire year an inverse relationship can be seen (Fig. 2). The concentration of phosphorus and cations (calcium and magnesium) in the harvested biomass also shows this trend (Table 2). However a comparison of phosphorus removal based on 24 hour total removal to mean daily removal, as determined by the 11:00 am samples for the fall quarter, indicates that the lower hydraulic

loading rate caused increased daily removal, but not increased diurnal removal (Table 3). The pH of the ATS/UV effluent showed an inverse relationship with flow rate, indicating that pH was most likely involved in the reduction of phosphorus and the cations (Fig. 2).

TABLE 2 COMPARISON OF ATS FALL QUARTER TOTAL HARVESTED SOLIDS COMPOSITION AND MEAN WEEKLY pH AT TWO HYDRAULIC LOADING RATES

Date	Hydraulic Loading (m <sup>3</sup> d <sup>-1</sup> )	Mean Weekly pH	Mean ± s.d. Harvested Solids (g m <sup>-2</sup> d <sup>-1</sup> )	P Content (g kg <sup>-1</sup> )	P Removed (g m <sup>-2</sup> d <sup>-1</sup> )	Mg Content (g kg <sup>-1</sup> )	Ca Content (g kg <sup>-1</sup> )
23-Sep	899	9.47	24.47 ± 0.20	21.23	0.52	25.13	26.70
21-Oct	436	10.08	19.73 ± 3.80	23.37	0.46	30.80	35.90

The productivity measured as harvested solids varied over the year, due to changes of season and solar irradiance, and had a mean of 23.8 ± 16.4 g m<sup>-2</sup> d<sup>-1</sup> (dry wt.), summer maximum of 60.9 g m<sup>-2</sup> d<sup>-1</sup> and winter minimum of 4.2 g m<sup>-2</sup> d<sup>-1</sup>. Based on the percentages of N and P in the harvested solids and the mean productivity, the yearly mean removal of phosphorus was 0.73 ± 0.28 g m<sup>-2</sup> d<sup>-1</sup>. The decrease of hydraulic loading rate in the fall quarter seemed to reduce the decline in productivity seen during the fall quarter (Fig. 3). A natural assemblage of bacteria, microalgae and periphyton developed on the floway. Species composition of the algal turf varied over the study period. For much of the year the predominant algal species were cyanobacteria (*Oscillatoria* and unidentified fine filamentous sp.) and diatoms (*Navicula* sp., *Nitzschia* sp. and *Cyclotella* sp.). However several green filamentous species (*Microspora* sp., *Cladophora* sp., *Ulothrix* sp., *Stigeoclonium* sp., *Spyrogyra* sp., *Tribonema* sp., and *Rhizoclonium* sp.) were prevalent on the floway during the summer and fall.

TABLE 3 COMPARISON OF MEAN DAILY PHOSPHORUS REMOVAL AND MEAN AND RANGE DAILY pH VALUES WITH INFLUENT CONCENTRATION AT TWO HYDRAULIC LOADING RATES DURING THE FALL QUARTER

Date	Hydraulic Loading (m <sup>3</sup> d <sup>-1</sup> )	Mean ATS Effluent pH	Total Phosphorus		
			Influent Concentration (mg l <sup>-1</sup> ) Means ± s.d.	Removal (mg l <sup>-1</sup> ) Means ± s.d.	Mass TP Removed (g m <sup>-2</sup> d <sup>-1</sup> )
Daily Means					
19-23 Sep	898	9.47	3.40 ± 0.08	2.05 ± 0.45	1.82
17-21 Oct	428	10.08	3.40 ± 0.05	2.65 ± 0.24	1.12
24 h Means					
20-21 Sep	898	9.27	3.35 ± 0.07	0.61 ± 1.62	0.54
19-20 Oct	428	9.81	3.30 ± 0.07	0.58 ± 1.71	0.25

## DISCUSSION

This study evaluated the capability of a large-scale Algal Turf Scrubber to remove phosphorus from secondary sewage effluent under ambient conditions over a one year period. The yearly mean values, and particularly the fall mean values, demonstrate the capability of this system to remove phosphorus (Tables 1a & b). Many of the operational parameters for the Patterson ATS were developed concurrently with data collection which accounts for the considerable variation in influent and effluent values for some of the parameters.

Periphyton may remove phosphorus from wastewaters by either filtration, adsorption, assimilation (including luxury uptake), or precipitation (Swift and Nicholas, 1987). Most of the total phosphorus in the Patterson treatment facility effluent was soluble reactive phosphorus (Tables 1a & b), indicating that removal was most likely by assimilation and precipitation.

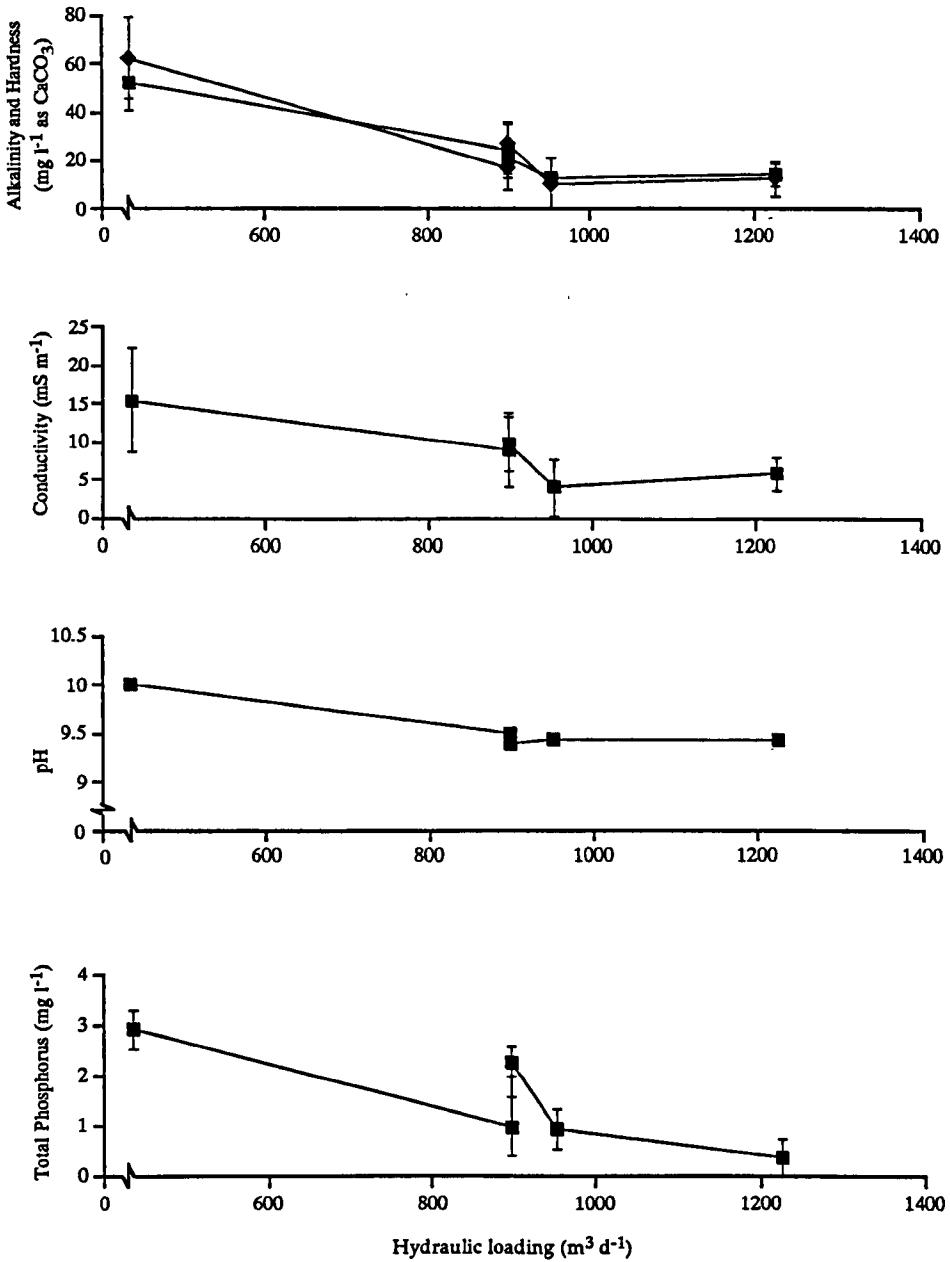


Figure 2. Total phosphorus removal, alkalinity, conductivity and hardness reduction and effluent pH of the ATS/UV system at different hydraulic loadings. Values are means  $\pm$  s.d. (n=19).

The inverse relationships between hydraulic loading and the pH, phosphorus removal, and hardness reductions of the ATS/UV system demonstrate that precipitation probably accounted for much of the phosphorus removal by the ATS (Fig. 2). As the hydraulic loading was reduced, the pH and hardness

reductions increased, as did the mean total phosphorus removal. Phosphorus precipitation may explain why the harvested solids from the ATS had a mean phosphorus content of 2.1 %, when periphyton biomass normally contains < 1 % phosphorus (Davis *et al.*, 1990; Adey *et al.*, 1993). The precipitation of phosphorus with cations (such as  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) at high pH is known to occur between pH 8.9 - 9.5, depending upon the buffering capacity of the water (Belsare and Belsare, 1987). The increase in the pH of the ATS/UV effluent was most likely a result of the algal turf being carbon limited, and the subsequent use of bicarbonate for photosynthesis (Soeder and Hegewald, 1988). Higher phosphorus removal at the lower hydraulic loading rate ( $1.40 \text{ m}^3 \text{ d}^{-1}$ ) during the fall quarter, which was measured by both the daily removal and the biomass content (Tables 2 and 3), were probably due to increased pH-mediated precipitation. The dissolution of some of this precipitate at night, when the pH declined to below 8.9 accounts for the lower 24 hour phosphorus removal rates (Table 3). The decrease in the mass of phosphorus removed by the ATS/UV system at the lower hydraulic loading rate was due to the lower volume of water treated, as well as a seasonal decrease in productivity of the floway in October compared to September (Tables 2 and 3; Fig. 3).

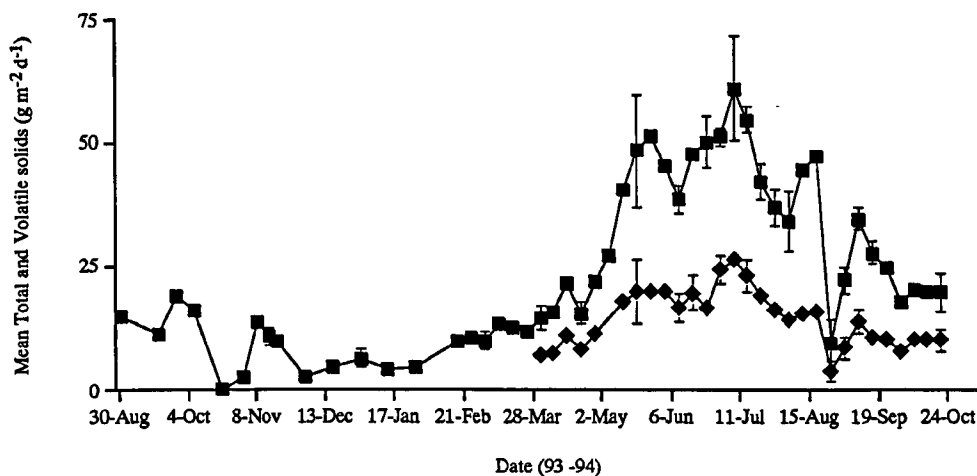


Figure 3. Total (■) and Volatile (◆) solids from the ATS. Values are means  $\pm$  s.d. of two composite samples, each from five sites.

Maintenance of the pH of the ATS/UV system effluent above that at which precipitation occurs may provide a simple means of optimising pH mediated phosphorus precipitation by the ATS. The pH may be easily maintained by controlling the length of time the wastewater is in contact with the algal turf. This may be done either by reducing the hydraulic loading rate of the floway, or passing the wastewater down a longer floway. Dissolution of precipitated phosphorus at night could possibly be prevented by either recirculating at night, or greatly reducing the flow at night such that no water is discharged.

Harvesting the floway simulates heavy grazing of the plant community which has been shown to stimulate algal growth and nutrient removal (Adey and Loveland, 1991). The maximum productivity (total solids dry weight) observed in this study ( $60.91 \text{ g m}^{-2} \text{ d}^{-1}$ ) is much greater than that previously reported on periphyton water treatment systems ( $22 \text{ g m}^{-2} \text{ d}^{-1}$ ; Davis *et al.*, 1990) and phytoplankton growing in sewage enriched outdoor mass cultures (Oswald, 1988). The harvested solids from the present study may seem extraordinarily high but this is likely due to a combination of factors, including the relatively high nutrient content of the Patterson treatment facility effluent, the shallow depth of the water (allowing for rapid gas exchange and high irradiance), fast current velocity permitting rapid nutrient assimilation and exchange, and relative absence of grazers (Davis *et al.*, 1990; Adey and Loveland, 1991). Sedimentation, filtration and precipitation of particulates on the floway surface probably also attributed to the high total solids values.

The ATS is a biological treatment system, consisting of a mixed assemblage of bacteria, phytoplankton and periphyton. The structure of the algal community was similar to that previously described (Adey and

Hackney, 1989; Adey and Loveland, 1991; Adey *et al.*, 1993), except in this study species diversity was lower and cyanobacteria and diatoms predominated during much of the year. The low species diversity and reduced performance of the ATS/UV system during the first three quarters were probably due to a lack of algal spores in the Patterson treatment facility effluent which are necessary for seeding of the floway. Higher algal species diversity was probably maintained on previous ATS floways by recirculating spore laden water through mesocosms (Adey and Loveland, 1991) or using influent from natural water bodies (Adey *et al.*, 1993).

The results presented in this paper indicate the potential of the ATS/UV system for phosphorus removal from secondary treated wastewater. The simplicity of ATS treatment systems and the ease with which configuration and operational parameters such as hydraulic loading, floway length and harvest period can be changed should enable process control and optimisation of the system for treatment of wastewaters with different phosphorus levels.

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